Team #2026092

RAFFLES GIRLS' SCHOOL

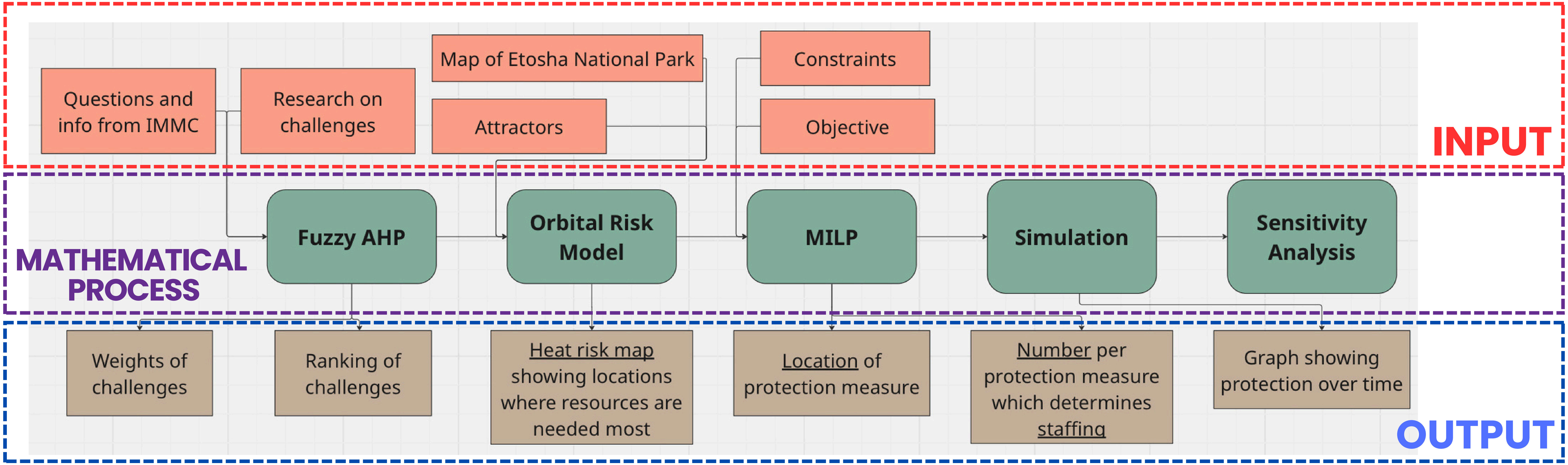
Ananya, Khoo Hui Ning, Shen Yan Xi, Catherine Goh Hao Xuan

How can a conservation agency deploy limited resources to maximise protection across a large national park?

Background

- Conservation threats in Etosha National Park are not evenly distributed
- These must be managed simultaneously with limited budget and manpower
- This transforms conservation into a resource allocation problem under uncertainty, which we can use mathematical modelling to solve

Overview of Model



Practical Assumptions

Assumption	Justification
No major corruption that compromises protection	- National parks are government-designated protected areas - Allows model to focus on optimal allocation
Poachers target **animal-dense areas** (e.g. waterholes)	- Maximised chances of encountering valuable wildlife
Road networks are used by **patrollers and poachers**	- Distinct and accessible routes, suited for efficiency which is common priority
Equipment and **workforce capacity** remains **constant**	- Undamaged equipment + 8-hour shifts everyday - Simplify staffing determination and equipment availability
Instant communication between all parties	- No poor connection so resources can be distributed correctly and predictably

Mathematical Assumptions

Assumption	Justification
Flat terrain, unless previously indicated or substantial	- Etosha National Park comprises mostly flat savannahs - Allow planar distance modelling to simplify time and distance calculations
Only **initial state** considered	- State will change according to application of model, but tracking this would overcomplicate model and improve its effectiveness negligibly
Flow of tourism, and hence **number of people**, is **constant**	- Simplify frequency of human-wildlife conflict by considering only location, and not time - Data on visitor arrival patterns unavailable
Protection measures travel at **constant speed** at all times	- Simplify simulation and provide reasonable estimate of average response times - Short term changes negligible impact on long term equipment and staffing needs

Challenges

- Poaching
- Invasive Species
- Wildfire
- Resource Exploitation
- Human-Wildlife Conflict

Criteria

Frequency

How often a challenge is faced?

Ecological Impact

How much impact it causes to the environment?

Mitigation Feasibility

How hard it is to mitigate?

Criteria

	Poaching	Invasive Species	Wildfire	Resource Exploitation	Human-Wildlife Conflict
Frequency	4 -- Endangered by snares and **hunting**	3 -- **200** new alien species annually	4 -- Fire affects hundreds of **millions** of hectares each year	3 -- occurs as **economic** incentive is high	3 -- Larger populations mean more **frequent** HWC
Ecological Impact	5 -- **Directly** endangers wildlife	4 -- Factor in **60%** of documented global plant and animal **extinction**	4 -- Damages **large** areas of habitat	3 -- results in **permanent** forest and habitat loss	3 -- Major challenge but **not immediately** destructive
Mitigation	4 -- Poachers **adapt**, and there is a highly active, **global market**	4 -- Invasive species spread **uncontrollably**; eradication is feasible only when detected early	3 -- Can be **mitigated** through prescribed burns, mechanical fuel reduction, and prevention planning, but requires **significant resources**	4 -- Possible but **hard** when **governance** is **weak** or enforcement is ineffective	3 -- Mitigated but requires collaboration with **public**
	13	12	11	10	9

The bigger the sum of numbers, the more severe the challenge and the more importance we need to place on mitigating it.

Criteria

For each challenge factor, we calculated the fuzzy geometric mean, then normalized fuzzy weights using the center-of-area method to obtain crisp weights suitable for ranking.

Challenge	Defuzzified Weight	Rank
Poaching	1.535	1
Invasive Species	0.800	2
Wildfires	0.384	3
Resource exploitation	0.184	4
Human-Wildlife Conflict (HWC)	0.096	5

Orbital Risk Model— Gaussian Kernel

- Risk is not uniform across the park, but rather, it clusters around geographic "attractors" and decays with distance.

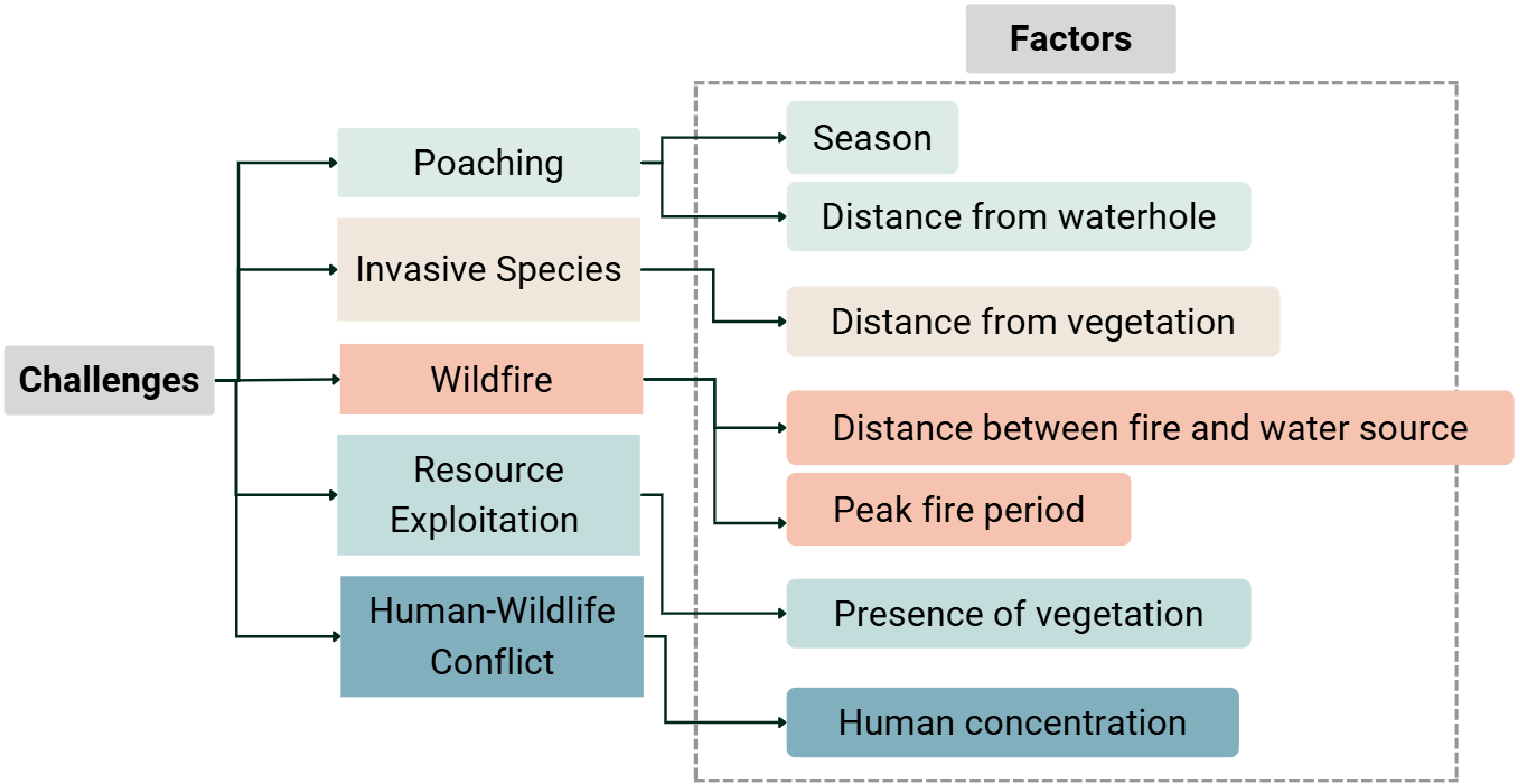
Gaussian Kernel

$$e^{-\frac{d(x,y)^2}{2\sigma(\tau)^2}}$$

- To model this spatial behaviour, we developed the Orbital Risk Model using a Gaussian Kernel Function, which represents the influence of a source that gradually decreases with distance.

