Scientific Geo-Tourism Development through Geomorphosite Evaluation: A Case Study of Hell's Gate National Park, Kenya

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Abstract: The Rift Valley Province of Kenya hosts some of East Africa's most iconic geomorphological landscapes, with Hell's Gate National Park exemplifying remarkable tectonic and volcanic landforms. Known for its dramatic cliffs, volcanic plugs, geothermal activity, and deep gorges, the park offers critical insights into the geomorphological evolution of the East African Rift System. Its accessibility from Nairobi and relatively low fees make it popular, yet its true significance lies in its diverse geomorphosites—landforms of scientific, educational, and cultural importance that reflect both natural history and indigenous heritage.

Although well-frequented, Hell's Gate faces challenges in developing scientific geo-tourism, including limited interpretive resources and pressures from unsustainable visitation. This study employs Reynard's (2006) geomorphosite appraisal model to assess the park's geo-heritage potential, integrating sentiment analysis of tourist reviews on social media to understand visitor experiences. The findings highlight the park's vast potential to promote sustainable geo-tourism, enhance geoscientific literacy, conserve natural heritage, and foster socio-economic benefits for local communities.

The study emphasizes the need for strategic policies that balance economic growth with ecological conservation and cultural preservation. Its insights provide a roadmap for governmental and conservation bodies to advance sustainable geo-tourism and safeguard Kenya's geomorphological heritage.

Keywords: Geomorphosite, Geological features, Geomorphological heritage, Conservation, Sustainable tourism, Carrying capacity

Introduction

Hell's Gate National Park in Kenya represents a quintessential landscape of geological marvels, encompassing a diverse array of geomorphosites of notable

scientific and educational significance. Its complex geological architecture has long attracted attention from geoscientists and researchers alike. Strategically located between Naivasha, Longonot, and Suswa, the park is part of the tectonically active East African Rift System. Mount Longonot, a prominent stratovolcano situated southeast of Lake Naivasha, last erupted in the 1860s, contributing to the region's volcanic legacy. Additionally, within the park boundaries lie two extinct volcanoes, Olkaria and Hobley, characterized by extensive obsidian deposits—igneous formations resulting from the rapid cooling of silica-rich lava. The park's geomorphological setting is renowned for its striking visual landscapes, including towering cliffs, intricately carved gorges, volcanic plugs, ash cones, and active geothermal fields, all of which bear testament to the protracted interplay of endogenic forces over geological timescales.

Formed through successive phases of volcanic and tectonic activity spanning millions of years, Hell's Gate's landscape continues to be reshaped by geothermal dynamics. Its geomorphological features are of paramount importance for understanding the geological evolution of the Rift Valley, offering empirical evidence of the ongoing tectonic and volcanic processes that define the region. Furthermore, the park plays a critical role in advancing knowledge of fluvial geomorphology, with its varied lithological formations and dissected terrain shaped by long-term fluvial erosion and sediment transport. Collectively, the volcanic, fluvial, and tectonic geomorphology offers an integrative perspective on the park's complex geomorphological development (Juliet et al., 2021). As part of the broader East African Rift Valley—a major geological province characterized by active volcanism, hydrothermal systems, and seismicity—Hell's Gate provides invaluable insights into the mechanics of continental rifting. Spanning approximately 68.25 square kilometers (UNESCO World Heritage Centre), the park also sustains diverse faunal assemblages, notably a significant herbivorous population (John, Warui & Kiringe, 1993).

In addition to its scientific prominence, Hell's Gate is among Kenya's leading tourist attractions, celebrated for its dramatic scenery, rich biodiversity, and cultural heritage. Recreational activities such as rock climbing, hiking, biking, and camping enhance its touristic appeal (Wendy, Chepkemei & Rop, 2020). However, increasing anthropogenic pressures pose challenges to its long-term conservation, underscoring the need for robust geo-conservation strategies. Systematic research on the park's geomorphosites is pivotal for developing sustainable scientific tourism models that integrate geoscientific education, environmental stewardship, and local economic development. Such initiatives are crucial not only for safeguarding the park's geoheritage but also for revitalizing Kenya's tourism industry, which has suffered significant setbacks due to the COVID-19 pandemic (Figure 1). As emphasized in Kenya's Vision 2030 (Government of Kenya, 2007), tourism remains a key pillar of national development.

Geoheritage, encompassing the diversity of geological formations, landforms, and landscapes of scientific, cultural, and aesthetic importance (Gray, 2005), provides a vital framework for evaluating Hell's Gate's geomorphological assets. The concept of geomorphosites—landforms distinguished by their exceptional geoscientific relevance—has emerged as a critical focal point for both conservation and scientific tourism (Panizza, 2001; Reynard, 2004). Scientific geo-tourism, a strategic extension of sustainable tourism, facilitates the public dissemination of geoscientific knowledge while promoting conservation ethics and fostering regional development (Dowling & Newsome, 2010). Despite its rich geodiversity, Hell's Gate National Park remains underexplored in global geoheritage scholarship. This study applies Reynard's (2008) geomorphosite assessment framework to systematically evaluate the park's geoheritage potential, aiming to identify pathways for advancing scientific geo-tourism and ensuring the sustainable management of this invaluable geological treasure.

Figure 1: Annual Tourist Arrival in Kenya
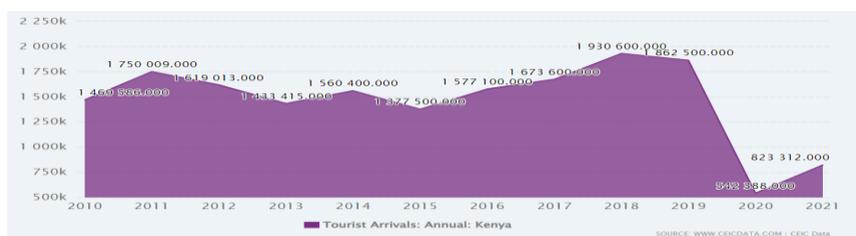
Source: Annual Tourism Sector Performance Report, Ministry of Tourism, Wildlife and Heritage,2022

Literature Review

The existing literature on Hell's Gate National Park and its geomorphosites remains relatively sparse, with few detailed scholarly contributions. Wendy Chepkemei Rop (2020), in the article *"Modelling the Impact of Geo-tourism on Geo-conservation of Hell's Gate National Park in Kenya,"* examines the interplay between geo-tourism and geo-conservation. The study focuses on prevalent geo-tourism activities, notably rock climbing and hiking, evaluating their role in sustaining the park's ecological and geoheritage integrity. Employing statistical modeling through linear regression, the research identifies a positive correlation between geo-tourism and geo-conservation, underscoring a symbiotic relationship that highlights the necessity of incorporating geo-tourism into conservation management strategies.

