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A facility location model to support the ecosystem restoration and sustainable management of the Bushbuckridge Nature Reserve in South Africa

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Abstract : Tourism is a major contributor to South Africa's economy. Before the COVID-19 pandemic, it accounted for about 8.6% of national GDP. Nature reserves play an essential role in this sector, as South Africa is a global leader in wildlife tourism. Large, privately managed parks (e.g., Kruger National Park and Pilanesberg National Park) have performed well over the years. However, smaller reserves—primarily those managed by provincial and local governments (e.g., Manyeleti Nature Reserve, Mariepskop Nature Reserve, and Bushbuckridge Nature Reserve)—have struggled to remain financially viable while also addressing the needs of surrounding communities. The Bushbuckridge Nature Reserve, located in Mpumalanga Province, South Africa, has recently set the objective of becoming a world-class nature reserve that maintains biodiversity integrity through conservation while permitting sustainable use of natural resources by neighbouring communities. In this work, we present an optimization model to help management explore and analyze options for ecosystem and wildlife restoration. The model can also serve as a tool to facilitate negotiations between reserve management and local communities and to incorporate their interests in the revitalization process. Specifically, we propose a facility location model to reshape the reserve's ecosystem and wildlife to maximize animal welfare and tourist appeal, while supporting optimal and sustainable use of natural resources by local communities. Computational experiments are presented to illustrate the model's potential for supporting decision-making.

Keywords : Integer programming; facility location problem; tourism industry; sustainable tourism; quadratic integer programming

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1 Introduction

Tourism is a major contributor to South Africa's economy. Indeed, travel and tourism contribute 8.6% of the South African economy and provide about 9.2% of total employment in the country (Malik-Nair, 2023). Tourist attractions such as nature reserves play an essential role in this sector, as South Africa is a global leader in wildlife tourism. However, some government-owned protected sites, such as Bushbuckridge Nature Reserve (BNR), have struggled to remain financially viable while also addressing the needs of local communities. Barnes et al. (2019) argue that "wildlife tourism offers both major economic potential for developing countries, even allowing for the necessary investment in infrastructure, and an opportunity to manage wildlife resources sustainably".

BNR subscribes to this notion, as it has recently set the objective of becoming a world-class nature reserve that maintains biodiversity integrity through conservation while permitting sustainable use of its natural resources by neighbouring communities (Municipality, 2017). BNR is located in the north of Mpumalanga Province, within the Bushbuckridge Local Municipality. It is surrounded by local communities. The reserve covers about 7,000 hectares and is co-managed by the Mpumalanga Tourism and Parks Agency (MTPA) and Communal Property Associations (CPAs) through an Integrated Management Plan. Notably, BNR is subject to land claims by two CPAs: the Sisonke CPA (95%) and the Injaka Waterval CPA (5%).

BNR presents an opportunity to restore and conserve the ecosystem because it used to be one of the province's best-managed and well-preserved nature reserves. Partnerships with local communities that honour their traditions and values—including discussions around human–wildlife conflict—are therefore paramount. Creating employment through restoration and conservation, integrating scientific activities, and reopening the reserve to tourists could contribute significantly to the tourism sector and to South Africa's gross domestic product (GDP) from this region.

Management has outlined plans to offer visitors and future generations a safe and unique nature experience (Government, 2004). Such plans aim to improve the reserve's ecological condition and visitor experience. Braithwaite and Reynolds (2002) note that high-quality wildlife experiences are arguably among the most valued nature-based experiences. At the same time, wildlife tourism seeks to increase the likelihood of memorable encounters while protecting wildlife resources (Braithwaite and Reynolds, 2002). These considerations highlight the importance of mathematical models for addressing challenges faced by protected sites such as BNR in the area of biodiversity. Biodiversity is described by Noss (1990) as the composition, structure, and function inferred at four levels of organization: regional–landscape, community–ecosystem, population–species, and genetic. Accordingly, through authorities such as the Mpumalanga Tourism and Parks Agency (MTPA), South Africa has recognized the importance of biodiversity protection through legislation. Hence, effective management of declared protected areas must consider biodiversity conservation.