- where d represents distance from an attractor and σ, controls how quickly risk spreads outward.

Challenges


Factors
Challenges
Poaching
Invasive Species
Wildfire
Resource Exploitation
Human-Wildlife Conflict
Season
Distance from waterhole
Distance from vegetation
Distance between fire and water source
Peak fire period
Presence of vegetation
Human concentration

Orbital Risk Model

- In this Orbital Risk Model, we adopt the idea where **each challenge is concentrated around attractors**, which are physical features where the challenge is most intense. The influence of each attractor decays exponentially with distance, forming a “challenge cloud”.
- We introduced $S(\tau)$, a dryness index that ranges from 0 (wet season) to 1 (peak dry season). It **follows a smooth sinusoidal cycle** that peaks on July 1 (day 182), and affects challenges such as poaching, human-wildlife conflict, and invasive species.
- Wildfires behave differently from other threats, so we created a separate fire danger index $F(\tau) = S(\tau)^2$. This means **fire risk stays low through most of the year but rises sharply as conditions become extremely dry**.
- Ranger camps are modeled as "protective clouds" as they reduce local risk through deterrence and rapid response. Using the same Gaussian form as threat clouds, each camp subtracts risk from poaching and human-wildlife conflict (as shown when calculating net risk).

Orbital Risk Model

Challenge	Attractor(s)	Key Formula Component
Poaching	51 waterholes	$\phi_{poach,w}(x, y, \tau) = W_{poach} \times S(\tau) \times e^{-\frac{d_w(x,y)^2}{2\sigma_{poach}(\tau)^2}}$
Wildfires	Vegetated areas	$\phi_{fire}(x, y, \tau) = W_{fire} \times F(\tau) \times e^{-\frac{d_{fuel}(x,y)^2}{2\sigma_{fire}(\tau)^2}}$
HWC	Roads, boundaries, picnic spots	$\phi_{HWC,a}(x, y, \tau) = W_{HWC} \cdot S(\tau) \cdot e^{\frac{da(x,y)^2}{2\sigma_{HWC}}}$
Resource Exploit	Vegetated areas	$\phi_{exploit}(x, y) = W_{exploit} \times e^{-\frac{d_{veg}(x,y)^2}{2\sigma^2_{exploit}}}$
Invasive Species	Vegetated areas	$\phi_{inv}(x, y, \tau) = W_{inv} \cdot S_{inv}(\tau) \cdot e^{-\frac{d_{veg}(x,y)^2}{2\sigma^2_{inv}}}$

In words:

Risk at any point = Weight × Seasonal factor × Exponential decay with distance

Calculating Net Risk

$$R_{net}(x, y, \tau) = max[0, \phi_{poaching} + \phi_{HWC} - \Psi(x, y)] + \phi_{wildfire} + \phi_{invasive\ species} + \phi_{resource\ exploitation}$$

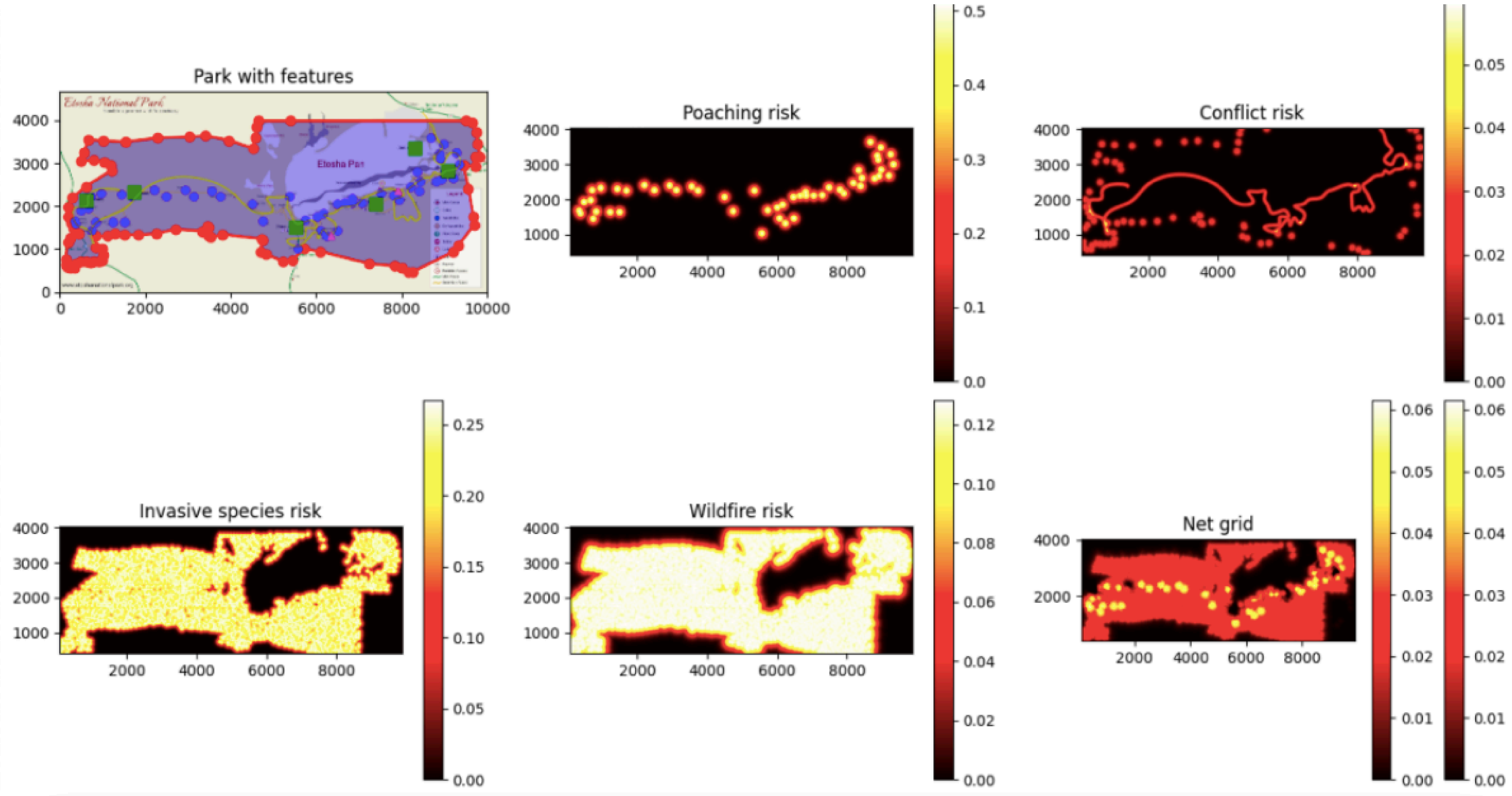


Fig.1: Risk heat maps for Etosha National Park

Defining Protection

- The net risk surface assigns a risk value to every point across the park. To obtain a single, meaningful measure of the park's overall risk burden, the net risk is integrated across the entire park area.
- The total risk over the entire park season at season τ is given by $R_{total}(\tau)$

This allows us to define protection mathematically as:

$$P(\tau) = 1 - \frac{R_{total}(\tau)}{max_{\tau'} R_{total}(\tau')}$$

A value of 1 indicates the park is at its safest (zero risk), while 0 indicates maximum vulnerability (peak risk with no protection).