Sandro Lovari and Mauro Lucherini (1992), in their article *"Larger Mammals as a Tourist Attraction: Factors Influencing Their Visibility in Hell's Gate National Park, Kenya,"* investigate the temporal and spatial dynamics of mammal visibility, emphasizing the influence of diel patterns and proximity to water sources. Their analysis, based on a census of large mammals during the dry season, reveals optimal wildlife viewing conditions at sunrise and sunset, with heightened concentrations near water pools. This work integrates ecological

dynamics with tourism satisfaction metrics, using a Customer Satisfaction Index to quantify tourist experiences.

Roger N. Scoon (2020), in *"Geotourism, Iconic Landforms, and Island-Style Speciation Patterns in National Parks of East Africa,"* contextualizes Hell's Gate within the broader framework of East African rift tectonics and volcanism. The study elaborates on the geomorphological processes shaping regional drainage systems and highlights the region's exceptional biodiversity, driven by unique geological and paleo-climatic conditions. Scoon posits that ongoing rifting and volcanism have created isolated geological environments, promoting island-style speciation on a continental scale, with implications for evolutionary biology and geoheritage conservation.

In a 2018 study, Scoon provides a detailed geological account of Lake Naivasha and Hell's Gate, focusing on the Olkaria Volcanic Complex and the Njorowa Gorge. The research underscores Olkaria's dual significance as a source of geothermal energy and a key geomorphological feature, noting its critical role in Kenya's energy infrastructure and the necessity of continuous monitoring due to its geological hazards.

John Abrahams and S. Getonto (2018) investigate the ecological ramifications of geothermal development in *Hell's Gate National Park, Nakuru County,* focusing on its impacts on avifaunal diversity. Their findings illuminate the environmental pressures exerted by geothermal power stations, particularly their influence on bird populations, advocating for sustainable energy practices that harmonize with biodiversity conservation.

Mwandigha and Naivasha (2020) explore the Olkaria geothermal project within HGNP, detailing its geological attractions—such as Olkaria Hill, Njorowa Gorge, volcanic cliffs, and pyroclastic deposits—alongside its infrastructural components. The study accentuates the park's dual identity as a hub for both geothermal energy production and geo-tourism, showcasing collaborative management between the Kenya Wildlife Service and KenGen to ensure sustainable environmental stewardship.

Camiña (2019) contributes ecological insights on Rüppell's Vulture (*Gyps rueppelli*), documenting a breeding colony in Hell's Gate. The study, conducted in February 2017, observed 16 incubating adults but noted the absence of chicks or juveniles, underscoring conservation concerns for this critically endangered species.

Collectively, the literature underscores Hell's Gate's rich geomorphological and ecological character, affirming its potential as a focal site for scientific geo-tourism and conservation research.

Objective

This study aims to systematically assess selected geomorphosites within Hell's Gate National Park, Kenya, to determine their potential for the advancement of scientific geo-tourism development.

Study Area

Hell's Gate National Park, encompassing an area of approximately 6,825 hectares, was officially designated as a national park in 1984. It is situated within Kenya's Rift Valley Province, geographically positioned between 0°30'E and 1°00'S latitude and approximately 36°30'E longitude (Map 1), located about 100 kilometers northwest of Nairobi (Sandro Lovari and Mauro Lucherini, 1992). The park (Map 2) is renowned for its remarkable geomorphological diversity and hosts several significant geological formations. For the purposes of this study, three key geomorphosites were selected for detailed assessment:

1. Hell's Gate Gorge
2. Fissure Tower
3. Lake Naivasha

Each of these geomorphosites embodies distinctive geological characteristics that exemplify key processes of volcanism, tectonism, and fluvial dynamics. They serve not only as natural laboratories for advancing geoscientific knowledge but also as critical indicators of ongoing geological phenomena. However, these sites are increasingly susceptible to degradation due to both natural geomorphic processes and anthropogenic pressures, underscoring the urgent need for integrated conservation and sustainable geo-tourism strategies.

Major Geomorphosites at Hell's Gate National Park:

1. Hell's Gate Gorge: Hell's Gate Gorge, an impressive geomorphological feature within Hell's Gate National Park, is a deep and narrow incision formed by the Njorowa Gorge River. Extending approximately 1.5 kilometers in length and reaching depths of up to 80 meters, the gorge exemplifies the interplay of volcanism, tectonism, and fluvial dynamics that have shaped the landscape of Kenya's Central Rift Valley (Image 1).

The genesis of the gorge is attributed to a combination of volcanic activity and subsequent erosional processes. Approximately 13 million years ago, extensive volcanic eruptions deposited successive lava flows across the valley floor. These basaltic and trachytic flows, punctuated by obsidian deposits, later became subject to sustained fluvial incision by the Njorowa Gorge River, gradually sculpting the current gorge morphology. The gorge walls exhibit distinct stratification of volcanic rocks, where contrasting lithologies and mineralogical compositions—basalt, obsidian, and trachyte—create a striking visual tapestry.
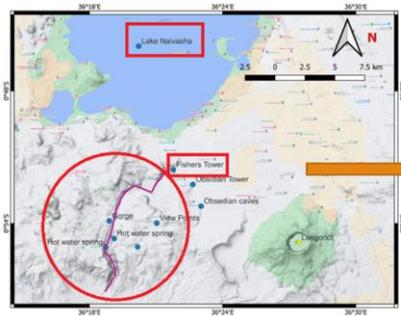
Map 1: Great East African Rift