Areas adjacent to the reserve have undergone habitat loss, and the size and density of human settlements in Bushbuckridge have increased (Coetzee and Averbeke, 2010). The activities of impoverished communities are seen as a major driver of landscape change. Increases in human-impacted vegetation suggest that rural settlements depend on adjacent communal lands for cattle grazing, fuelwood, and medicinal plants. These factors further stress the importance of the nature reserve as a conservation area and the need for detailed terrestrial biodiversity data.

In addition, BNR has the potential to contribute to conservation as mandated by the National Biodiversity Act (Act No. 10 of 2004) (Government, 2004) and the Mpumalanga Nature Conservation (Act No. 10 of 1998) (Mpumalanga, 1998). The reserve's value as a significant catchment area and its position in the Kruger to Canyons Biosphere Reserve, as an ecological corridor, should be viewed as added advantages. The envisaged activities in the nature reserve will link the Blyde River Canyon Nature Reserve and Kruger National Park to maintain and improve the movement of animals and plants through reserves and potentially improve the resilience of ecosystems to climate change.

As in many other nature reserves, human–wildlife conflict and coexistence are serious challenges. This is also the case for BNR, where livestock from boundary communities enter the reserve because parts of the fence are damaged. Nyhus (2016) notes that human interactions with wildlife are a defining experience of human existence, although these interactions can be positive or negative. People compete with wildlife for food and resources and have eradicated dangerous species, co-opted and domesticated valuable species, and applied a wide range of social, behavioral, and technical approaches to reduce negative interactions with wildlife (Nyhus, 2016). If such conflicts are not addressed, they may lead to the decline or local extinction of species, as well as human fatalities and economic losses.

In this manuscript, we develop a mathematical optimization model to determine what can be done to revive the BNR ecosystem, since there is currently little wildlife or meaningful activity there. The proposed approach integrates ecological, environmental, and socio-economic components. These are intended to address the needs of all stakeholders who may be affected by the revitalization of the nature reserve. We narrow the objectives and scope to restoring biodiversity and ecological functionality, with a focus on species reintroduction, vegetation recovery, soil rehabilitation, and water management. The proposed facility location model can support reserve management in developing an initial plan for locating animal species and reintroducing vegetation within BNR, with the aim of supporting sustainable tourism, keeping the reserve attractive to wildlife, and easing coexistence with neighbouring local communities. The model can also facilitate negotiations between reserve management and local communities by incorporating their interests in the revitalization process. Computational experiments are carried out to show the potential of the model in supporting decision-making.

In our approach, we consider the problem as a variant of the well-known facility location problem (Drezner and Hamacher, 2002; Eiselt and Marianov, 2011). Indeed, the study of location problems dates back to the early 1900s, with Alfred Weber's single-warehouse problem (Drezner and Hamacher, 2002), which aimed to determine where to locate a warehouse to serve a set of customers at minimum service cost. More generally, facility location problems aim to determine optimal locations for a set of facilities by minimizing or maximizing objectives for satisfying existing and/or projected demand, subject to constraints in a given space (Laporte et al., 2019; Hale and Moberg, 2003). Turkoglu and Genevois (2020) provide a relatively recent comprehensive review of the scientific literature on facility location problems. In general, facility location problems can be modelled as linear integer programs when it suffices to locate facilities. However, when there are interactions between pairs of facilities that must be accounted for, quadratic integer models are more appropriate (Amaral, 2008). In the problem at hand, since interactions between facilities play an important role (e.g., predators hunt prey; herbivores need vegetation for survival), we employ a binary quadratic formulation. To the best of our knowledge, our study is the first to deploy facility location models in the tourism industry. Furthermore, our proposed model is not just a simple application of a general facility location model; rather, it draws from discussions with BNR stakeholders to develop a model that captures key aspects of the reserve's restoration plan while preserving stakeholder interests. To the best of our knowledge, this work is also among the first to propose a mathematical optimization model to support tourism activities.

In the remainder of the manuscript, we describe the problem in Section 2. We then present the proposed facility location model for the BNR revitalisation process in Section 3. In Section 4, we provide results for the proposed model and discuss how stakeholders can interpret them. Lastly, in Section 5, we provide concluding remarks and highlight next steps for the overall project.