THREAT
DETECT
ARREST
RUBICON

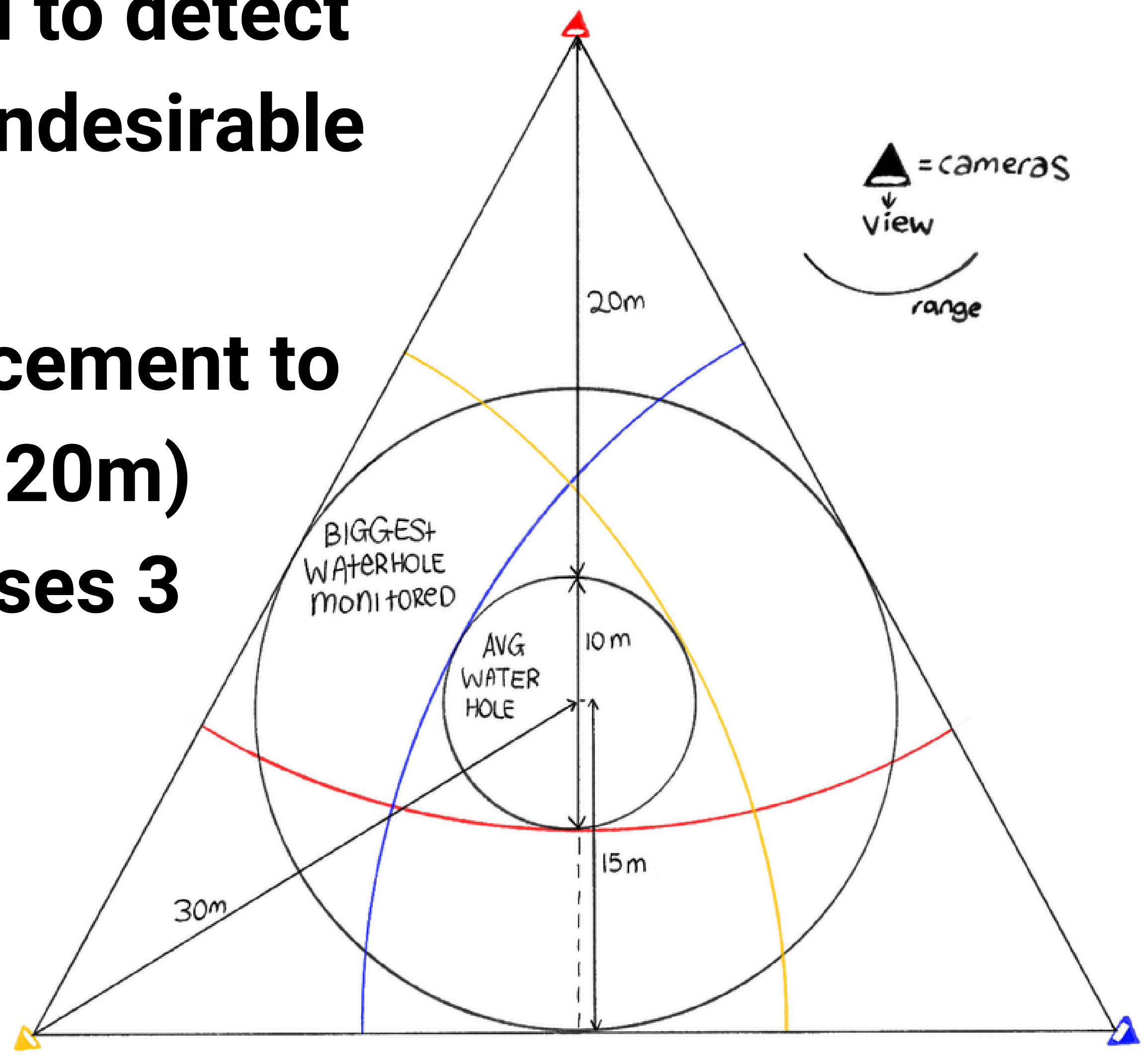
Untargeted Measures

Used for Detection of Threats

Camera Traps

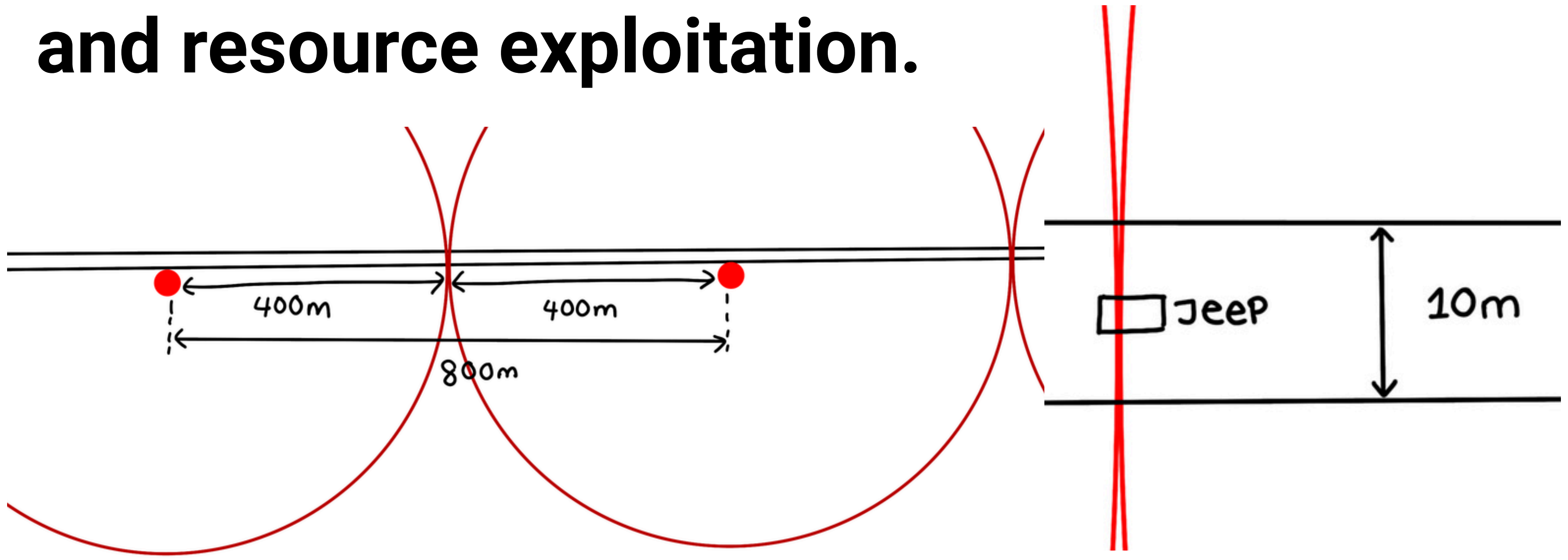
Can be used to detect Poaching/Undesirable HWC.

Optimal placement to cover a (10-20m) waterhole uses 3 cameras.



Laser Speed Cameras

Can be used to detect wildfires along the road, and transports for poaching and resource exploitation.



Placed along roads with distances of 800m. (2x400m, which is effective distance)

Targeted Measures

Used to Subdue Threats

Jeeps

Rangers working with the jeeps work in 3 8h shifts for full coverage.

Adaptable to address many problems, but best used for Poaching and Human Wildlife Conflict

Stationed at Ranger Camps

*We specifically used the Jeep Wranglers as it came up a lot during research and can be standardised

Drones

We used agricultural drones, which could carry water to extinguish Wildfires, and film evidence for Resource Exploitation.

Placed at drone points every 13 km (=drone coverage radius)

Placed along roads with distances of 800m. (2x400m, which is effective distance)

Mixed-Integer Linear Programming (MILP)

- In our resource allocation model, Mixed Integer Linear Programming (MILP) was used as it finds the **optimal number and placement of protection resources** to maximise risk reduction while respecting budget, minimum requirements, and operational limits.

How many units of each tool should be deployed, and where should they be placed, to maximise total risk reduction while respecting budget and operational constraints?

Decision Variables:

- **Camera traps:** For each waterhole $w \in W$, let $y_w \in \{0, 1\}$ indicate whether the waterhole receives three cameras. Then the number of camera traps at waterhole w is $3y_w$
- **Laser cameras:** For each road point $j \in R$, let $z_j \in \{0, 1\}$ indicate whether a laser camera is placed at that point
- **Patrol jeeps:** For each camp $a \in A$, let $x_a \in Z \geq 0$ be the number of jeeps stationed at each camp
- **Drones:** For each drone base $d \in D$, let $u_d \in Z \geq 0$ be the number of drones based there

MILP Objectives and Constraints

We use Multi-Integer Linear Programming (MILP) to maximise the total reduction, with **<u>our objective being to maximise the total risk reduction over the park.</u>**

The decision variables were also subjected to the following constraints:

- Budget Constraints

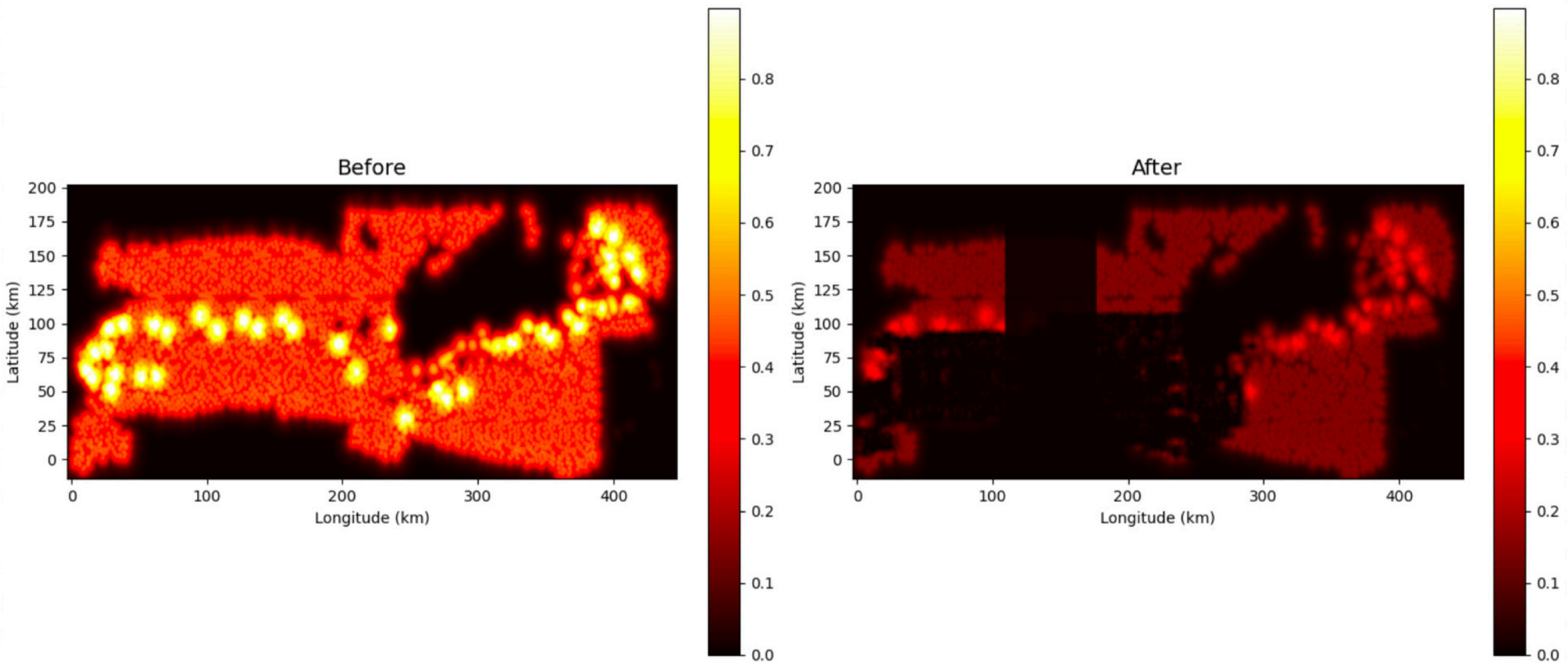
$$\sum_{w} 3_{yw} \cdot c_{camera\,trap} + \sum_{j} z_{j} \cdot c_{laser\,camera} + \sum_{C} x_{C} \cdot c_{jeep} + \sum_{d} u_{d} \cdot c_{drone} \leq budget$$