. *Source*: http://images.encarta.msn.com/
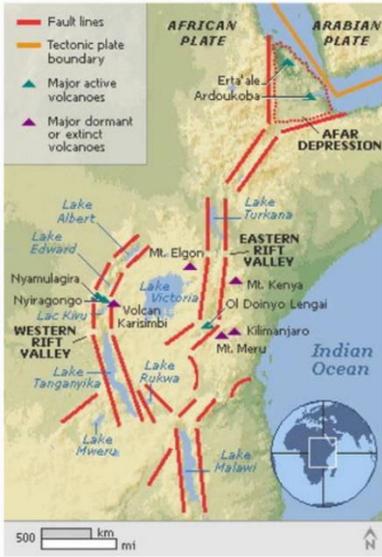
Map 2: Study Area Location

HELL'S GATE NATIONAL PARK LAYOUT
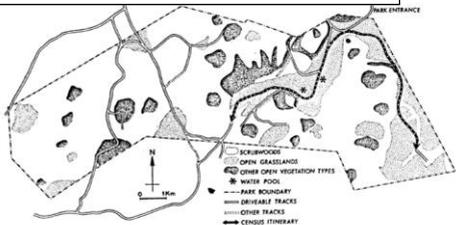
Source: Authors, 2023

Source: Sandro, Lovari., Mauro, Lucherini. (1992).

Key Geological Processes:

- Volcanism: A series of eruptive events approximately 13 million years ago resulted in widespread lava emplacement, infilling pre-existing depressions and creating a foundation for subsequent geomorphic development.
- Rift Faulting: Situated within the tectonically active Great Rift Valley, Hell's Gate National Park is characterized by significant crustal extension. The ongoing divergence between the African and Arabian tectonic plates has produced a network of faults and rift-related valleys, with the Njorowa Gorge River occupying a fault-aligned structural depression.
- Fluvial Erosion: The erosive force of the Njorowa Gorge River, augmented by the steep gradient and the mechanical resilience of volcanic substrates, progressively dissected the lava flows, culminating in the gorge's present-day form. The incision process also reveals evidence of sediment transport, channel migration, and terrace formation, integral to understanding fluvial geomorphology in rift settings.

Hell's Gate Gorge is typified by towering volcanic cliffs, ephemeral waterfalls, and localized geothermal manifestations such as hot springs. The gorge serves as a natural laboratory illustrating riverine incision into pyroclastic and lava-dominated terrains. Visitors traversing the gorge can directly observe geomorphic features that demonstrate active processes of erosion, sediment deposition, and landscape adjustment (Image 2). Additionally, the geomorphology reflects historical fluvial dynamics, including channel migration patterns and the influence of climatic variability on hydrological regimes.

The region's soils, derived predominantly from volcanic and lacustrine deposits, are porous and exhibit limited water retention capacity. As a result, surface runoff from precipitation events rapidly infiltrates the substrate, reducing overland flow and influencing geomorphic processes (Sandro Lovari and Mauro Lucherini, 1992).

Detailed examination of fluvial landforms such as terraces, meanders, and sedimentary facies within the gorge offers chronological insights into the evolution of the local drainage network and broader landscape transformations over geological time scales.

Today, Hell's Gate Gorge stands as both a significant geoheritage site and a focal point for geo-tourism. It provides critical data for reconstructing the volcanic and tectonic history of the Central Rift Valley and supports diverse biotic communities uniquely adapted to this dynamic environment.

Image 1: Hells Gate Gorge

Hell's Gate National Park

Source:https://www.lakenakurukenya.com/hells-gate-national-park/

Image 2: Hells Gate Gorge

Source: https://www.travelblog.org/Photos/7273599

2. Fischer's Tower: Fischer's Tower is an iconic geomorphological feature within Hell's Gate National Park, characterized as a volcanic plug rising approximately 25 meters in height, composed predominantly of basaltic rock (Image 3). The tower derives its name from Gustav Fischer, a German explorer who notably ascended the structure in 1883, marking its first recorded climb (Kenya Wildlife Service, 2016).

The formation of Fischer's Tower is attributed to volcanic activity dating back approximately 35 million years. During this period, magmatic intrusions ascended through fissures within the Earth's crust, a process integral to the park's volcanic landscape evolution. As the magma ascended and encountered cooler near-surface conditions, it solidified within the fissure, forming a dense, erosion-resistant volcanic plug. Over geological time, extensive weathering and erosion removed the less resistant surrounding material, progressively exposing the resilient basaltic core that stands prominently today (Image 3).

Key Geological Processes:

- **Volcanism:** The genesis of Fischer's Tower is rooted in volcanic eruptions approximately 35 million years ago, during which fissural vents allowed magma to intrude into the overlying strata.
- **Magma Intrusion and Plug Formation:** The ascending magma intruded into a pre-existing fissure, where it cooled and crystallized in situ to form a solid igneous core—a volcanic plug. Such plugs typically occupy the central conduit or vent of an extinct volcano.
- **Differential Erosion:** Subsequent erosional processes acted upon the landscape, preferentially wearing down the surrounding softer pyroclastic and sedimentary rocks while leaving the hard, basaltic plug relatively intact. This differential erosion underscores the tower's current prominence within the park's geomorphological framework.

Fischer's Tower is not only of geological significance but also serves as a focal point for adventure tourism, particularly rock climbing, offering panoramic views of the Rift Valley escarpment and adjacent volcanic features. Ecologically, it provides critical nesting habitats for raptors such as vultures and eagles, further enriching its biodiversity value.

Culturally, the tower is embedded in Maasai folklore, symbolizing a Maasai girl who, according to legend, was transformed into stone as a consequence of defying familial authority prior to her wedding (Kenya Wildlife Service, 2016). This intertwining of geological and cultural narratives enhances the tower's stature as both a natural and heritage landmark.

Fischer's Tower thus exemplifies the interaction of deep-seated igneous processes and surface geomorphic dynamics, standing as a testament to the region's volcanic history and as a prominent feature within the Central Rift Valley's Geomorphosite inventory.