2 Problem description

BNR is at a pivotal point: ecological activity is low, boundary infrastructure is compromised, and tourism value is under-realized; yet the reserve sits in a strategic corridor between Blyde River Canyon Nature Reserve and Kruger National Park. Adjacent communal lands support grazing, fuelwood, and medicinal-plant collection, intensifying pressure at the park–people interface. Fence failures allow

two-way incursions—livestock into the reserve and wildlife into community areas—thereby increasing human–wildlife conflict, eroding biodiversity, reducing visitor safety and satisfaction, and weakening local support for conservation.

In the BNR Management Plan, the authorities set targets to restore degraded vegetation and to reintroduce animal species, while ensuring that the environment is suitable for their survival. More precisely, they aim to plant trees and control invasive plants to create vegetation that is attractive to wildlife and supports tourism. They also aim to reintroduce animal species while restoring habitats that are suitable for each species and capable of sustaining their populations. The current spatial layout of BNR is split into forty-one zones, as shown in Figure 1. This zonation was developed based on existing vegetation and landscape structure. Within this context, the authorities must select an implementable initial spatial layout across the forty-one zones for a finite set of "facilities"—wildlife species or groups, habitat features (e.g., trees and lakes), and built structures (e.g., offices, accommodation, and dams). Facilities must be positioned so that the plan maximizes visibility from existing paths and trails and provides safe wildlife viewing for visitors, while preserving ecological integrity and reducing conflict near community boundaries. The layout must satisfy a set of non-negotiable constraints. For example, predators must be kept at safe distances from accommodation and offices and away from boundary zones; incompatible species must not be co-located; species with strong habitat requirements must be placed only in feasible zones (e.g., hippos and crocodiles in zones with permanent water); and per-zone capacity and compatibility limits must prevent overcrowding and unsafe co-occurrence.