- Integrality constraints (to ensure to restrict decision variables to integers)
- Forced contraints (to ensure a baseline level of protection)

MILP Results

Protection measure	Number of units
Camera traps	153
Laser cameras	500
Patrol jeeps	6
Drones	50
Total per shift	–
Total FTE (3 shifts)	**–**

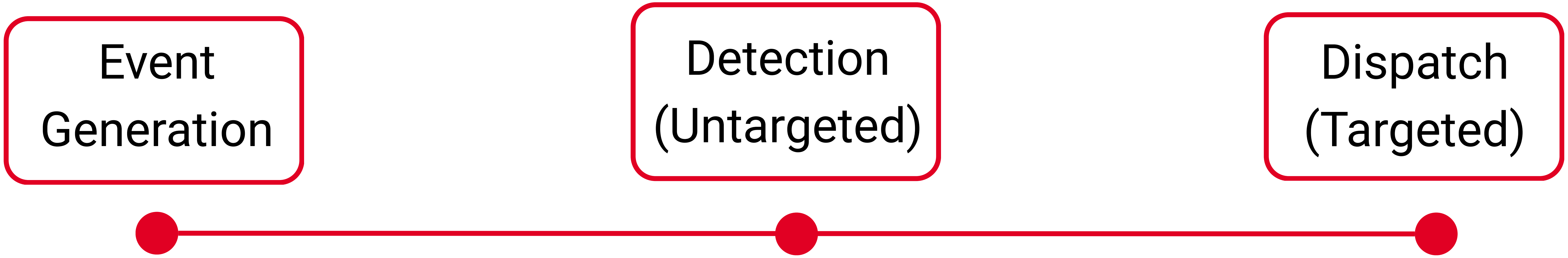
MILP Results



Simulation

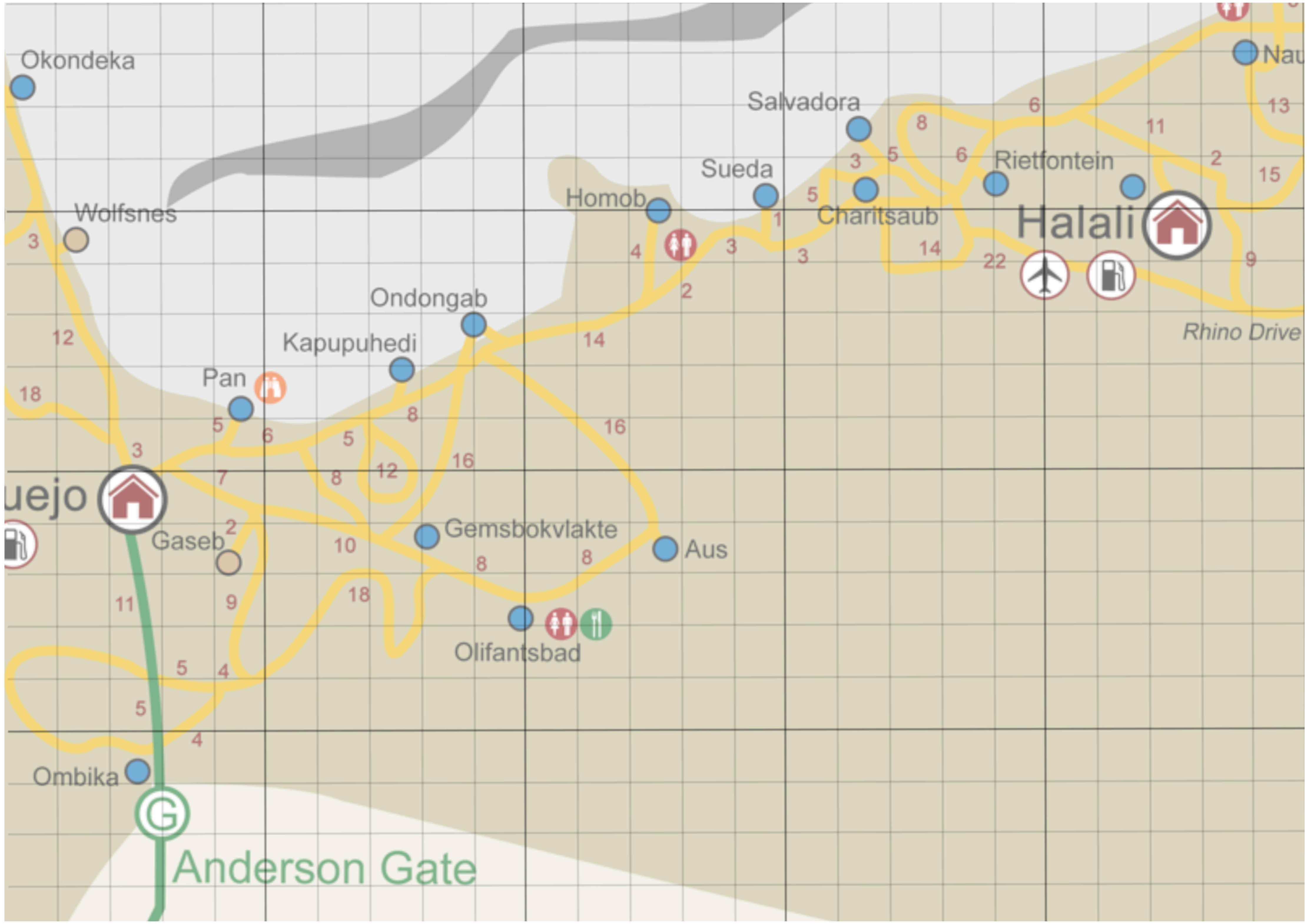
Calculates 1 event per hour every day for a year.

For each event 3 phases:

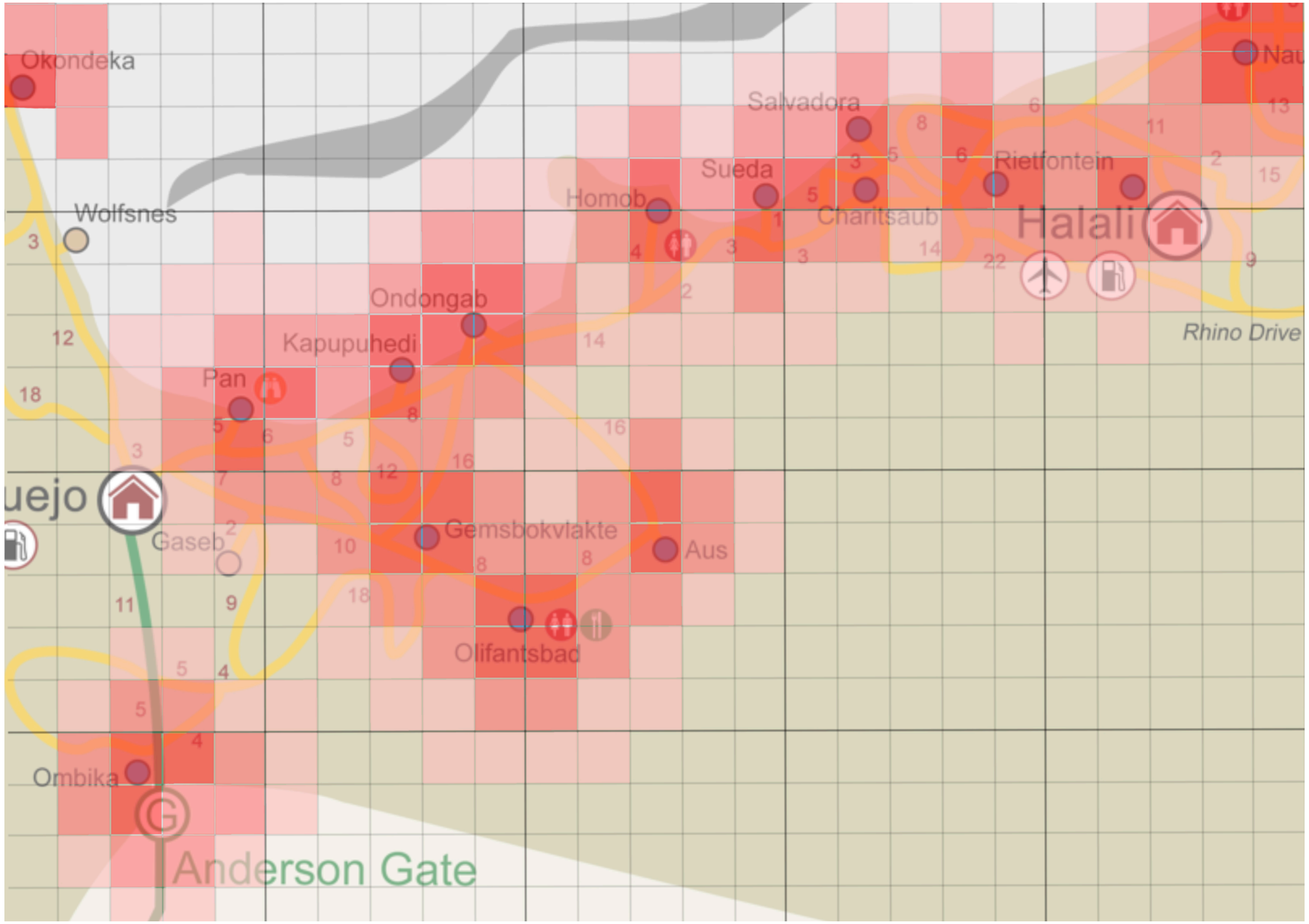


Computes Protection, Detection and Subduation Metrics

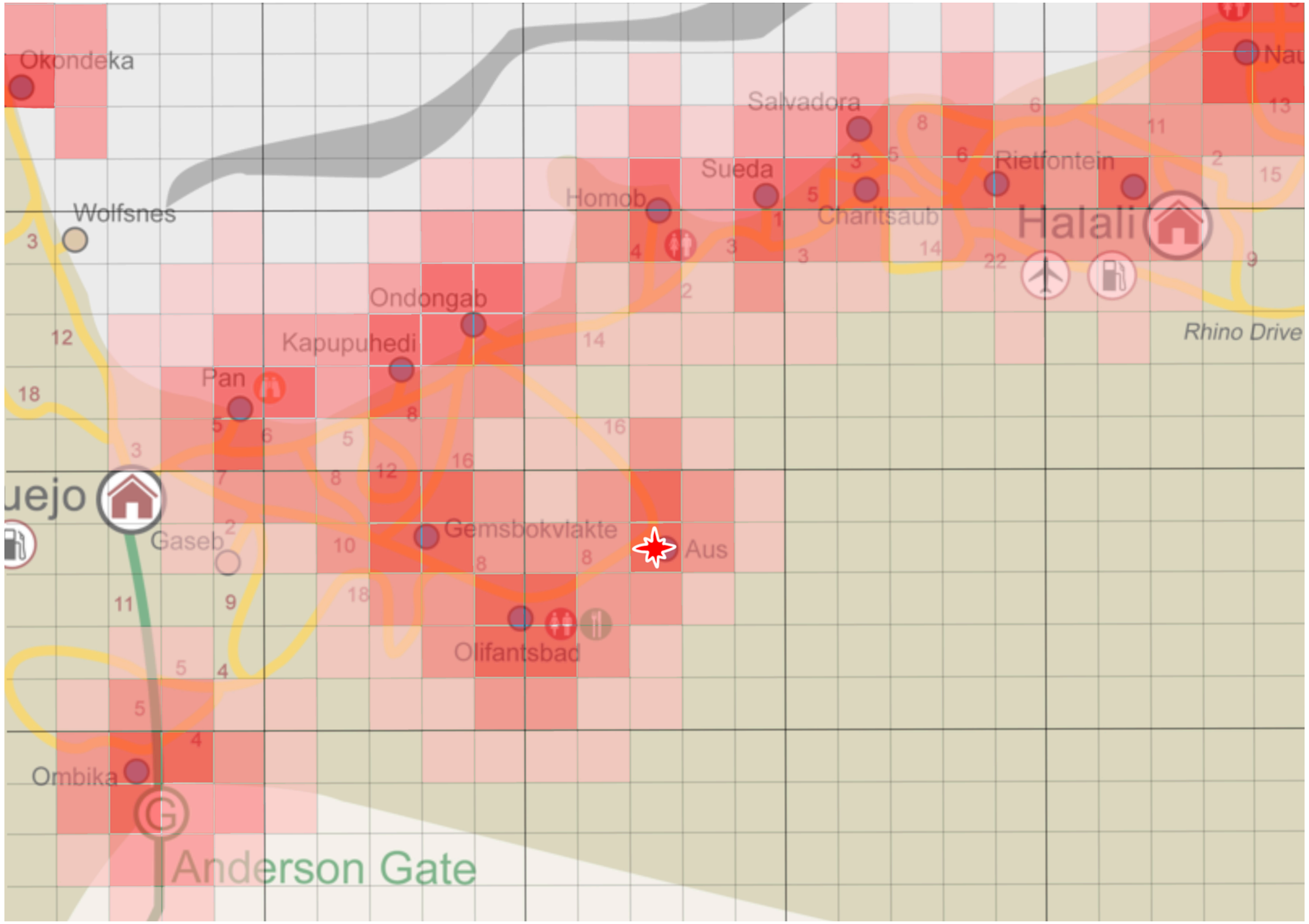
Event Generation

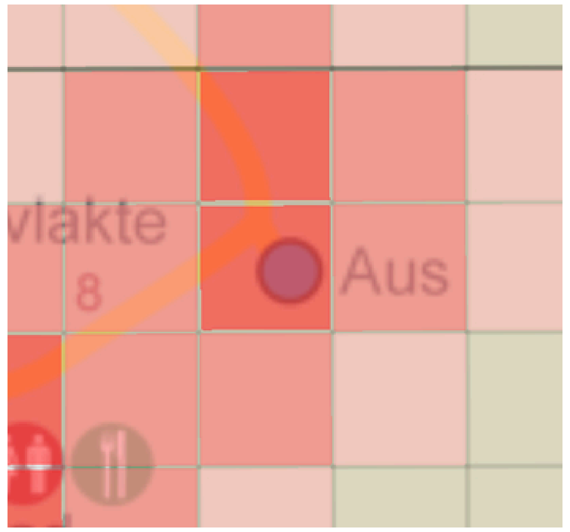


Event Generation



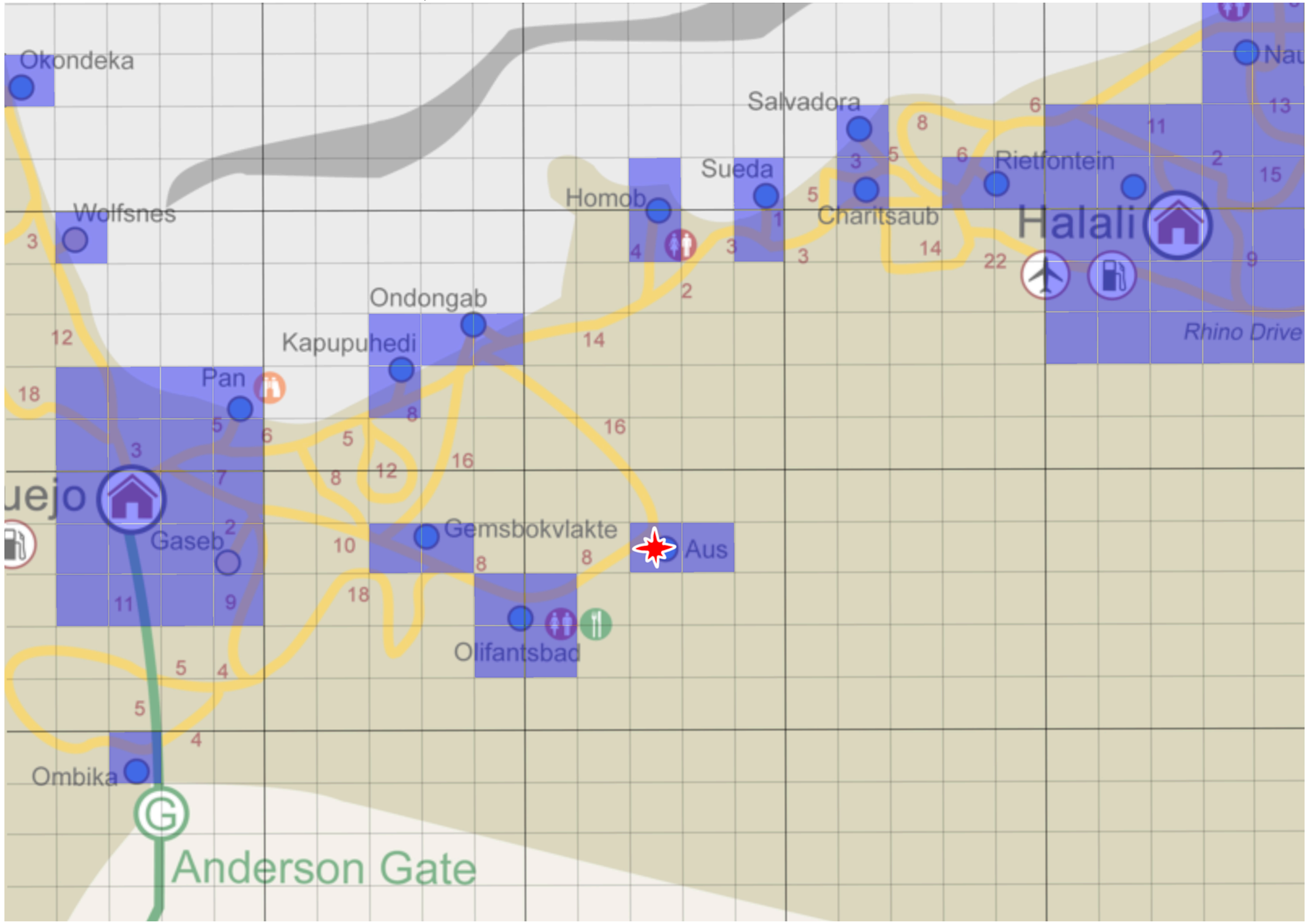
Event Generation



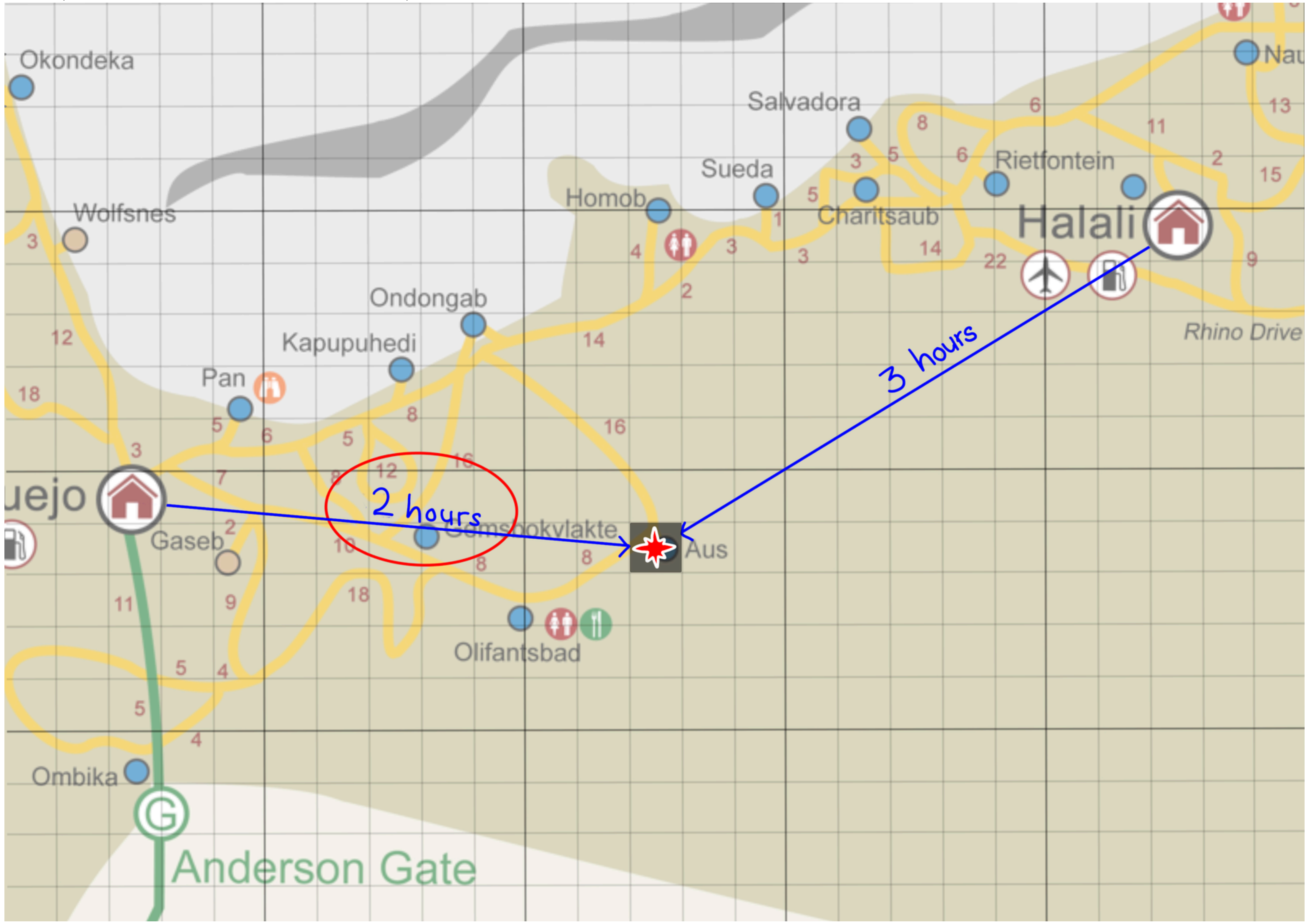


Poaching: 70%
Invasive species: 20%
Wildfires: 10%

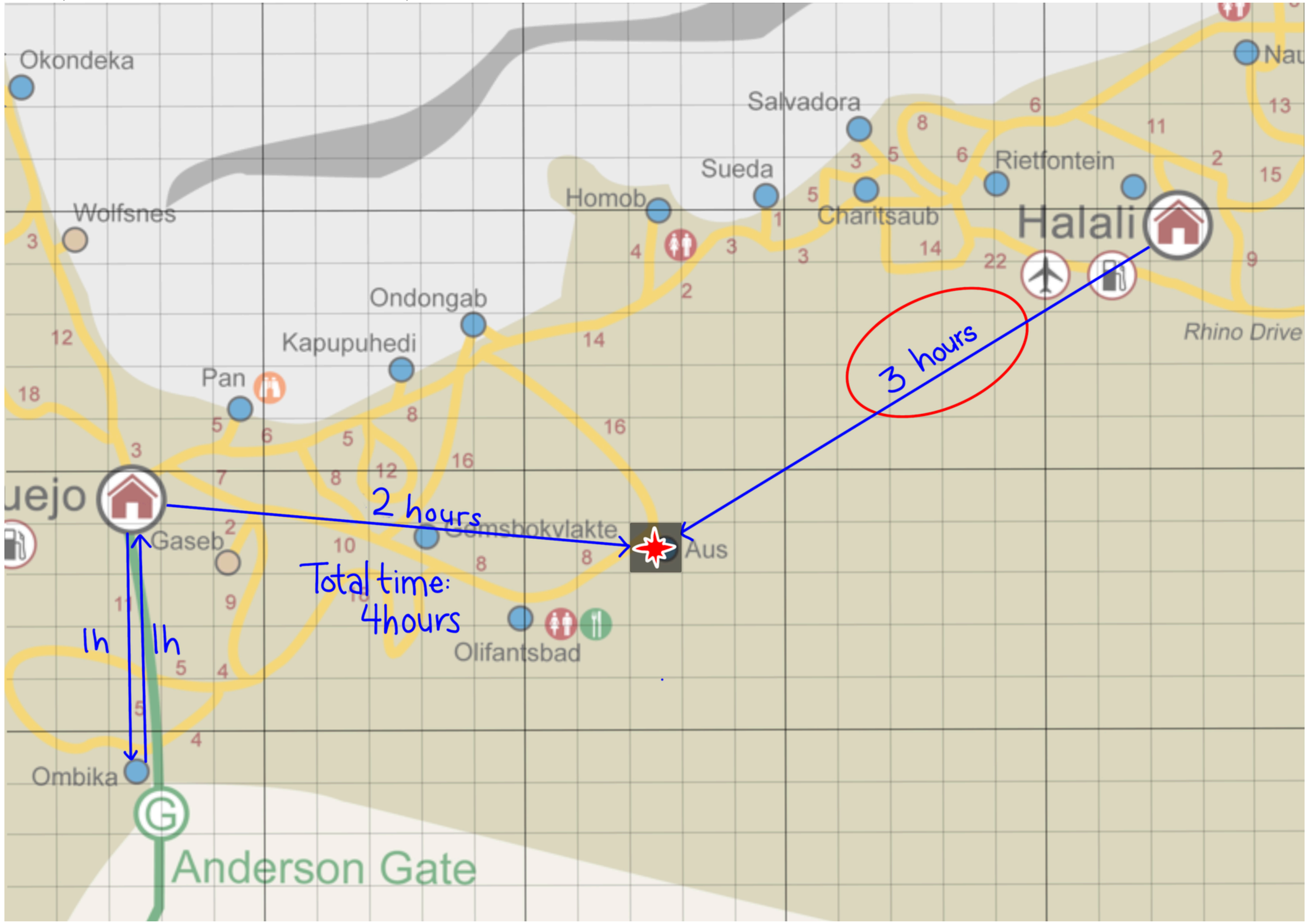
Detection (Untargeted)



Subduation (Targeted)



Subduation (Targeted)



Resultant Metrics

$$\text{Protection Metric} = \frac{\text{Subdued events}}{\text{Total events}} \times 100\%$$

$$\text{OR} \quad \text{Subduation metric} \times \text{Detection Metric}$$

$$\text{Detection Metric} = \frac{\text{Detected events}}{\text{Total events}} \times 100\%$$

$$\text{Subduation Metric} = \frac{\text{Subdued events}}{\text{Detected events}} \times 100\%$$