Image 3: Fischer's Tower

Source: https://africantourer.com/attraction/fischer's-tower

3. Lake Naivasha: Lake Naivasha is a significant freshwater body located within the eastern segment of the Great Rift Valley in Kenya. Geographically positioned at an elevation of approximately 1,884 meters (6,181 feet) above sea level, it is recognized as the highest lake along the eastern branch of the Rift Valley system. The lake spans an area of about 139 square kilometers (54 square miles), with its deepest point reaching approximately 30 meters (98 feet), underscoring its importance as both a hydrological and ecological feature of the region (Image 4).

The formation of Lake Naivasha is intrinsically linked to the combined effects of volcanic and tectonic processes. Approximately 2.5 million years ago, successive episodes of volcanic eruptions occurred in the vicinity, resulting in extensive lava flows that subsequently dammed the Njorowa Gorge River. This natural damming led to the impoundment of water and the eventual development of the lake basin, a process typical of Rift Valley lacustrine systems where volcanotectonic activity plays a pivotal role in basin formation and hydrological evolution.

Lake Naivasha's location approximately 80 kilometers northwest of Nairobi further enhances its accessibility and significance. The lake's ecological and hydrological value was formally recognized in 1995 when it was designated as a

RAMSAR site, thereby acknowledging its status as a wetland of international importance under the Ramsar Convention (Harper et al., 2011). This designation reflects the lake's vital role in supporting diverse aquatic and terrestrial biodiversity, as well as its function in regional water balance and local livelihoods.

From a geomorphological perspective, Lake Naivasha serves as a prime example of Rift Valley lake formation driven by the interplay of volcanic damming and tectonic faulting. Its catchment area is marked by geological features associated with rifting, including lava plains, fault scarps, and geothermal activity, which continue to influence the lake's morphology and hydrology.

In summary, Lake Naivasha epitomizes the dynamic interactions between endogenic (volcanic and tectonic) and exogenic (fluvial and lacustrine) processes within the Rift Valley landscape. Its status as both a Geomorphosite and an ecological hotspot underscores the importance of integrated conservation and management strategies aimed at sustaining its multifaceted environmental and socio-economic functions.

Image 4: Lake Naivasha

Source: [Travel Guide Lake Nakuru and Lake Naivasha: Great Rift Valley's soda lakes (wild-wings-safaris.com)](#)

Lake Naivasha: Geological Processes and Formation

Lake Naivasha is situated within the tectonically active zone of the Great Rift Valley, a region formed by the divergent movement of the African and Arabian tectonic plates. This tectonic separation has given rise to a series of fault lines and associated valleys, with Lake Naivasha lying along one such fault. The lake's hydrology is influenced by several tributary rivers, including the Njorowa Gorge

River, Gilgil River, and Malewa River. It is an endorheic lake, meaning it has no external outlet, and its water levels fluctuate based on seasonal rainfall and the volume of inflowing water (Image 4).

The formation of Lake Naivasha is closely tied to volcanic and tectonic processes that have shaped the Rift Valley landscape. Approximately 2.5 million years ago, a series of volcanic eruptions in the region generated extensive lava flows. These flows dammed the Njorowa Gorge River, leading to the creation of the lake. The lava damming process exemplifies the complex interaction between volcanic and fluvial dynamics in Rift Valley Lake formation.

The tectonic setting of Lake Naivasha is significant, as it lies within the active zone of the Great Rift Valley, where the African and Arabian plates continue to diverge. This tectonic activity results in ongoing faulting and valley formation, which contributes to the structural features surrounding the lake. The lake itself has evolved through the accumulation of rainwater and runoff from surrounding catchments, gradually enlarging and deepening over time due to the inflow of water from the Njorowa Gorge River and other local rivers.

Lake Naivasha's ecological importance cannot be overstated. It serves as a critical habitat for a diverse range of wildlife, including species such as giraffes, zebras, hippos, and crocodiles. The lake's unique position within the Rift Valley ecosystem, along with its relatively high altitude, makes it a key site for both biodiversity conservation and eco-tourism. The lake's shoreline and its proximity to other geological features in the area further enhance its appeal as a popular destination for tourists, who can engage in activities such as boat trips, fishing, and relaxation along the shore.

The formation of Lake Naivasha illustrates the dynamic interplay between volcanic activity, tectonic faulting, and fluvial processes within the context of the Great Rift Valley. Its continued evolution and ecological significance make it a valuable resource for both scientific study and environmental conservation.

Theoretical Framework:

Geotourism, as articulated by Boskov et al. (2015), represents a specialized form of tourism that focuses on the exploration of geological, geomorphological, and landscape features. It promotes a deep understanding of geosites while encouraging sustainable tourism practices (Dowling, 2013; Ngwira, 2019). A pivotal model in the study of geotourism is Reynard's framework, which explores the interplay between geomorphology and tourism (Figure 2). This model is particularly useful for the development and promotion of scientific geotourism at Hell's Gate National Park.

Reynard (2008) asserts that the geomorphological and geological attributes of a site form its "original offer" – the primary attraction that underpins tourist activities. These geomorphological features serve as the core of the geotourism experience, offering a foundation for activities such as hiking, rock climbing, and leisurely bush walks (Wendy Chepkemei Rop, 2020). Reynard's model also

emphasizes the importance of developing supporting infrastructure, including educational trails, informational booklets, and guided tours, to enhance the visitor experience and maximize the potential of existing attractions.

The model further highlights the significance of geodiversity and its intrinsic value to human activities, as emphasized by Gray (2004). By leveraging this framework, stakeholders can design and promote geotourism products that are both engaging and educational, fostering a deeper appreciation of the region's geological heritage. Moreover, tourism activities at isolated geosites can create seasonal employment opportunities, thus benefiting local communities.

In the context of Hell's Gate National Park, applying Reynard's model to identify and assess the park's most significant geomorphological features allows for the development of tailored geotourism products and experiences. These initiatives can raise public awareness of the park's geo-heritage, attract a broader range of visitors, stimulate the local economy, and support ongoing conservation efforts. The potential of scientific geotourism for Hell's Gate National Park is thus assessed through Reynard's Geomorphosite model (Figure 2), providing a framework for sustainable tourism development and the promotion of the park's unique geological assets.

