Stationing Security: Protecting Wildlife from Pollution, Poachers, and Potential Fires

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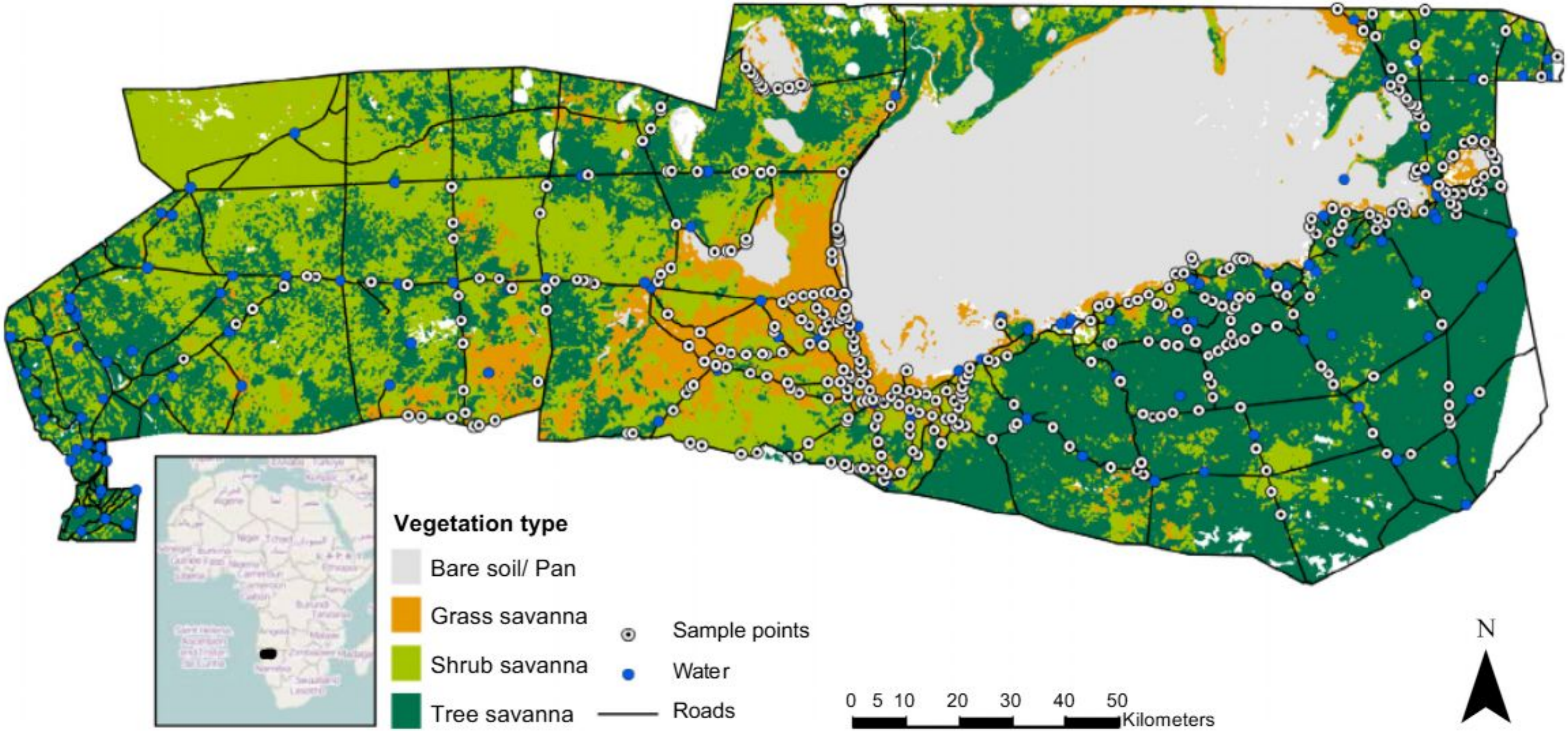
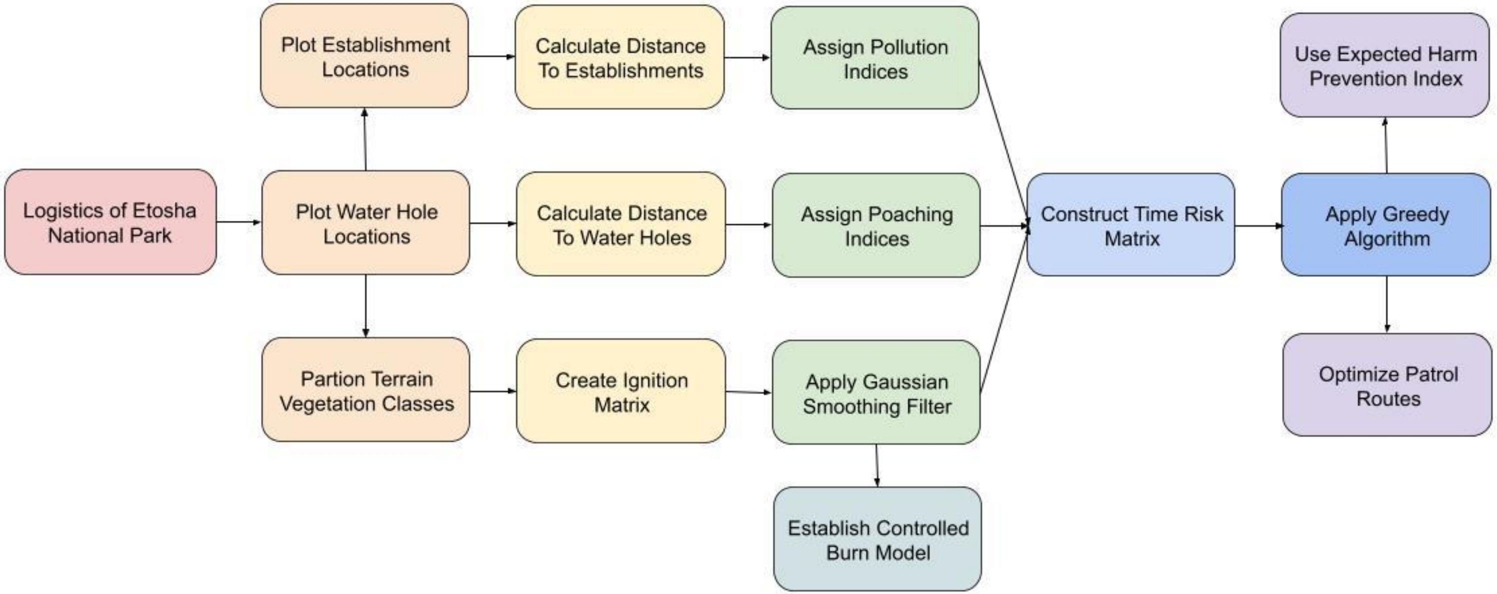
Background

Map of Etosha National Park



Overview


Plot Establishment Locations
Calculate Distance To Establishments
Assign Pollution Indices
Use Expected Harm Prevention Index
Logistics of Etosha National Park
Plot Water Hole Locations
Calculate Distance To Water Holes
Assign Poaching Indices
Construct Time Risk Matrix
Apply Greedy Algorithm
Partion Terrain Vegetation Classes
Create Ignition Matrix
Apply Gaussian Smoothing Filter
Optimize Patrol Routes
Establish Controlled Burn Model

1. Wildlife Protection

Threat #1: Pollutants

Assumptions

1) The majority of pollutants will be around locations frequently visited by tourists (i.e. roads and buildings)
2) The cleaning of pollutants is a medium priority when compared to other threats
3) The pollution index will follow the inverse square law since waste can travel in three Dimensions