Sensitivity Analysis – Orbital Risk Model

Five parameters were selected to represent the main sources of uncertainty: the FAHP weight of poaching, the baseline bandwidths for poaching and wildfires, the timing of the seasonal peak, and the effectiveness of ranger camps.

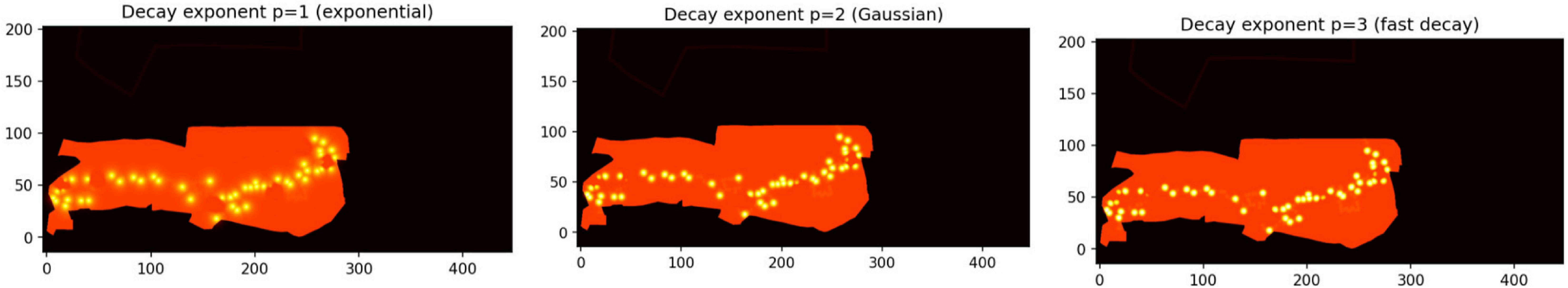
Parameter	Variation	R_{total}	ΔR_{total} (%)	Spearman ρ
Baseline	–	11 100	–	1.000
W_{poach}	0.409	10 975	−1.12	0.992
	0.614	11 226	+1.14	0.994
$\sigma_{poach,0}$	1 km	10 670	−3.87	0.815
	4 km	12 256	+10.42	0.859
$\sigma_{fire,0}$	1.5 km	11 100	0.00	1.000
	6 km	11 100	0.00	1.000
τ_{peak}	152	11 100	0.00	1.000
	212	11 100	0.00	1.000
α	0.4	11 118	+0.16	0.984
	0.8	11 087	−0.11	0.988

The Spearman rank correlation coefficients are all above 0.81, indicating that the spatial order of risk remains largely unchanged across variations.