Figure 2: Reynard Model
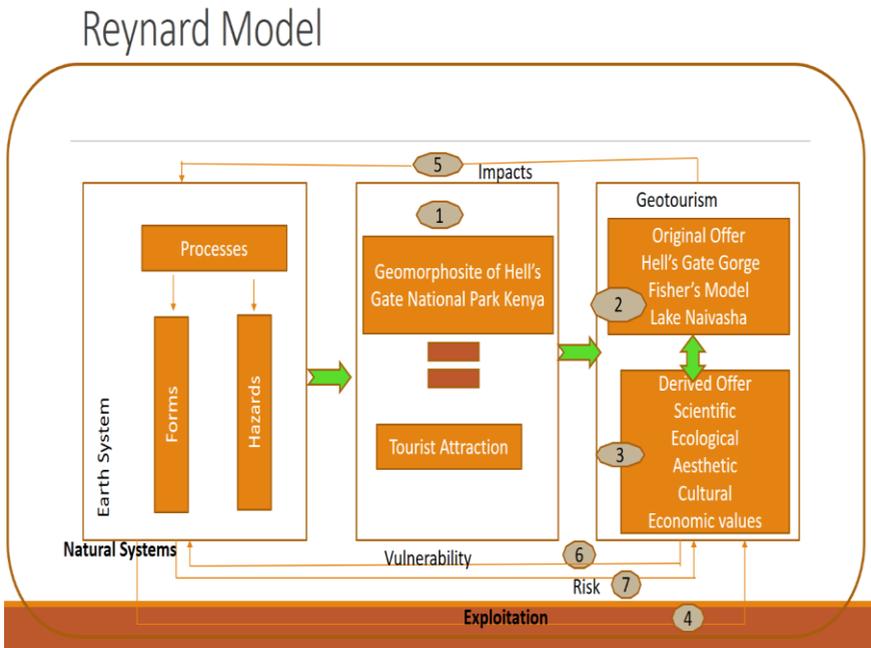
Source: — Reynard Model for Scientific Research and Tourist Promotion of Geomorphological Heritage (Source: Reynard, 2008; modified by authors).

The model provides a holistic framework for sustainable tourism development (Reynard & Brilha, 2018). It incorporates comprehensive assessment methods to evaluate geosites and geomorphosites from multiple perspectives (Arora, K., Rajput, S., & Anand, R. R., 2020).

MATERIAL AND METHODS

This study focused on three of the most visited and geomorphologically significant sites within Hell's Gate National Park, selecting them as geo-sites for evaluation. The chosen sites were Hell's Gate Gorge, Fischer's Tower, and Lake Naivasha. Subsequently, a tourism perception study was conducted for these geomorphosites, analysing their scientific, educational, economic, and conservation values through sentiment analysis. Data were gathered from social media platforms such as YouTube, Facebook, and other online content sources.

Sentiment analysis, a crucial domain in tourism research, involves extracting and interpreting the sentiments expressed by users in textual data. It serves as a valuable tool for understanding tourist opinions and preferences, thereby aiding in the enhancement of tourist satisfaction and experience. The surge in sentiment analysis research within the tourism sector, particularly post-COVID-19, highlights the increasing importance of social media as a tool for gauging public sentiment (Asra, Yaqub, 2023). Since its inception in the 1970s, sentiment analysis has played a significant role in evaluating tourist perspectives, making it particularly relevant for this study, as it captures visitor perceptions of the geomorphosites in Hell's Gate National Park.

Feedback from visitors was categorized as either positive, negative, or neutral, based on five key parameters aligned with the Reynard Model (2008), which are:

1. Scientific Value
2. Ecological Value
3. Cultural Value
4. Aesthetic Value
5. Economic Value

For each of these criteria, the frequency of positive and negative feedback was analyzed to generate scores that reflect the tourism potential of each geomorphosite. The inclusion of visitor feedback is integral to the Reynard model, as it recognizes the visitor as a central actor in the tourism experience. Without the participation of visitors, tourism activities would lose their significance. Therefore, understanding visitor sentiments is essential to the model's framework.

Each geomorphosite within Hell's Gate National Park was assessed using the Reynard Model, assigning scores to each of the criteria based on the frequency and nature of the feedback. The combination of sentiment analysis and the Reynard Model provides a comprehensive approach to understanding the

geomorphosites, bridging scientific evaluations with public perceptions. This integrated methodology enables the identification of sites with high tourism potential, as well as the prioritization of those requiring further development or conservation efforts.

For instance, a geomorphosite that scores highly on both the Reynard Model and sentiment analysis would be deemed a high-priority site for scientific geo-tourism development. Such a site is considered not only scientifically significant but also appreciated by visitors, making it a focal point for conservation and tourism initiatives. This integrated approach allows for the strategic promotion and development of Hell's Gate National Park as a geo-tourism destination.

Methodology: Geomorphosite Evaluation

The study applies Reynard's (2008) Geomorphosite Assessment Model, which evaluates landforms based on the following criteria:

- Scientific Value: Includes rarity, representativeness, integrity, and interpretive potential.
- Educational Value: Based on accessibility, didactic potential, and visibility of processes.
- Touristic Value: Assesses aesthetic appeal, infrastructure, and visitor experience.
- Protection Value: Considers legal status, vulnerability, and current conservation measures.

The evaluation incorporated field observations, GPS mapping, photographic documentation, and review of geological and conservation literature (Anand et al., 2023). Selected geomorphosites were assessed using descriptive and comparative methods to score their relative significance.

SWOT Analysis of Scientific Geo-Tourism in Hell's Gate National Park

| Strengths	Weaknesses
Unique geomorphosites with scientific, aesthetic, and educational value.	Limited interpretive infrastructure and signage.
Proximity to Nairobi and accessible infrastructure.	Vulnerability to natural hazards like flash floods.
Presence of geothermal features and active landforms.	Inconsistent conservation enforcement.
Opportunities	Threats
Integration with educational and scientific research.	Environmental degradation from over-tourism.
Development of sustainable geo-trails and geoheritage interpretation.	Unregulated development and geothermal exploitation.
Potential for UNESCO Global Geopark designation.	Climate-related impacts on landscape stability.