Pollution Index Formula

Pollution
Weight

Numerical
Pollution Index

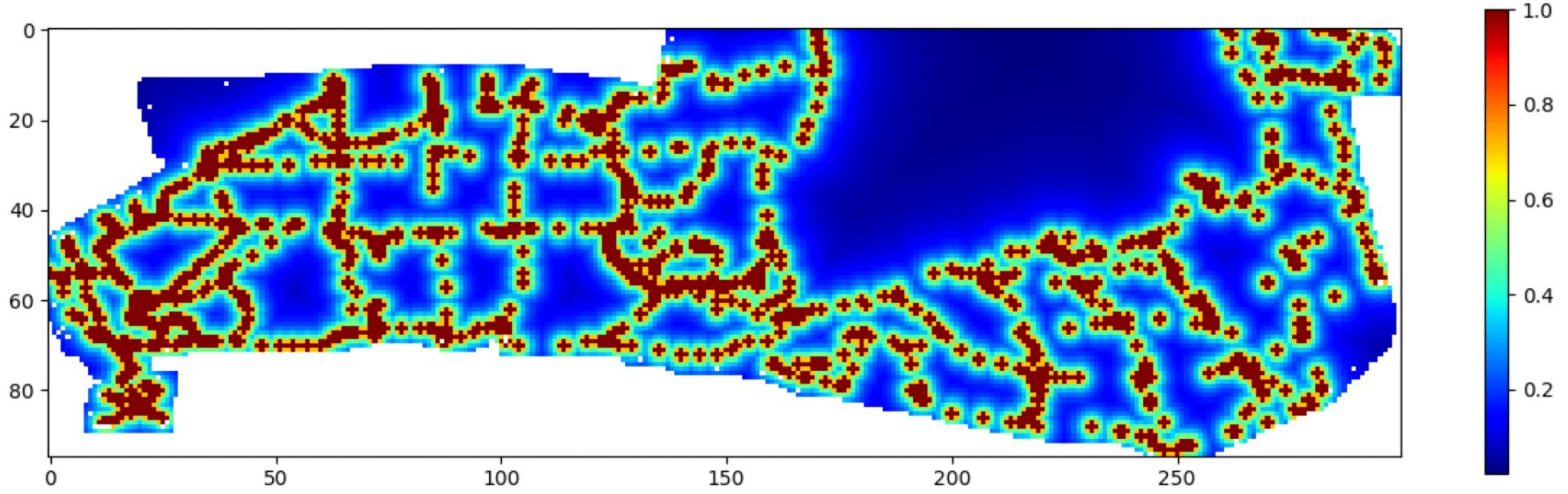
$$s_{pollute}(L) = min(\sum_{e \in \mathcal{E}} \frac{W_{pollution}}{\max\left(d(L,e)^2,\ 1\right)}, 1) = min(\sum_{e \in \mathcal{E}} \frac{W_{pollution}}{\max\left((L_x - e_x)^2 + (L_y - e_y)^2,\ 1\right)}, 1)$$

Squared distance
between tiles ‘T’ and ‘w’

Pollution Index Breakdown

$$s_{pollute}(L) = min(\sum_{e \in \mathcal{E}} \frac{W_{pollution}}{\max\left(d(L,e)^2,\ 1\right)}, 1) = min(\sum_{e \in \mathcal{E}} \frac{W_{pollution}}{\max\left((L_x - e_x)^2 + (L_y - e_y)^2,\ 1\right)}, 1)$$

- The function s in this formula represents the pollution index of a 1x1 tile.
  - For some tile L, s is the inverse of the smallest distance to a road or establishment.
- Closer to Establishment (e) → Higher pollution index(s)



A map of Etosha National Park (in 1km x 1km tiles) with the pollution index function applied.

Threat #2: Poaching

Assumptions

1) Fauna density is concentrated around watering holes, which are essential for survival
2) The response time to poaching reports should be less than 20 minutes.
3) The poaching index will follow the inverse square law since poachers operate in all three dimensions.

Poaching Index Formula

Numerical Poaching Index

Poaching Weight

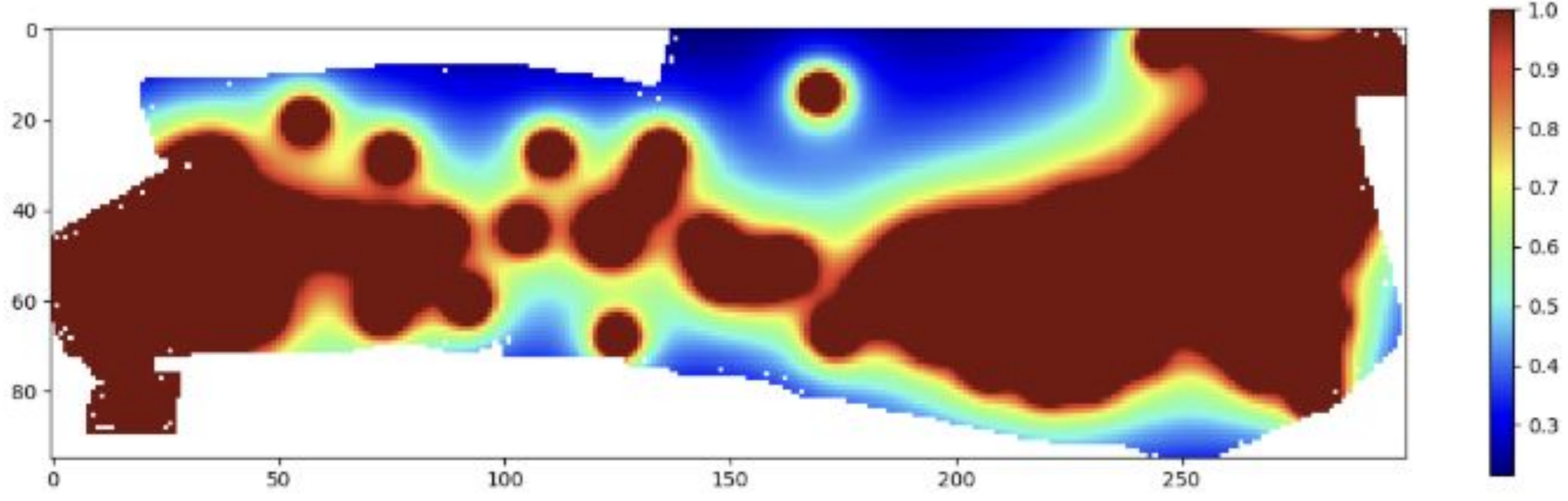
$$s_{poach} = min(\sum_{w \in \mathcal{W}} \frac{W_{poaching}}{max(d(T,w)^2, 1)}, 1) = min(\sum_{w \in \mathcal{W}} \frac{W_{poaching}}{max((T_x - w_x)^2 + (T_y - w_y)^2, 1)}, 1)$$

Squared distance between tiles ‘T’ and ‘w’

Poaching Index Breakdown

$$s_{poach} = min(\sum_{w \in \mathcal{W}} \frac{W_{poaching}}{max(d(T,w)^2, 1)}, 1) = min(\sum_{w \in \mathcal{W}} \frac{W_{poaching}}{max((T_x - w_x)^2 + (T_y - w_y)^2, 1)}, 1)$$

- ❖ The function s in this formula represents the poaching index of a 1x1 tile.
  - ➢ For some tile T, s is the sum of the square inverses of the distance to each water hole.
- ❖ Closer to more Water Holes (w) → Higher poaching index(s)



A map of Etosha National Park (in 1km x 1km tiles) with the poaching index function applied.

2. Wildfire Prevention and Response

Assumptions

1) The distribution of vegetation remains static.
2) The baseline fire risk matrix is calculated under a zero-wind condition.
3) If a cell exceeds a calculated risk threshold, it is considered prone to ignition.
4) Any fire starting in a cell originates from the geometric center of that cell.
5) Responders mobilize instantly.

Fire Risk

❖ Landscape partitioned into four discrete vegetation classes.