Sensitivity Analysis – Orbital Risk Model

In the baseline model, the influence of an attractor decays as a Gaussian: $\exp(-d^2/2\sigma^2)$, which corresponds to an exponent p=2. We replaced this with a generalised exponential $\exp(-(d/\sigma)^p)$ using p=1and p=3, keeping the same σ values.

Exponent p	Total Risk	Change (%)	Spearman ρ (vs. p=2)
1 (Exponential)	12 283	+28.7	0.965
2 (Gaussian)	9 545	–	1.000
3 (Fast decay)	7 812	−18.2	0.972

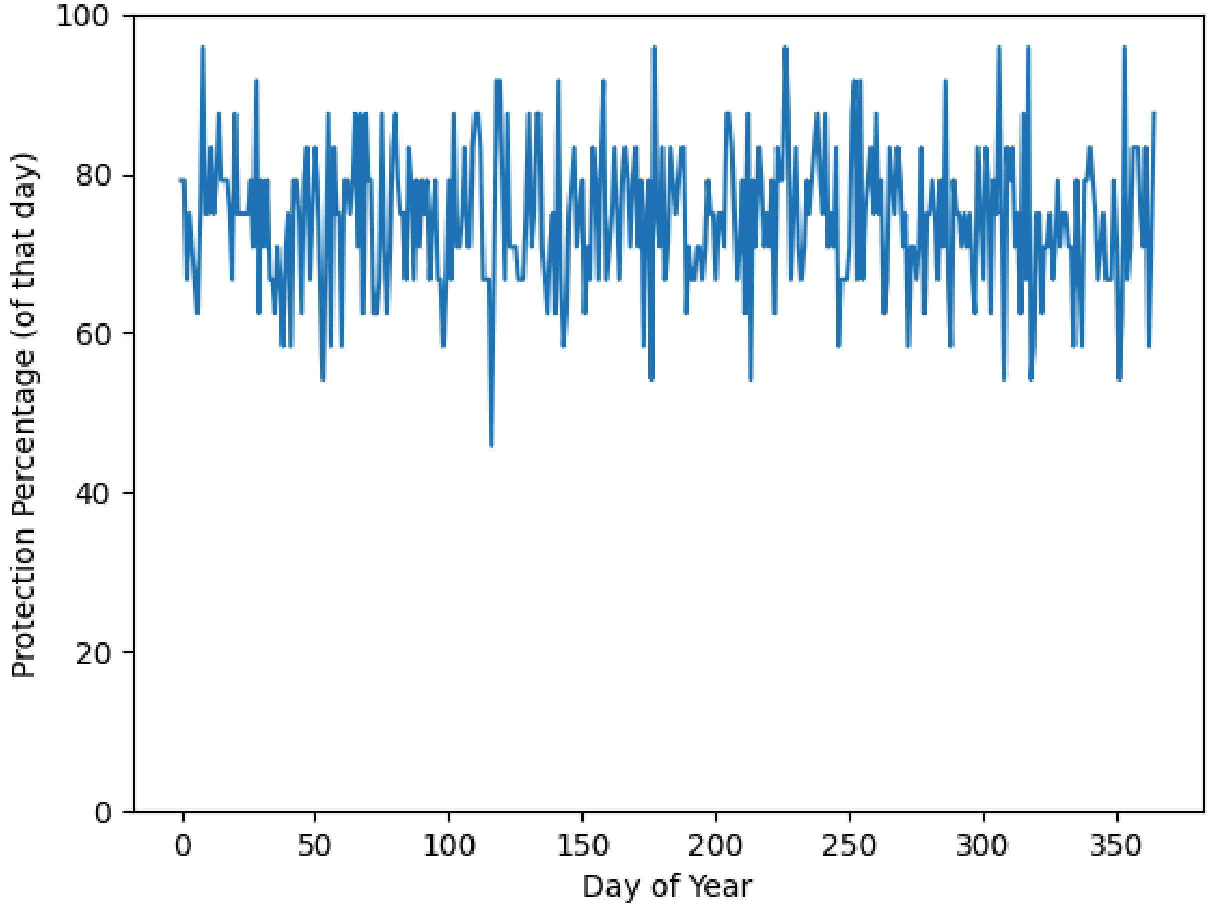


Overall, our sensitivity analysis shows that the orbital risk model can be used with confidence for the resource allocation and simulation stages.

Sensitivity Analysis – Simulation

Limited Targeted Measures

(default) Jeeps + Drones



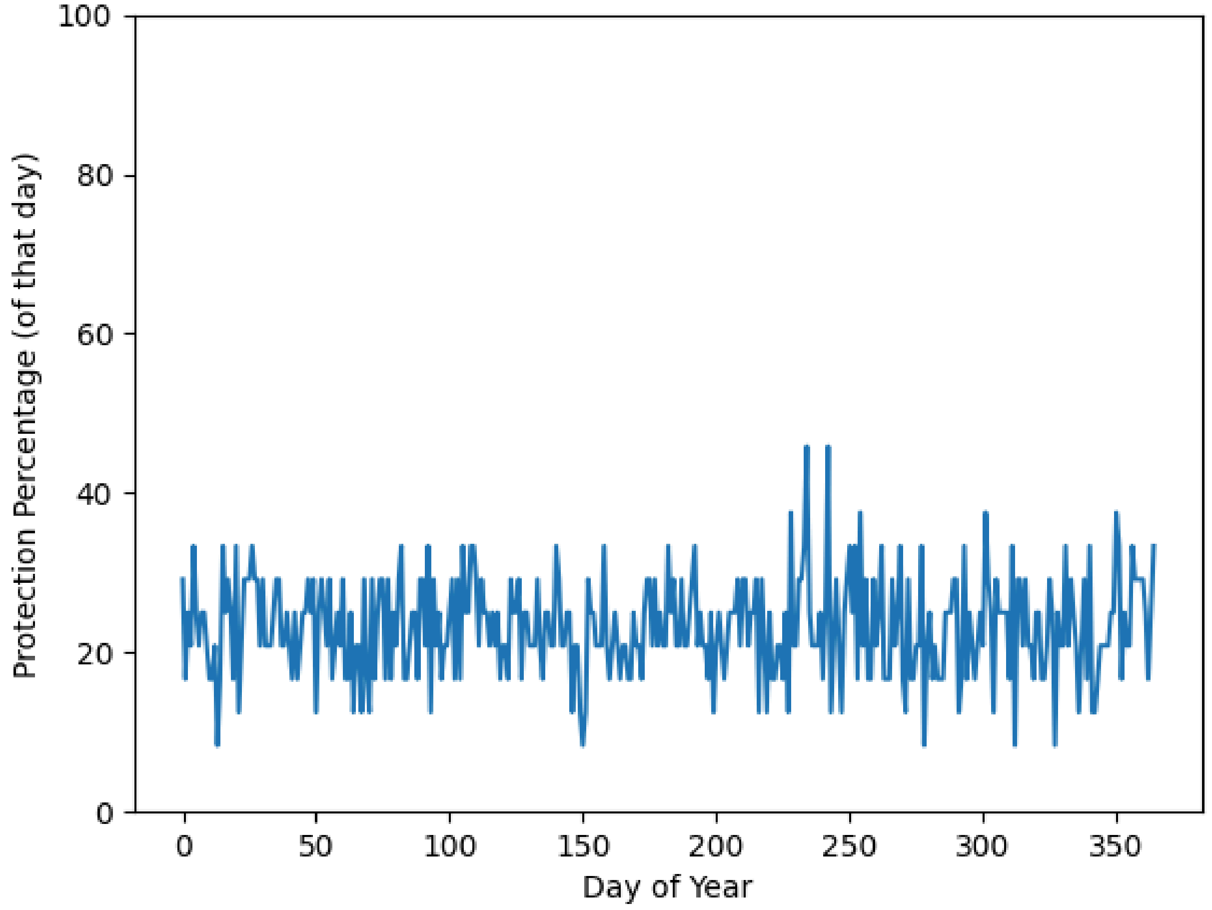
Average Protection Metric: **74.34%** over the year.

P(t) ≥ 70.0 for 72.60% of the time.

P(t) ≥ 60.0 for 94.25% of the time.

Standard Deviation: 8.769367459158277

Jeeps



Average Protection Metric: **23.16%** over the year.

P(t) ≥ 20.0 for 76.71% of the time.