Geomorphosite Evaluation of Hell's Gate National Park

Geomorphosite	Scientific Value	Educational Value	Touristic Value	Protection Value
Hell's Gate Gorge	High: Classic example of fault-guided fluvial incision and geothermal erosion.	High: Easily accessible with visible processes; ideal for field teaching.	High: Visually dramatic; popular hiking trail.	Moderate: No specific legal status; erosion and flash floods pose threats.
Fischer's Tower	High: Volcanic plug showing differential weathering and resistant lithology.	Moderate–High: Clear structure, good for volcanic landform interpretation.	High: Landmark for photography, rock climbing, and cultural interpretation.	Moderate: Subject to weathering and unregulated visitor activities.
Central Tower	High: Volcanic remnant with panoramic view; important for volcanic morphology.	Moderate: Good observation point, less signage for interpretation.	Moderate–High: Adventure interest, aesthetic prominence.	Low–Moderate: No protective signage or geosite zoning.
Obsidian Caves & Springs	High: Rare volcanic glass outcrops; active geothermal features.	High: Opportunities to teach about volcanism, hydrothermal systems.	High: Unique geothermal setting; potential for spa/eco-tourism.	Moderate: Sensitive to over-visitation and geothermal drilling impacts nearby.
Lake Naivasha (fringe)	Moderate–High: Rift lake dynamics, hydrological changes, and sedimentation patterns.	Moderate: Less accessible from the park; still offers teaching potential.	Moderate: Birdwatching, lakeside tourism outside the main park area.	Moderate: Some protection under wetland and Ramsar frameworks.

6. Discussion and Implications for Geoheritage Conservation

The geomorphosites of Hell's Gate provide opportunities for multi-level geoeducation—from school field trips to advanced academic research. The integration of geo-trails, interpretive panels, and digital apps can enhance the visitor experience and awareness of geoscientific values. The SWOT analysis reveals that while strengths and opportunities are significant, threats such as over-tourism and geothermal exploitation need urgent mitigation through policies and public education.

Designating the area as a UNESCO Global Geopark or enhancing its visibility in Kenya's national geoheritage strategy could offer long-term protection and community-based development (Gray, 2005; Reynard et al., 2016). Partnerships with universities, conservation NGOs, and tourism authorities can support infrastructure development and environmental monitoring.

Reynard Model for Hell's gate george
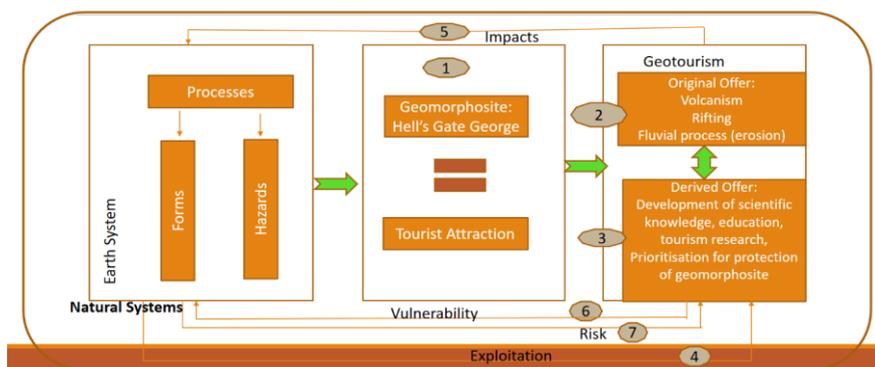
Source: Reynard Model for Scientific Research and Tourist Promotion of Geomorphological Heritage (Source: Reynard, 2008; modified by authors,2024)

Table 1: Sentiment Analysis of Hell's Gate Gorge as per Renayard Model and its Score

Sentiment Analysis of Hell's Gate Gorge as per Reynard model

Criterion	Sentiment	Frequency	Social media platform major Comments
Rarity	Positive	90%	Hell's Gate Gorge is a unique geocomposite with features such as towering cliffs, waterfalls, hot springs, and geothermal activity.
Representativeness	Positive	85%	Hell's Gate Gorge is a good representative of a volcanic gorge.
Integrity	Positive	80%	Hell's Gate Gorge is relatively intact and has not been disturbed by much human activity.
Vulnerability	Negative	10%	Hell's Gate Gorge is vulnerable to erosion and climate change.

Reynard Model Score: Hell's Gate Gorge

| Hell's Gate Gorge	score
Scientific value	3
Ecological value	3
Cultural value	2
Aesthetic value	3
Economic value	3
Total	14

Source: Authors,2024

Hell's Gate Gorge could be a very important potential site for scientific tourism however It is important to manage Hell's Gate Gorge sustainably to protect its significance for future generations as tourism promotion can lead to overcrowding and environmental degradation.

A significant constraint in the development of Scientific tourism at this site was observed is that it is associated with flash floods leading to a toll on human lives and animals without any warning and time and again news of tourist casualties is highlighted in the news. This issue can be resolved through technology and digital tourism experiences like Augmented Reality.

Development of smartphone-based Ex-situ educational products to study features through QR codes. This will enable digital tourists to educate and obtain training without risks. It will also help reduce pollution and protect the site-associated environment and wildlife as the gorge is also home to a variety of wildlife, including zebras, giraffes, and buffalo. However, these animals are vulnerable to poaching and habitat loss.