Vegetation Type	Combustion Profile	Fuel Index (F)	Protection Weight (W)
Grass	High fine-fuel load; rapid spread	1.0	2.0
Shrub	moderate load; intermediate spread	0.7	1.5
Tree	heavy load; slow initial spread	0.5	1.0
Salt Pan / Road	Non-combustible surface	0.0	0.0

Calitz, Wynand, et al. İnvestigating Species-Level Flammability across Five Biomes in the Eastern Cape, South Africa. *South African Journal of Botany*, vol. 101, Nov. 2015, pp. 32-39, https://doi.org/10.1016/j.sajb.2015.07.005

Fire Risk Matrix

Dryness Index

$$D = T \times (1 - H)$$

Dryness Temperature Humidity

Ignition Matrix

$$I_{x,y} = D \cdot F_{x,y}$$

Fuel Matrix

Fuel Continuity

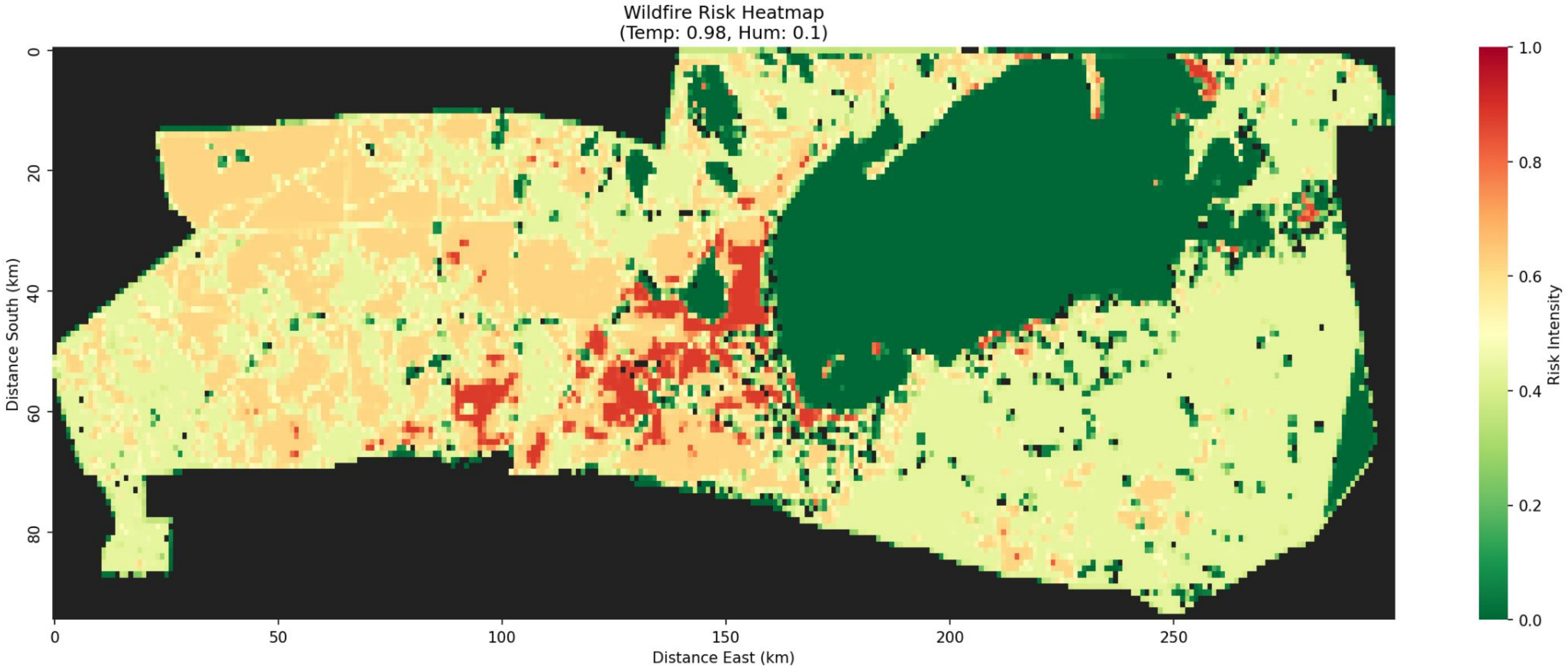
$$I_{smooth} = I \cdot G_\sigma \quad \text{where} \quad G_\sigma(i,j) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Spread Vulnerability (Convolution)

$$\mathcal{R}_{high} = \frac{(I_{smooth} \cdot K) + I}{2}$$

Fire Risk Matrix cont.

❖ Matrix Downsampled into 300 km by 95 km grid.



Protection Value

❖ Protection weights account for biodiversity importance.

$$\mathcal{P}_{i,j} = \mathcal{R}_{1km}(i,j) \cdot W_{i,j}$$

Protection Matrix

1 km Risk Matrix

Protection Weights

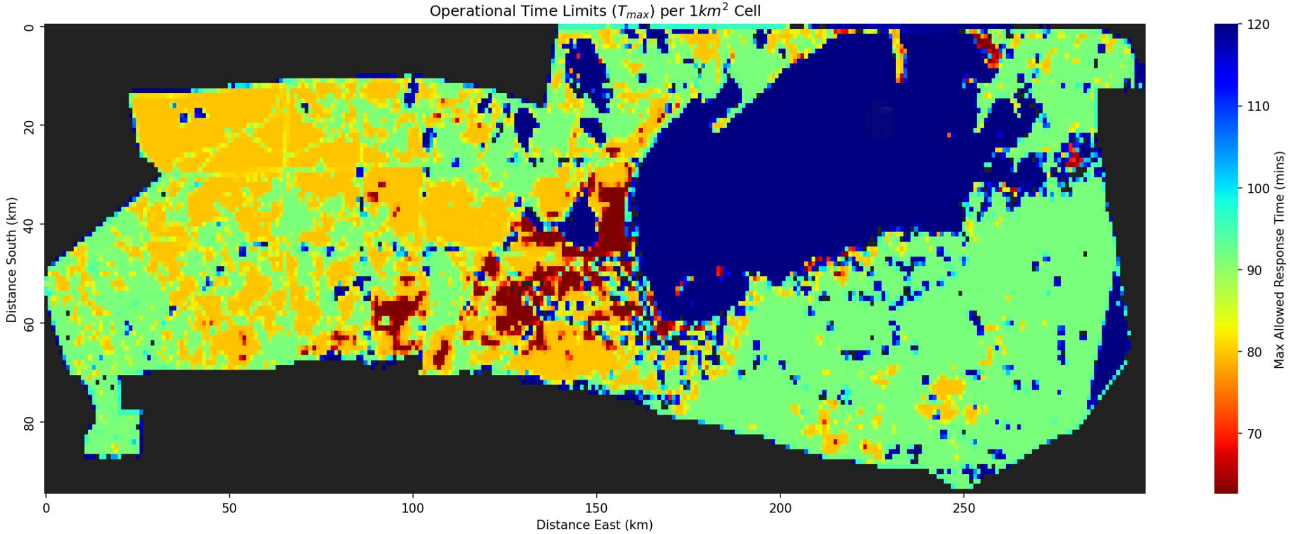
Time Risk Matrix

$$T_{max}(i,j) = \max\left(T_{base} - (\rho \cdot \mathcal{P}_{i,j}),\quad T_{min}\right)$$

Risk Penalty

Protection Matrix

- ❖ Static response time not efficient.
- ❖ Created dynamic time risk matrix based on cell risks.
- ❖ Minimum reasonable response time is 30 minutes.



Ranger kinematics

❖ Model ranger movement based on terrain.

➢ Travel speed is linear based on terrain type.

➢ No physical barriers impede the route.