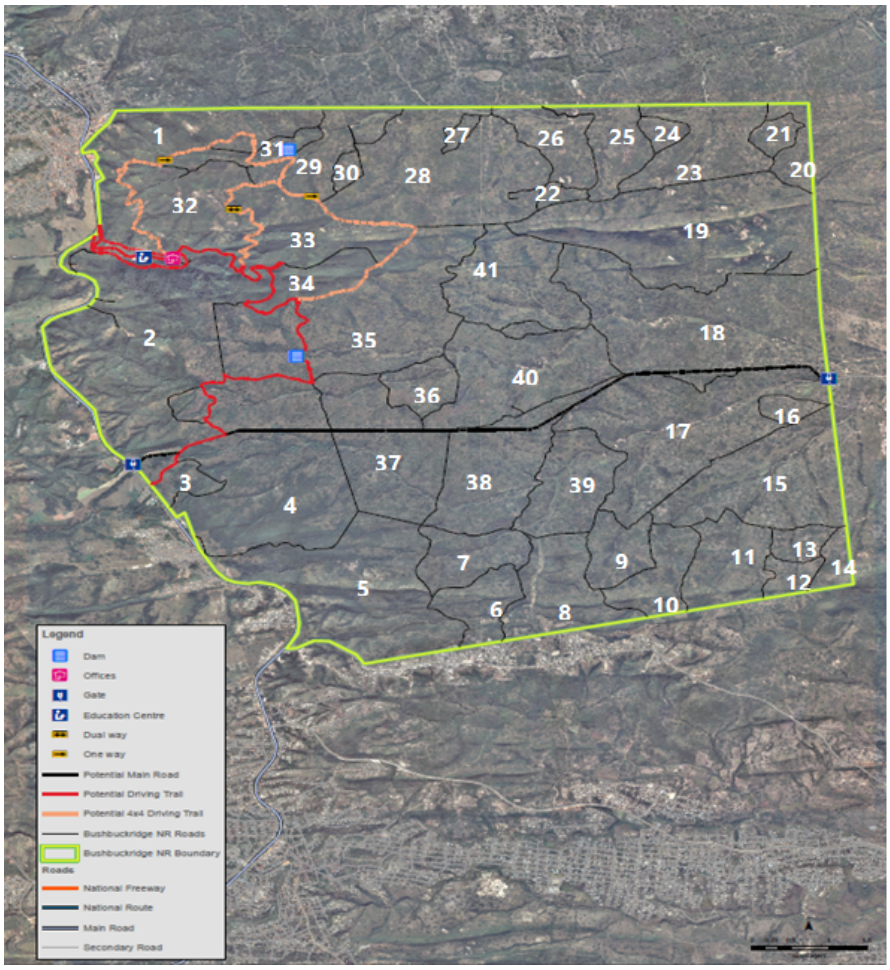


Figure 1: Zonation of Bushbuckridge Nature Reserve.

To support this decision, we formulate a facility location optimization model that assigns facilities to zones using visibility scores derived from routes and viewpoints, together with feasibility masks that reflect ecological and safety rules. Distance-based prohibitions enforce predator–infrastructure separation, boundary rules curb high-risk placements, and capacity constraints limit per-zone load by class (wildlife, vegetation, and structures). The objective is to maximize total safe visibility subject to these constraints, producing a practical baseline layout that can be implemented within current budgets and used to guide phased restoration, conflict mitigation, and the reopening of tourism. Success is measured by improved visitor viewing opportunities, reduced predicted conflict exposure along boundary segments, and ecologically sensible starting configurations for priority species and habitats.

3 The proposed facility location model

In this section, we develop a facility location model to optimally distribute facilities (both wildlife and physical infrastructure, such as park offices, dams, and accommodation facilities) within the nature reserve. The objective is to design an initial layout that assists management in planning a viable revitalization strategy. Facilities should not be placed arbitrarily; instead, they must be strategically positioned to maximize the tourist experience while ensuring ecological sustainability and reducing human–wildlife conflict. All physical structures should be easily accessible, and animals should be placed in locations where they are visible to visitors. In addition, wildlife placement should support a self-sustaining ecosystem for as long as possible.

3.1 The parameters of the model

We start by defining the parameters of our model as follows:

- $\mathcal{I}$: the set of all facilities, indexed by i.
- $\mathcal{J}$: the set of all locations, indexed by j.
- d_{ij}: the adaptability factor of location j for hosting facility i.
- f_{ij}: the visibility factor of facility i at location j.
- $\mathcal{J}_j$: the set of locations directly adjacent to j.
- $\mathcal{J}_B$: the set of locations on the boundary of the nature reserve.
- $\mathcal{I}_P$: the set of facilities classified as predators.
- $\mathcal{I}_V$: the set of facilities classified as prey.

3.2 The decision variables

We employ binary decision variables to indicate whether a facility is assigned to a given zone of the nature reserve.

$$X_{ij} = \begin{cases} 1 & \text{if facility } i \text{ is placed at location } j, \forall i \in \mathcal{I},\ j \in \mathcal{J}, \\ 0 & \text{otherwise.} \end{cases}$$

3.3 The objective function

The objective of the proposed facility location model for BNR is to place animals in locations where they can best adapt, while enhancing visitor experience by maximizing wildlife visibility. Thus, we formulate the objective function as:

$$\max_{X} \quad \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} \sum_{k\in\mathcal{I}} \sum_{l\in\mathcal{J}} d_{ij} f_{kl} X_{ij} X_{kl}.$$

The quadratic term models interactions that must exist between facilities (animal species) in order to maximize overall wildlife survival in the nature reserve.

3.4 The constraints

The objective function is subject to several constraints that ensure ecological balance, visitor safety, and sustainable resource use. We present these constraints below.