Image 5: Media Reports about Flash Flood
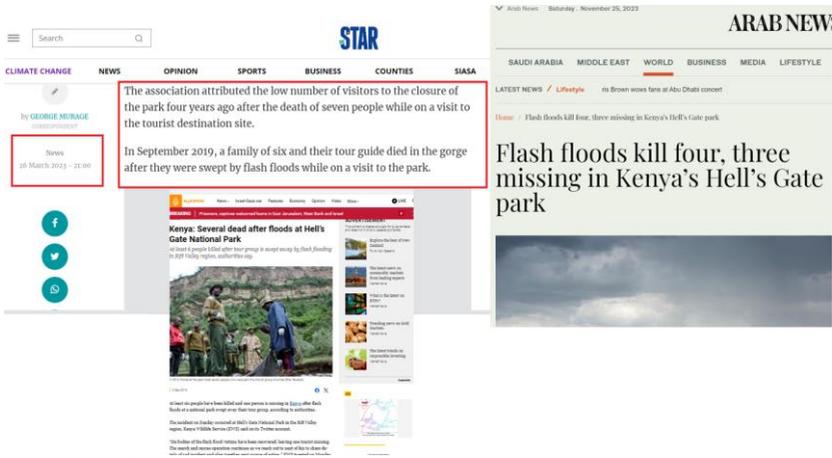
Source: Compile by Authors,2024

Fischer's Tower: Fischer's Tower scored high on the scientific value, aesthetic value, and economic value criteria in the Reynard model, but it scored lower on the integrity criterion. The model score is slightly lower than the score assigned to Hell's Gate Gorge, which reflects the fact that Fischer's Tower is not as ecologically or culturally significant as Hell's Gate Gorge. However, Fischer's Tower is still a valuable geomorphosite with a high scientific, aesthetic, and economic value. Looking at its high score in the context of scientific value it could become one of the important sites for scientific tourism in Hells Gate Park.

Figure 4: Reynard Model for Fischer's Tower
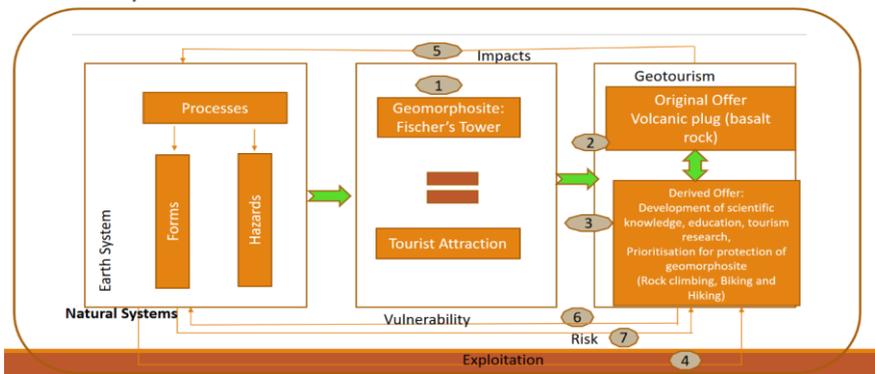
Source ─: Reynard Model for Scientific Research and Tourist Promotion of Geomorphological Heritage (Source: Reynard, 2008; modified by authors,2024)

Table 2: Sentiment Analysis of Fischer's Tower as per Renayard Model and its Score

Sentiment Analysis of Fischer's Tower as per Reynard model

Criterion	Sentiment	Frequency	Social media platform major Comments
Rarity	Positive	95%	Fischer's Tower is a very rare geomorphosite. It is a volcanic rock formation that is over 30 million years old.
Representativeness	Positive	90%	Fischer's Tower is a good representative of a volcanic rock formation. It is also a good representative of the geology of the Hell's Gate National Park.
Integrity	Positive	85%	Fischer's Tower is relatively intact and has not been disturbed by much human activity.
Vulnerability	Negative	10%	Fischer's Tower is vulnerable to vandalism and erosion.

Reynard Model Score: Fischer Tower

Fischer's Tower	score
Scientific value	3
Ecological value	2
Cultural value	2
Aesthetic value	3
Economic value	3
Total	13

Source: Author 2024

However, it is important to note that the tower is vulnerable to erosion, as it is a popular tourist destination for rock climbers and hikers, which could impact its significance in the future. The tower is also home to a variety of wildlife, including birds and bats. It is important to manage Fischer's Tower sustainably to protect its scientific significance for future generations. This can be done by limiting vandalism, reducing erosion, and protecting wildlife. Here are some specific actions that can be taken to protect Fischer's Tower:

- Installation of educational signage to inform visitors about the importance of the tower and the need to respect it.
- Increase patrols of the area to deter vandals.
- Implement erosion control measures, such as planting vegetation around the tower.
- Monitor the tower for signs of damage and take corrective action as needed.
- Work with local communities to develop a sustainable management plan for the tower.

By taking these steps, it can be ensured that Fischer's Tower remains a valuable geomorphosite for future generations to enjoy.

Lake Naivasha: Approximately 5% of the total 1.5 million worldwide visitors yearly pass through Lake Naivasha region in Kenya (The Economic Impact of Travel and Tourism, 2014). Lake Naivasha scored high on the scientific value and ecological value criteria in the Reynard model, but it scored lower on the aesthetic value and economic value criteria due to its vulnerability to human activity. The Reynard model score suggests that Lake Naivasha is a highly valued geomorphosite with a high scientific, ecological, aesthetic, and economic value. The lake also has some cultural value, but this could be improved through better management and conservation efforts.

Figure 5: Reynard Model for Lake Naivasha
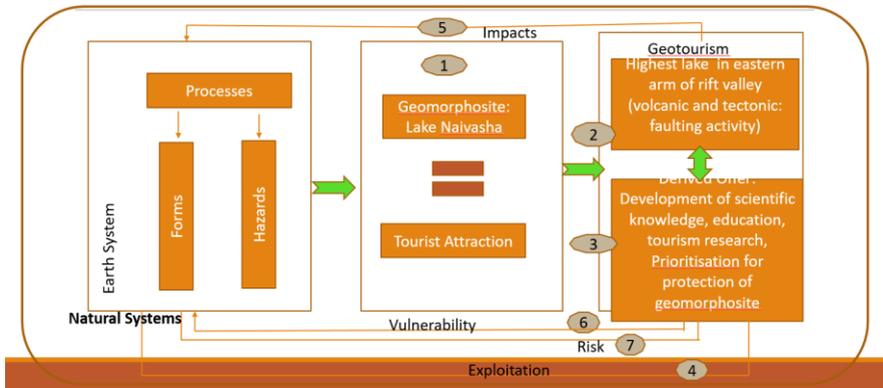
Source:—Reynard Model for Scientific Research and Tourist Promotion of Geomorphological Heritage (Source: Reynard, 2008; modified by authors)

Table 3: Sentiment Analysis of Fischer's Tower as per Renayard Model and its Score

Sentiment analysis of Lake Naivasha as per the Reynard model of Geomorphosite

Sentiment analysis	Frequency	Social media platform major Comments
Positive	85%	Lake Naivasha is a beautiful and diverse freshwater lake. Visitors are impressed by the lake's scenery, wildlife, and recreational opportunities.
Negative	15%	Lake Naivasha is vulnerable to pollution, overfishing, and climate change.