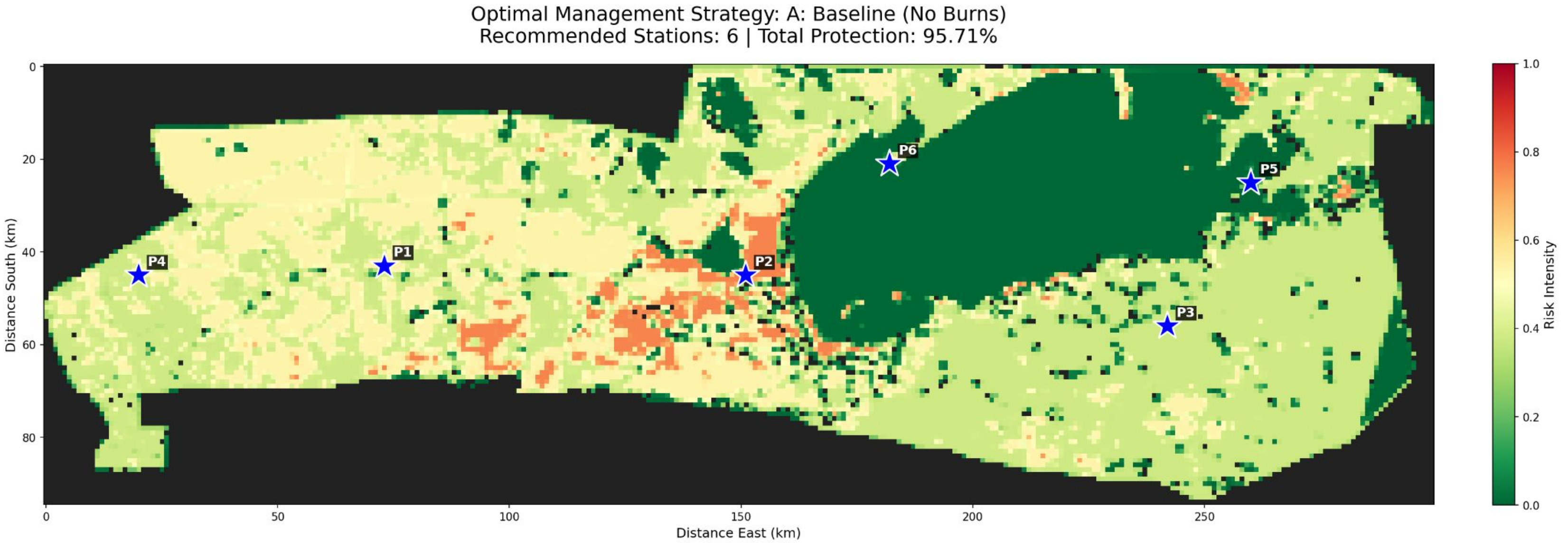
V_{road}	60 km/h
$V_{offroad}$	30 km/h

$$\tau(x_t, y_t) = \frac{\sqrt{(x_t - x_s)^2 + (y_t - y_s)^2}}{V(x_t, y_t)}$$

Ranger Post Placement

- ❖ Greedy algorithm
- ❖ Infrastructure feasibility
  - ➢ No placement in salt pan.

Strategy	Stations	Coverage	Burn Area
A	6	95.71%	0 km^2

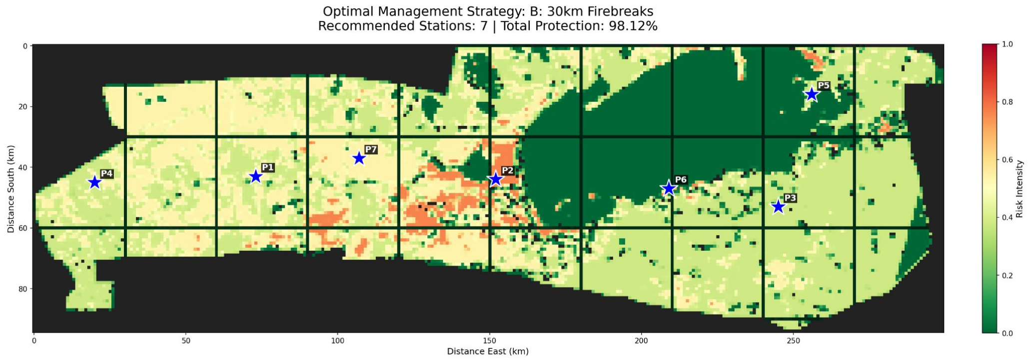


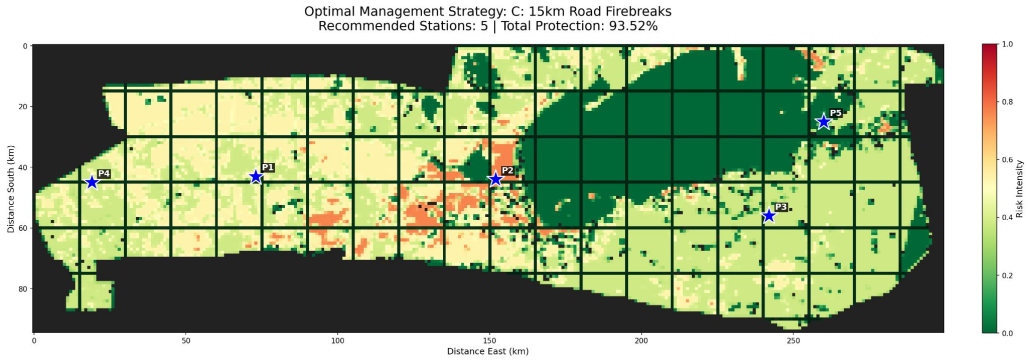
Controlled Burns

- ❖ Apply burn mask that reduces burn risk to 15% in targeted squares.
- ❖ Used 2 main strategies:
  - ➢ Strategic Grids
  - ➢ Mosaic Targeting

Strategic Grids

- ❖ Linear 1km firebreaks.
- ❖ Split landscape into blocks.



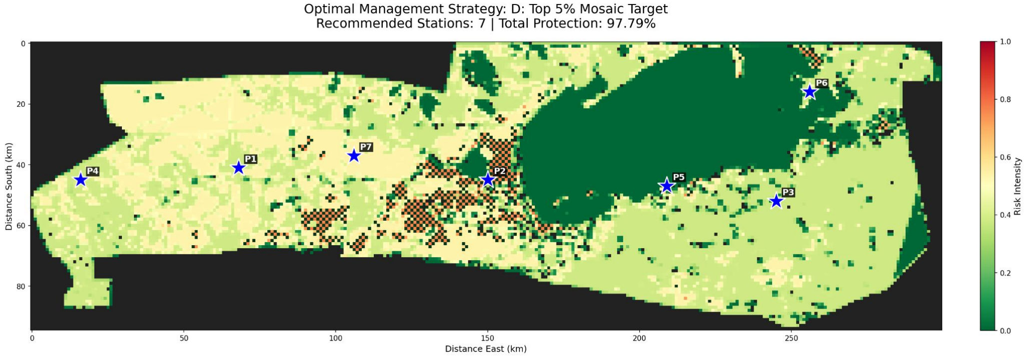


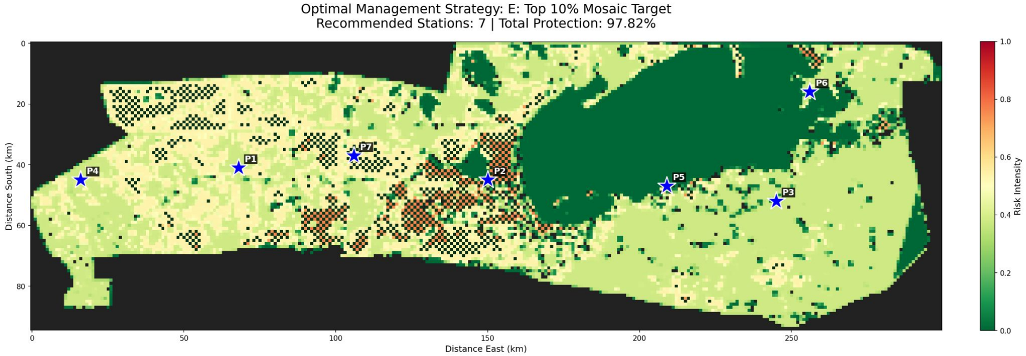
Strategy	Stations	Coverage	Burn Area
B	7	98.12%	1300 km^2
C	5	93.52%	2592 km^2