1. Each facility must be assigned to exactly one location:
$$\sum_{j\in\mathcal{J}} X_{ij} = 1, \quad \forall i \in \mathcal{I}.$$
2. To prevent overcrowding, each location can host at most two facilities:
$$\sum_{i\in\mathcal{I}} X_{ij} \leq 2, \quad \forall j \in \mathcal{J}.$$
3. Offices and accommodation facilities must be placed at a safe distance from predators:
$$\sum_{i\in\mathcal{I}_P} X_{ij'} \leq 1 - X_{oj}, \quad \forall j \in \mathcal{J},\ j' \in \mathcal{J}_j.$$
where $\mathcal{I}_P$ is the set of predators, $\mathcal{J}_j$ represents locations adjacent to j, and X_{oj} is the variable for office placement.
4. Vegetation must be allocated near the boundary to provide resources such as firewood and medicinal plants for local communities:
$$\sum_{j\in\mathcal{J}_B} X_{\text{Trees},j} \geq 1,$$
where $\mathcal{J}_B$ denotes locations on the boundary of the nature reserve.
5. Herbivores should be placed near boundary locations to allow for controlled hunting:
$$\sum_{i\in\mathcal{I}_V} \sum_{j\in\mathcal{J}_B} X_{ij} \geq 1.$$
where $\mathcal{I}_V$ represents prey species.
6. Following the above constraint, predators cannot be placed near boundary locations:
$$\sum_{i\in\mathcal{I}_P} \sum_{j\in\mathcal{J}_B} X_{ij} = 0.$$
7. Predators and prey cannot be placed in the same location to support ecosystem stability:
$$X_{kj} + X_{lj} \leq 1, \quad k \in \mathcal{I}_V,\ l \in \mathcal{I}_P, \quad \forall j \in \mathcal{J}.$$
This avoids rapid prey depletion after reintroduction.
8. Certain animal species, such as cheetahs and baboons, cannot cohabit due to natural conflicts:
$$X_{3,j} + X_{19,j} \leq 1, \quad \forall j \in \mathcal{J},$$
where $X_{3,j}$ denotes allocating cheetahs to location j and $X_{19,j}$ denotes allocating baboons to location j.
9. For the first phase of the restoration, management would like the offices and accommodation buildings to be located in zone 32, since existing buildings there could be renovated and reused.
$$X_{\text{o},32} = 1.$$
10. For crocodile survival, conservation scientists recommend that a lake should be located in the same zone as the crocodiles or in an immediately adjacent zone.
$$X_{\text{Crocodile},j} \leq \sum_{j'\in\mathcal{J}_j} X_{\text{Lakes},j'}, \qquad \forall j \in \mathcal{J},$$

11. Unlike crocodiles, hippopotamuses require a lake in their immediate environment to survive.

$$X_{\text{Hippopotamus},j} = X_{\text{Lakes},j}, \qquad \forall j \in \mathcal{J}.$$

12. The final set of constraints highlights diet preferences within predator communities. For example, lions prefer zebras and buffaloes, while cheetahs and wild dogs prefer bucks. These constraints are written as follows:

$$\begin{aligned}
X_{ij} &\leq \sum_{j' \in J_j} X_{\text{Lion},j'}, && \forall i \in \{\text{Zebra}, \text{Buffalo}\},\ \forall j \in \mathcal{J}, \\
X_{\text{Buck},j} &\leq \sum_{j' \in \mathcal{J}_j} X_{\text{Leopard},j'}, && \forall j \in \mathcal{J}, \\
X_{\text{Buck},j} &\leq \sum_{j' \in \mathcal{J}_j} X_{\text{Wild dogs},j'}, && \forall j \in \mathcal{J}, \\
X_{\text{Warthog},j} &\leq \sum_{j' \in \mathcal{J}_j} X_{\text{Cheetah},j'}, && \forall j \in \mathcal{J}, \\
X_{\text{Warthog},j} &\leq \sum_{j' \in J_j} X_{\text{Hyena},j'}, && \forall j \in \mathcal{J}.
\end{aligned}$$

Remark 1. The proposed optimization model takes the form of a binary quadratic program. The ability of commercial solvers to handle such models is still quite limited. To solve our model, we first linearize the quadratic objective function using the McCormick linearization technique (McCormick, 1979). This approach introduces a new decision variable to represent each quadratic product of variables; the resulting nonlinear terms (which then appear in the constraints) are replaced using triangular inequalities from Padberg's study of the Boolean polytope (Padberg, 1989). This technique increases the number of decision variables, but given the linear nature of the reformulated model, commercial solvers can then be used to find an optimal solution.