Reynard Model Score: Lake Naivasha

Lake Naivasha	Score
Scientific value	2
Ecological value	3
Cultural value	2
Aesthetic value	3
Economic value	3
Total	13

Source: Authors, 2024

Visitors' Perception and Challenges for Lake Naivasha's Sustainability

Visitors to Lake Naivasha are often impressed by the lake's scenic beauty, diverse wildlife, and recreational opportunities. However, the lake faces several challenges that threaten its long-term viability, including pollution, overfishing, and the impacts of climate change. These factors pose significant risks to the lake's geomorphological value, particularly as its water levels have recently declined. This decline is attributed to a combination of factors such as climate change, excessive water extraction for irrigation, and deforestation (Awange et al., 2013).

The population within the Lake Naivasha basin has experienced rapid growth, increasing from 20,000 in 1970 to approximately 375,000 by 2009 (KNBS, 2009). This urban expansion is marked by a growth rate of about 3.1% annually, with a substantial concentration of population in urban areas, yielding a density of roughly 500 people per square kilometer. Over the past three decades, the urban population has grown nearly tenfold, rising from 7,000 in 1969 to 67,000 in 2002 (Njiru et al., 2017). Such rapid population growth exacerbates the challenges faced by the lake, as increased demand for resources leads to higher pollution and resource depletion.

In light of these pressures, it is essential to adopt a proactive approach to ensure the sustainability of Lake Naivasha as a valuable geomorphosite. Some targeted actions include:

1. **Reducing pollution** from agricultural runoff and industrial activities.
2. Implementing sustainable fishing practices to mitigate overfishing.
3. **Establishing protective measures** against climate change impacts and other environmental threats.
4. **Promoting sustainable tourism** to minimize the ecological footprint around the lake.
5. **Collaborating with local communities** to enhance the sustainable management of the lake.

By adopting these strategies, the long-term sustainability of Lake Naivasha as a geomorphosite can be ensured, preserving its unique features for future generations.

Understanding Carrying Capacity in the Development of Scientific Geotourism

The development of scientific geo-tourism requires an understanding of the carrying capacity of a site, which is defined as the maximum number of visitors that can be accommodated without causing harm to the geomorphosite or its surrounding environment. Various factors influence the carrying capacity, including:

1. The size of the geomorphosite.
2. The fragility of the rocks and minerals within the site.
3. The sensitivity of the surrounding ecosystem.

In certain instances, carrying capacity may also be constrained by the availability of critical infrastructure, such as parking facilities and sanitation services. At Hell's Gate National Park, the availability of drinking water is a significant issue. The park lacks enduring natural water sources, which necessitates the use of artificially fed water troughs for resident wildlife. To address this, the management has constructed five water troughs and drilled a borehole to supplement the water provided by the Ministry of Water pipeline (Kenya Wildlife Service, 2018).

The Kenya Wildlife Service (KWS) is responsible for managing the geomorphosites within the park, ensuring that these sites are not overcrowded and that tourism activities do not damage the natural environment. Furthermore, KWS plays a vital role in educating visitors about the importance of conserving Kenya's geological heritage. Given the limited infrastructure and water resources at the park, it is crucial for KWS to monitor and regulate the growth of scientific geo-tourism to avoid exceeding the carrying capacity of the park.

Limitations of the Study

It is important to note that the Reynard model is just one of several methods used to assess the value of geomorphological heritage. Other models and approaches may offer additional insights into the management and development of geo-tourism at Hell's Gate National Park.

Recommendations for Sustainable Scientific Geo-Tourism Development

To prioritize the sustainable development of scientific geo-tourism in Hell's Gate National Park, several actions can be taken:

- **Development of a mobile application**: This could provide visitors with up-to-date information about the park's trails, wildlife, and geological features. Despite the availability of tourism materials such as brochures and guidebooks, these resources are often outdated and underutilized (Kenya Wildlife Service, 2018). A mobile app could bridge this gap and enhance the visitor experience by providing accurate, real-time information.

- **Protection of vulnerable geomorphosites**: The park authorities should focus on conserving geomorphosites that are highly valued by visitors but are also susceptible to environmental threats. For instance, Fischer's Tower and Lake Naivasha are key geomorphosites that require focused management efforts.

- **Regulation of pollution and overfishing**: Stricter measures should be implemented to limit pollution and overfishing in Lake Naivasha, including the enforcement of water extraction and fishing regulations.

- **Ongoing monitoring and corrective action**: Continuous monitoring of geomorphosites should be conducted to identify potential damage and take appropriate corrective actions, such as implementing erosion control measures and repairing any physical damage to the sites.

- **Collaboration with local communities**: A sustainable management plan for the park should be developed in collaboration with local communities to ensure that the needs of both the environment and the local population are met.

Conclusion

In conclusion, the Reynard model provides a valuable framework for assessing the tourism potential of the geomorphosites in Hell's Gate National Park. However, it is crucial to consider its limitations, as well as the impact of human activity, to ensure the preservation of the park's unique geological features. Further research is necessary to refine the model and enhance its accuracy in predicting changes to the park's geomorphology. The unique geology and diverse wildlife of the park make it a significant destination for geo-tourism and conservation, requiring careful planning and sustainable management practices.

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