Mosaic Targeting

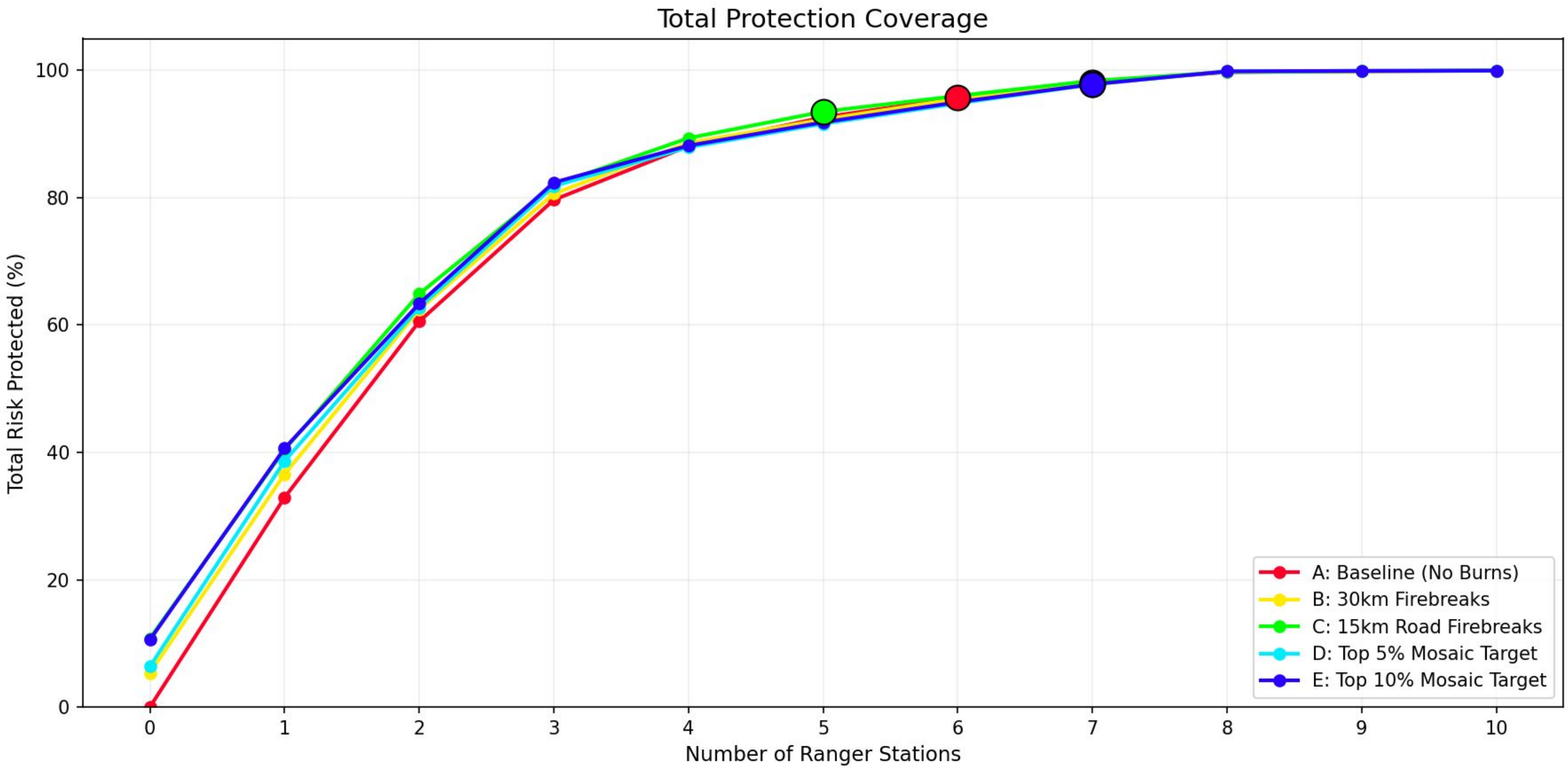
- ❖ Target highest risk cells.
- ❖ Allows habitat continuity.