4 Computational experiments

In this section, we report and analyze results from computational experiments conducted to assess the extent to which the proposed model can assist BNR management in achieving its restoration plan. We first describe the dataset used in the experiments.

4.1 Dataset

For our experiments, we used the current zonation of BNR (Municipality, 2017), shown in Figure 1. The reserve is divided into 41 zones in which facilities can potentially be located. At the time of this work, the exact list of facilities (animal species and vegetation types) planned for reintroduction was not yet known; therefore, we compiled a representative list of species commonly found in other South African nature reserves. The resulting list of facilities is provided in Table 1. We now discuss how the main model parameters were calibrated for the experiments.

4.1.1 Visibility factor

The visibility factors quantify the tourist experience. When tourists visit a nature reserve, their satisfaction depends largely on how well they can see different animal species without leaving the established trails. Thus, visibility is mainly determined by animal size and by the distance from the trails.

We classify animal species into three visibility classes (1, 2, and 3). Class 1 includes animals that can be placed farther away because they have low visibility requirements. Class 2 includes animals

Table 1: Facilities to be distributed in the nature reserve.

No	Facility	No	Facility	No	Facility
1	Lion	9	Wild dogs	17	Hyena
2	Rhino	10	Guinea fowls	18	Ostrich
3	Cheetah	11	Crocodile	19	Baboon
4	Elephant	12	Buck	20	Lakes
5	Buffalo	13	Snakes	21	Tall trees
6	Hippopotamus	14	Birds	22	Thorn trees
7	Giraffe	15	Leopard	23	Buildings
8	Zebra	16	Warthog	24	Fruit trees

with moderate visibility requirements. Class 3 includes animals that should be located close to the trails for better visibility. The full classification used in this work is provided in Table A1 (Appendix).

In addition, for each zone on the reserve map, we compute a normalized distance to the existing trail network. For each location, this normalized distance is calculated based on the approximate center of the zone and its closest point on the trails. Using these two metrics, we approximate the visibility parameter for each facility $i \in \mathcal{I}$ at each location $j \in \mathcal{J}$ as:

$$f_{ij} = \begin{cases} 0, & \text{if one of the following conditions is satisfied:} \\ & \quad D_j > 0.50, \quad K_i = 3, \\ & \quad D_j (< 0.5 \text{ or } > 0.7), \quad K_i = 2, \\ & \quad D_j > 0.9, \quad K_i = 1 \\ \dfrac{D_j}{K_i}, & \text{otherwise,} \end{cases}$$

where D_j is the normalized distance of location j with respect to the trail paths, and K_i is the class to which the facility belongs, as shown in Table A1.

4.1.2 Adaptability score

In our model, the adaptability score assesses how suitable a given location is for each animal group. Because we were not able (at the time of this work) to assess each location individually in terms of suitability for different animal groups, we calibrated adaptability based on (i) the vegetation requirements of the animals and (ii) the vegetation index observed across the reserve.

We classified animal species into three classes according to vegetation needs. Class 1 includes animals that strongly depend on vegetation for survival. Class 2 includes animals with moderate vegetation needs. Class 3 includes animals that can survive with limited vegetation. The full classification used in this work is provided in Table A1 (Appendix).

For the vegetation index at different locations in the reserve, we extracted publicly available information from (Portal, 2026). The exported data are shown in Figure 2, which reports a vegetation indicator for each of the 41 locations in BNR.

Using this vegetation index, we could then approximate an adaptability score d_{ij} of a facility $i \in \mathcal{I}$ with respect to each location $j \in \mathcal{J}$ as:

$$d_{ij} = \begin{cases} 0, & \text{if one of the following conditions is satisfied:} \\ & \quad V_j > 0.5, \quad L_i \in \{2, 3\}, \\ & \quad V_j < 0.8, \quad L_i = 1 \\ \dfrac{V_j}{L_i}, & \text{otherwise,} \end{cases}$$

where V_j is the vegetation index of location j as extracted from Figure 2, and L_i is the classification of facility i in terms of its vegetation need, as shown in Table A1.