Strategy	Stations	Coverage	Burn Area
D	7	97.79%	488 km^2
E	7	97.82%	1011 km^2



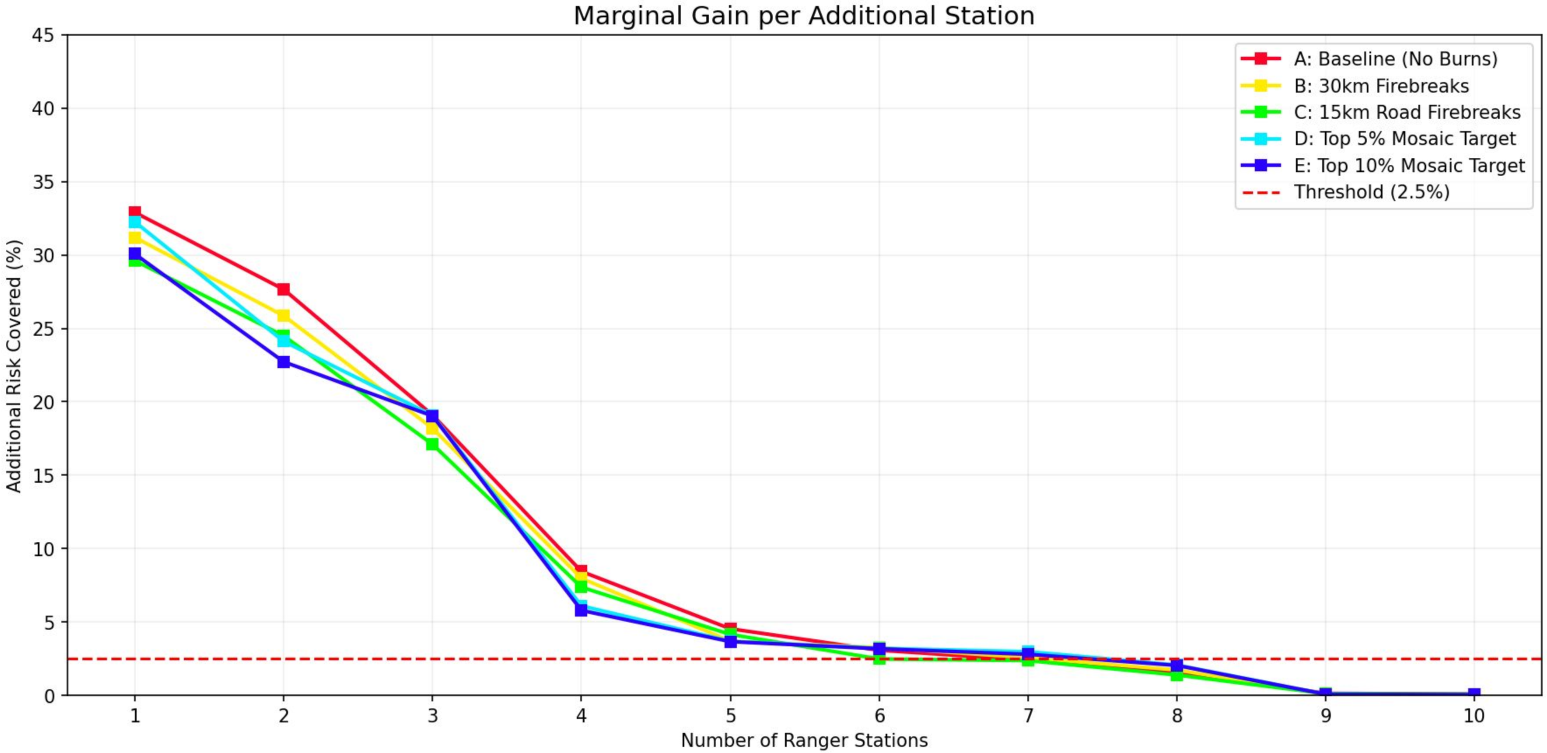


Strategy Analysis

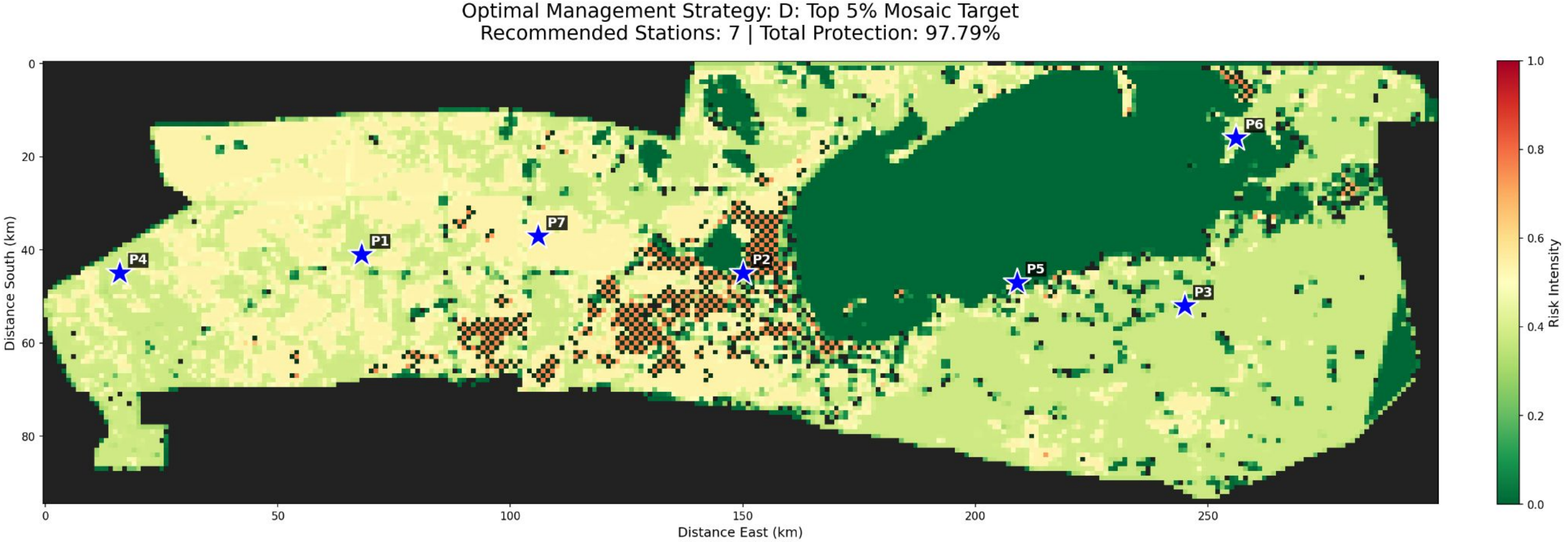


Cutoff Threshold

❖ Saturation threshold of 2.5%.



	Strategy	Stations	Coverage (%)	Burn Area (km^2)
A	Baseline (No Burns)	6	95.71	0
B	30km Firebreaks	7	98.12	1300
C	15km Road Firebreaks	5	93.52	2592
D	Top 5% Mosaic Target	7	97.79	488
E	Top 10% Mosaic Target	7	97.82	1011



3. Expected Harm Prevention Index

Model Integration

Expected Harm Prevention Index (EHPI)

$$\mathrm{EHPI}(t) = \frac{\sum_i \sum_k V_i \, \Lambda_{i,k} \, P_{i,k}(t)}{\sum_i \sum_k V_i \, \Lambda_{i,k}}$$

- ❖ V_i: Conservation value of cell *i*
- ❖ Λ_i,k: Threat pressure of threat *k* in cell *i*
- ❖ P_i,k: Probability that threat *k* is successfully prevented in cell *i*

EHPI = Prevented Harm / Total Expected Harm

Breakdown of EHPI

$$V_i \, \Lambda_{i,k} \, P_{i,k}(t)$$

How much do we care about this cell?

How much danger is present?

How much of that danger can we stop?

Expected harm.

Expected harm prevented.

V_i Formula

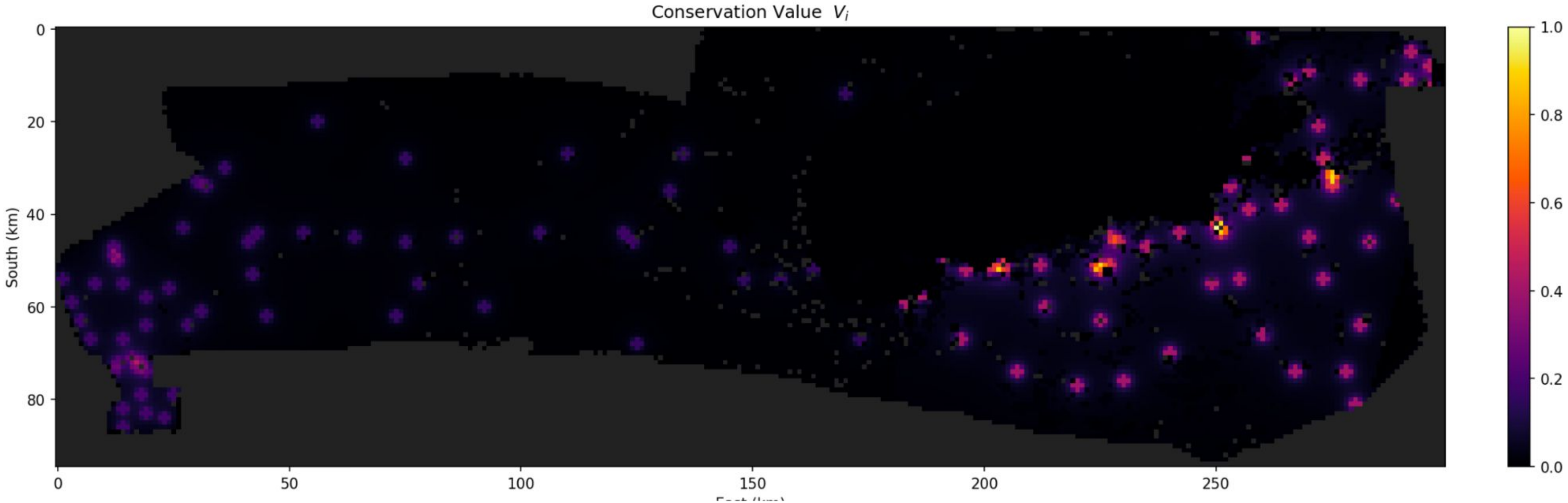
Species	Weight w_s	IUCN Status
Black Rhinoceros	10	Critically Endangered
Elephant	6	Vulnerable
Lion	5	Vulnerable
Plains Herbivores	2	Least Concern
Birds	1	Least Concern

$$V_i = \sum_{s \in \mathcal{S}} w_s \, q_{i,s}$$

$$q_{i,s} = \sum_{w \in \mathcal{W}} \frac{1}{\max(d(i,w)^2,\ 1)}$$

- ❖ w_s: conservation priority weight for species s
- ❖ q_(i,s): estimated species density in cell i
- ❖ Like our poaching model, q_i,s uses inverse-square distance to waterholes, but here it estimates relative wildlife density and is later normalized into the conservation value

Spatial distribution of conservation value V_i across Etosha



Threat Pressure Λ_i,k

Threats of type k are derived directly from our primary risk models

- $\Lambda_{i,\text{fire}} = \mathcal{R}_{1\text{km}}(i)$ — Spatially explicit wildfire risk (Part 2).
- $\Lambda_{i,\text{poach}} = s_{\text{poach}}(i)$ — Poaching pressure based on water access (Part 1).
- $\Lambda_{i,\text{pollute}} = s_{\text{pollute}}(i)$ — Pollution intensity along tourist corridors (Part 1).

Protection per Cell

$$P_{i,k}(t) = D_i(t) \cdot \left[\delta_k + (1 - \delta_k) \cdot R_i(t, \theta_k)\right]$$

Detection Probability

Deterrence

Probability of Successful Response

- δ_poach: 0.3
- δ_fire: 0
- δ_pollute: 0.5

Detection Probability

$$D_i(t) = e^{-\lambda_i \cdot (t - t_{\text{last}}(i))}$$

- ❖ D_i(t): detection probability in cell i
- ❖ t−tlast(i): time since the cell was last observed
- ❖ λ_i: decay rate based on terrain visibility

Terrain Type	λ_i **(hr**$^{-1}$**)**	**Observational Rationale**
Salt Pan	0.003	Unobstructed horizons; high visibility
Grass Savanna	0.008	Moderate visual obstruction
Shrub Savanna	0.018	Significant brush obstruction
Tree Savanna	0.025	Reduced ground-level visibility

II.

Let

$$\tau = t - t_{\text{last}}(i)$$

Such that τ = time since the cell was last observed.

Then

If a surveillance object observes the same cell every T hours, then during one revisit cycle, τ runs from 0 to T.

So we get $D_i(\tau) = e^{-\lambda_i \tau}$

III.

As you might've noticed, our EHPI is a point in time model, not a continuous simulation. This means that we need one detection value per cell. Thus, we average it by taking the integral.

$$\bar{D}_i = \frac{1}{T}\int_0^T D_i(\tau)\,d\tau = \frac{1}{T}\left[-\frac{1}{\lambda_i}e^{-\lambda_i \tau}\right]_0^T$$

$$\boxed{\bar{D}_i = \frac{1 - e^{-\lambda_i T}}{\lambda_i T}}$$

Asset	**Coverage**	**Effect on** D_i
Ranger patrol	3 km radius	Resets to 1.0
Drone flyover	5 km radius	Resets to 1.0
Waterhole camera	Cell + neighbors	Maintains ≥ 0.8
Satellite pass	Park-wide (6 hr)	Sets ≥ 0.4

Response Probability

$$R_i(\theta_k) = e^{-d_{\text{nearest}}(i)/\theta_k}$$

- ❖ d_nearest(i): distance from cell i to the nearest ranger station
- ❖ θ_k: threat specific response distance scale
- ❖ Farther from a station means lower probability of successful response
  - ➢ θ_poach = 12 km
  - ➢ θ_fire = 20 km
  - ➢ θ_pollute = 40 km

Expected Harm Prevention Index (EHPI)

$$\mathrm{EHPI}(t) = \frac{\sum_i \sum_k V_i \, \Lambda_{i,k} \, P_{i,k}(t)}{\sum_i \sum_k V_i \, \Lambda_{i,k}}$$

- ❖ V_i: Conservation value of cell *i*
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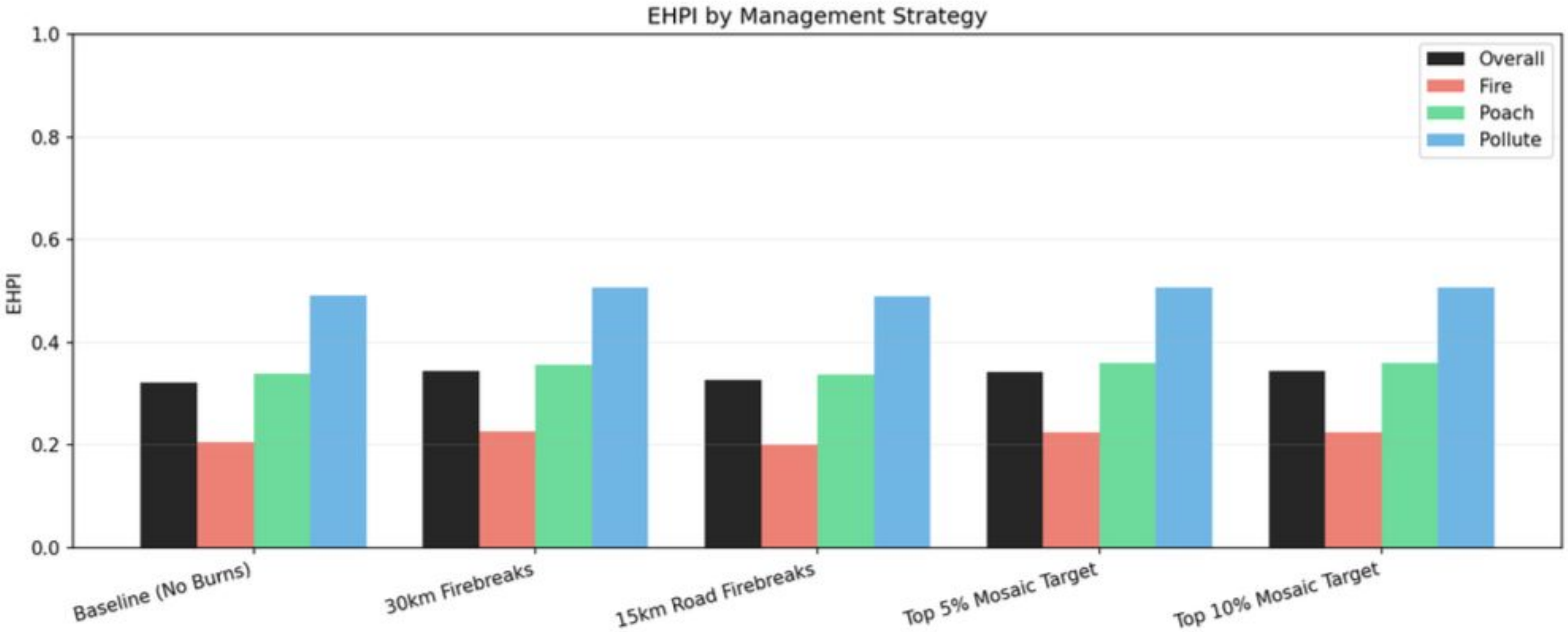
EHPI = Prevented Harm / Total Expected Harm

Results from EHPI

Strategy	Stations	EHPI	Fire	Poach	Pollute
Baseline (No Burns)	6	0.3223	0.205	0.339	0.490
30km Firebreaks	7	0.3436	0.225	0.356	0.507
15km Road Firebreaks	5	0.3274	0.201	0.338	0.489
Top 5% Mosaic Target	7	0.3422	0.225	0.360	0.508
Top 10% Mosaic Target	7	0.3431	0.225	0.360	0.508



Stackelberg Game

- Our rangers are leaders and the poachers are followers
- From each ranger station, find 8 closest waterholes, create feasible routes through nearby waterholes and discard routes that are too long. We assume poachers are smart. Thus they should follow the equation:

$$i^* = \arg\max_i V_i \Lambda_{i,\mathrm{poach}} \left(1 - \sum_r p_r P_{i,r}\right)$$

- V_i*Λ_i,poach = value * poaching risk
- p_r = probability of patrol route r
- P_i,r = protection cell i receives from route r
- ∑p_r*P_i,r = expected protection
- 1−∑p_rP_i,r = remaining vulnerability

- Then, rangers should follow the following:

  where z is the protection value of the least protected cell. We will then maximize z to basically throw off the poachers.

$$\sum_r p_r P_{i,r} \geq z \qquad \forall i$$

$$\sum_r p_r = 1, \qquad p_r \geq 0$$

Results from Implementation of Stackelberg

Table 8: EHPI comparison: static stations vs. Stackelberg patrols.