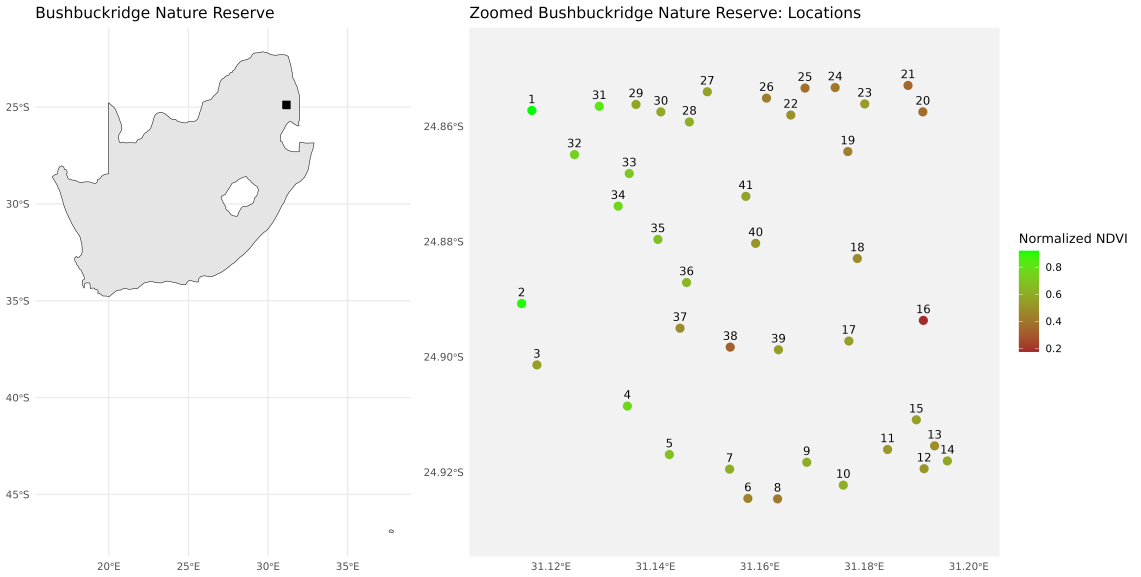


Figure 2: Average vegetation index used to determine adaptability. NDVI product obtained from FEWS NET/USGS: https://earlywarning.usgs.gov/fews/product/940/.

4.2 Results and analysis

The linearized version of the model presented in Section 3 was implemented in Python (Foundation, 2026) and solved using Gurobi Optimizer (version 10.0) (Gurobi Optimization, 2026). The resulting solution is shown in Figure 3, which illustrates the arrangement of wildlife species, vegetation, water bodies, and built facilities across the 41 zones. The figure highlights how facilities are placed to satisfy the model's environmental and safety constraints.