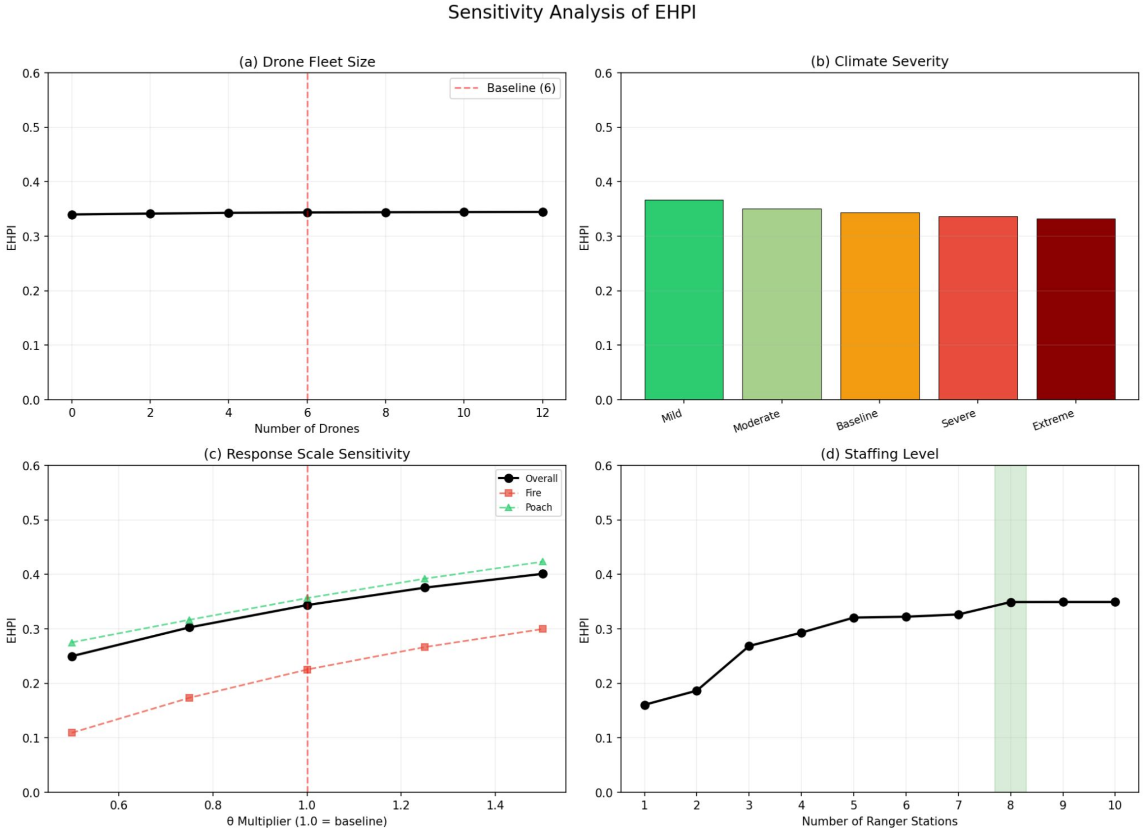
	EHPI (overall)	**Poaching**	**Min Protection** z^*
Static stations only	0.344	0.356	—
Stackelberg patrols	0.345	0.374	0.284

4. Sensitivity Analysis

Sensitivity Analysis

Parameter	**Value**	**EHPI**	**ΔEHPI**	**Fire**	**Poach**	**Pollute**
Drone fleet	0 drones	0.3400	−0.0037	0.222	0.355	0.502
	6 drones	**0.3436**	**0.0000**	**0.225**	**0.356**	**0.507**
	12 drones	0.3446	+0.0010	0.226	0.357	0.508
Climate (T, H)	Mild (0.70, 0.25)	0.3671	+0.0234	0.225	0.356	0.507
	Baseline (0.85, 0.10)	**0.3436**	**0.0000**	**0.225**	**0.356**	**0.507**
	Severe (0.90, 0.05)	0.3367	−0.0069	0.225	0.356	0.507
	Extreme (0.95, 0.03)	0.3321	−0.0115	0.225	0.356	0.507
Response θ (multiplier)	0.50× (θ_p=6, θ_f=10)	0.2498	−0.0938	0.109	0.275	0.441
	0.75× (θ_p=9, θ_f=15)	0.3027	−0.0410	0.173	0.317	0.481
	1.00× (θ_p=12, θ_f=20)	**0.3436**	**0.0000**	**0.225**	**0.356**	**0.507**
	1.25× (θ_p=15, θ_f=25)	0.3756	+0.0320	0.267	0.392	0.525
	1.50× (θ_p=18, θ_f=30)	0.4010	+0.0574	0.300	0.423	0.538
Staffing (N)	2 stations	0.1866	−0.1398	0.055	0.245	0.364
	5 stations	0.3207	−0.0058	0.203	0.338	0.489
	7 stations	**0.3264**	**0.0000**	**0.211**	**0.341**	**0.492**
	8 stations	0.3492	+0.0228	0.238	0.362	0.510
	10 stations	0.3493	+0.0229	0.238	0.362	0.510

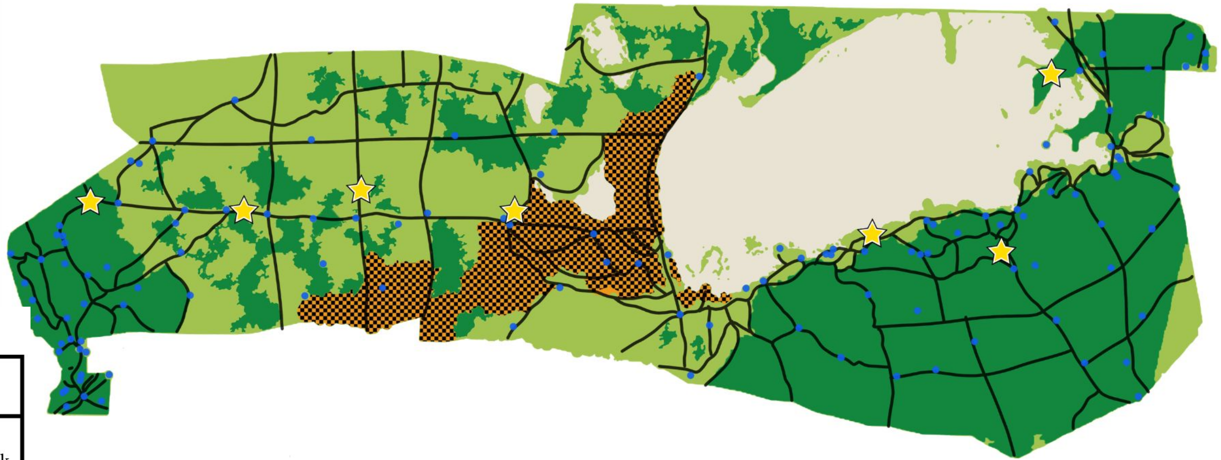
Sensitivity Analysis Visualized



5. Strengths and Weaknesses

Strengths	Weaknesses
1) Our model accounts for a multitude of threats 2) Our model is generalizable 3) Rangers are given dynamic response times 4) The Stackelberg patrol model adds another layer of security to the park 5) Variables / Constants can easily be modified to simulate different environments	1) Ranger travel times are Euclidean 2) Temporary environment events are unaccounted for 3) Species distribution is not dependent on the species type 4) Usage of a greedy algorithm for security placement

Final Proposal



Costs:

Item	#	One-Time Cost (USD)	Annual Cost (USD)	Staffing Notes
Ranger Stations	7	1,225,000	35,000	37 staff per station, work distributed
Monitoring Cameras	86	258,000	17,200	1-2 staff per shift to monitor feeds
Drones	6	120,000	42,000	8-10 trained operators
Controlled Burns	1/Season	50,000	50,000	10-15 personnel per burn

Total Upfront Cost: $1,653,000 **($N 27,456,330)**

Annual Maintenance Cost: $144,200 **($N 2,395,162)**

Total Staff: 295

Total Burn Area: 488 square kilometers

Legend:

- Ranger Stations
- Water Holes and Cameras
- Existing Roads
- Burn Targeted Grassland
- Shrubland
- Tree-filled Savanna
- Salt Pan

Thank You!