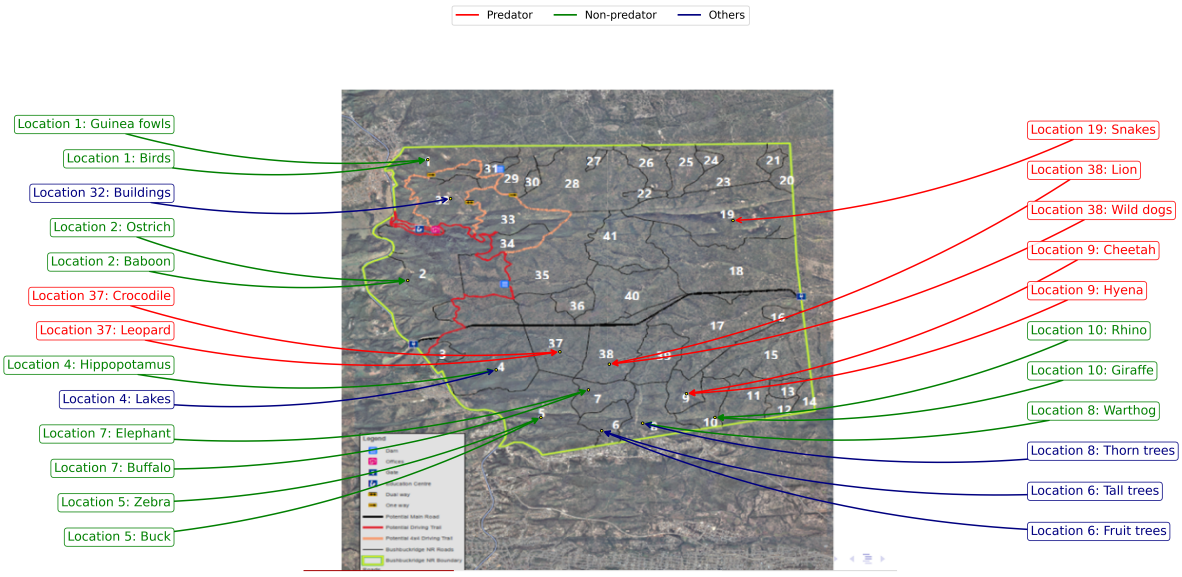


Figure 3: Distribution of facilities in a location grid.

The offices and accommodation are located in Zone 32, which is accessible via vehicle trails. In directly adjacent zones, the solution recommends locating only low-risk species such as guinea fowl, birds, and ostriches. Tall trees, thorn trees, fruit trees, and buck are placed in zones near the border, where they are accessible to local communities for wood collection, traditional medicines, and controlled hunting, without requiring entry into unprotected parts of the reserve. The lake is located in Zone 4, providing direct access for crocodiles, buffalo, zebra, and buck. This placement supports water availability while maintaining ecological diversity. Predators and prey are strategically separated, as required by the constraints, to reduce immediate predation after reintroduction.

From a management perspective, this spatial distribution enables a critical assessment of facility placement. High-density areas may serve as focal points for tourism and conservation activities, whereas underutilized zones may present opportunities for further development or ecological preservation. If certain high-biodiversity areas are overly developed, this may indicate a risk of ecosystem strain; conversely, underutilized zones may indicate untapped opportunities for sustainable tourism and conservation.

5 Conclusion

In this manuscript, we developed a mathematical model to support ecosystem revitalization in BNR, Mpumalanga, South Africa. The reserve is undergoing renovations, and management is seeking strategies to reintroduce wildlife. The main objectives are to restore and conserve the ecosystem and to address human–wildlife conflict through innovative solutions. To this end, we proposed a facility location model that supports an initial restoration plan while accounting for human–wildlife conflict. The model allows animals and physical structures to be distributed optimally across the reserve. Reserve management may use this model to allocate available facilities in a way that maximizes tourism potential while respecting ecological and safety requirements.

We conclude that revitalizing BNR requires an integrated approach with contributions from all stakeholders. Collaboration with surrounding communities and scientific institutions across the country is needed to ensure the reserve's long-term sustainability. Future work and possible extensions include calibrating the model with site-specific data from Bushbuckridge and integrating it with population growth and movement models. In addition, we plan to investigate solution approaches for the nonlinear facility design problem using more realistic parameters.

A Appendix

A.1 Vegetation and visibility classes

The vegetation and visibility classes are defined on a three-level scale ranging from 1 to 3.

Vegetation Class

- Class 1: high need for vegetation,
- Class 2: moderate need for vegetation,
- Class 3: low need for vegetation.

Visibility Class

- Class 1: can be placed farther away / low visibility requirement,
- Class 2: moderate visibility requirement,
- Class 3: should remain close / highly visible.

Table A1: Vegetation and visibility classification.

Facilities	Vegetation Class(L)	Visibility Class(K)
Lion	2	2
Rhino	1	1
Cheetah	3	2
Elephant	1	1
Buffalo	1	1
Hippopotamus	1	1
Giraffe	1	1
Zebra	1	2
Wild dogs	2	3
Guinea fowls	2	3
Crocodile	3	2
Buck	1	2
Snakes	2	3
Birds	3	3
Leopard	2	2
Warthog	2	3
Hyena	2	2
Ostrich	3	2
Baboon	2	3
Lakes	3	1
Tall trees	3	1
Thorn trees	3	2
Buildings	3	1
Fruit trees	3	1

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