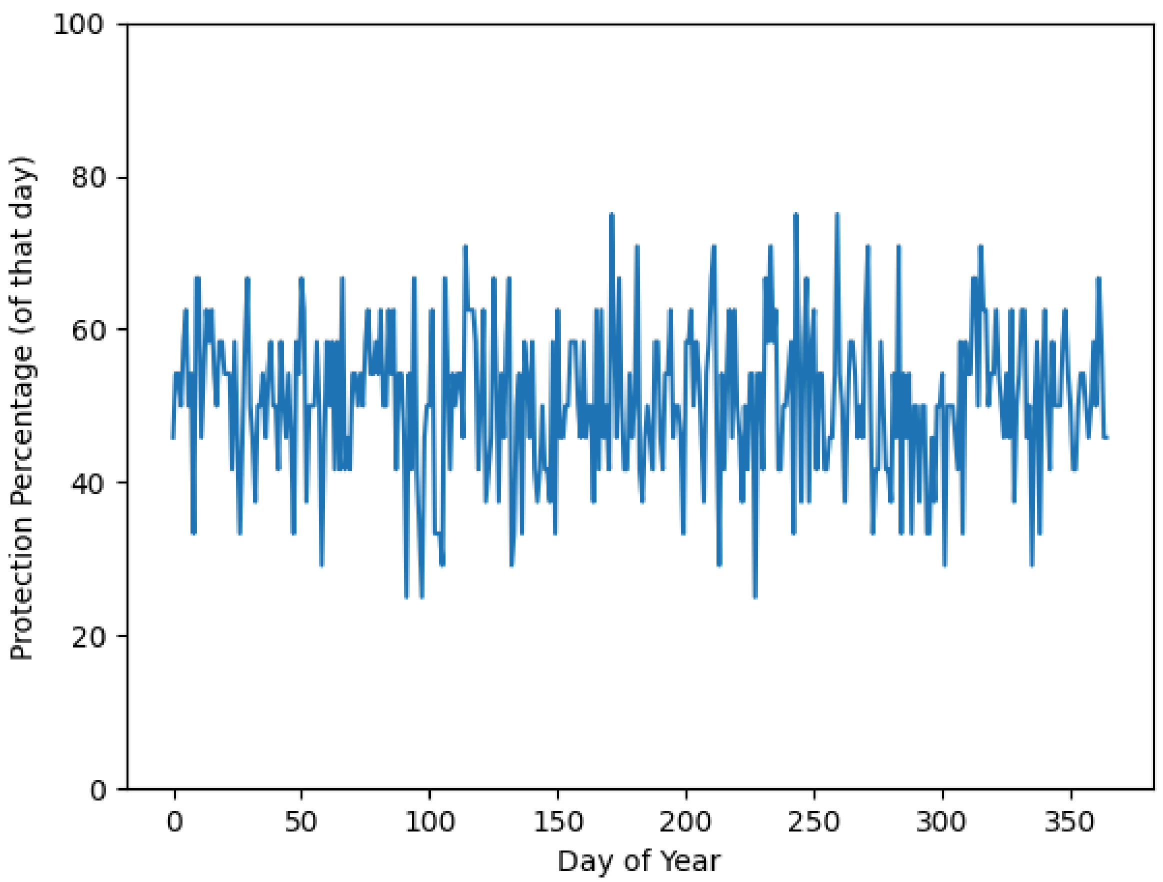
P(t) ≥ 10.0 for 98.63% of the time.

Standard Deviation: 6.129871256028077 5

Sensitivity Analysis – Simulation

Deadlines To Accomplish Tasks Differ

1 Hour Deadline



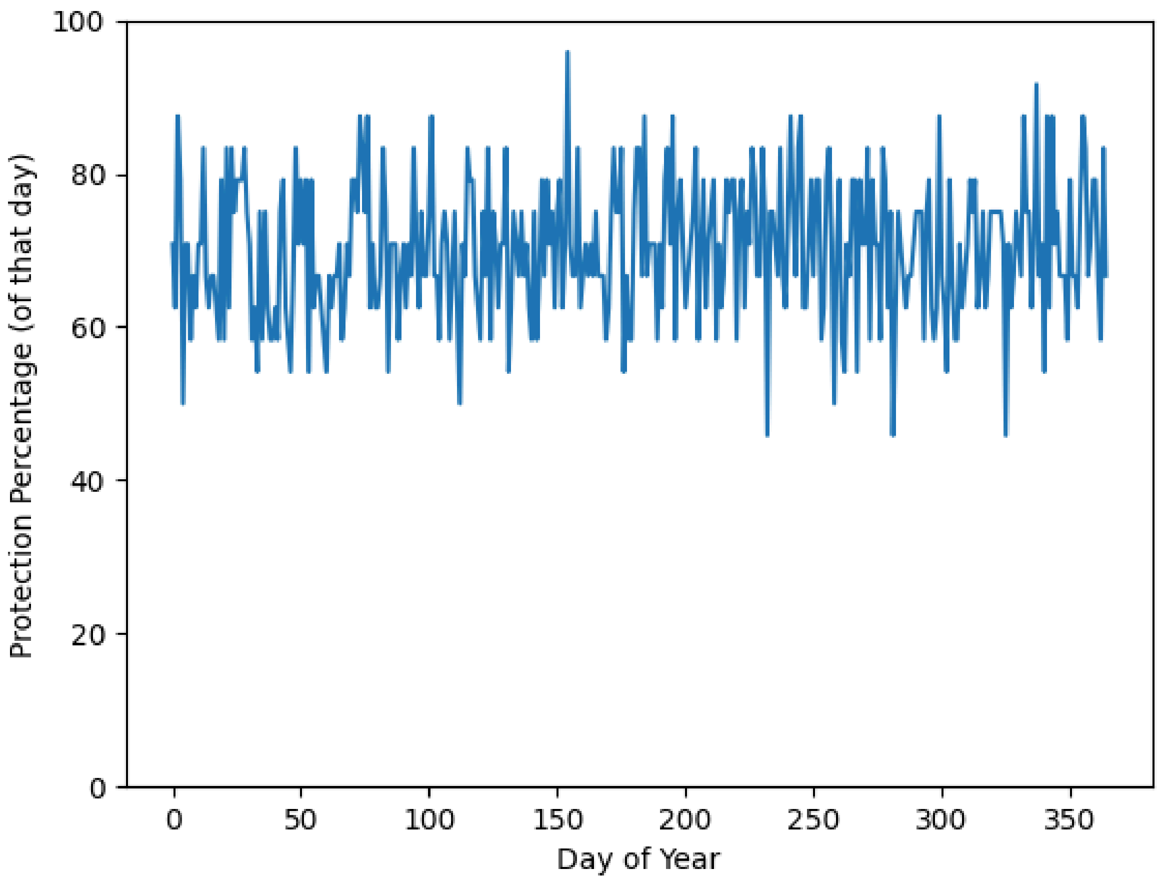
Average Protection Metric: **50.76%**

P(t) ≥ 50.0 for 64.38% of the time.

P(t) ≥ 40.0 for 87.67% of the time.

Standard Deviation: 9.686636419659067

2 Hour Deadline



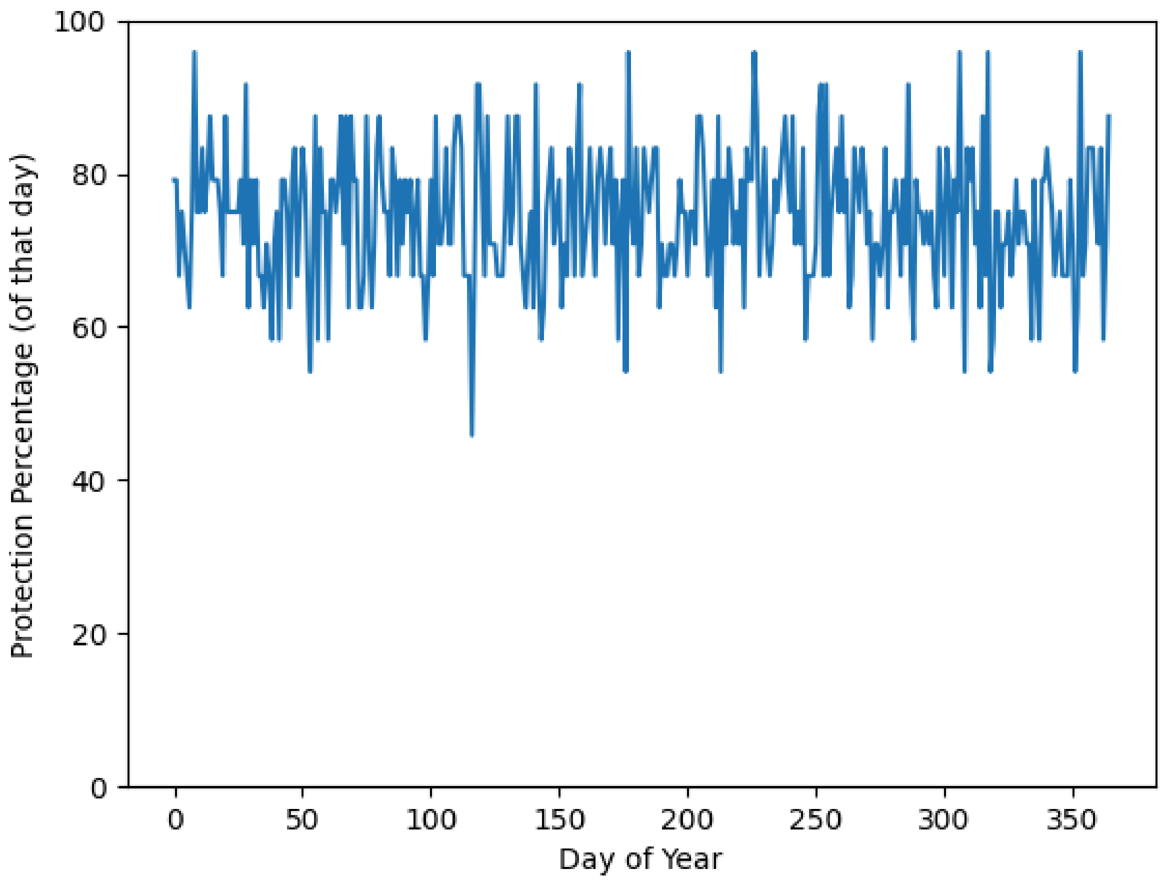
Average Protection Metric: **70.07%**

P(t) ≥ 70.0 for 54.25% of the time.

P(t) ≥ 60.0 for 85.48% of the time.

Standard Deviation: 8.898370706492633

(default) 4 Hour Deadline



Average Protection Metric: **74.34%**

P(t) ≥ 70.0 for 72.60% of the time.

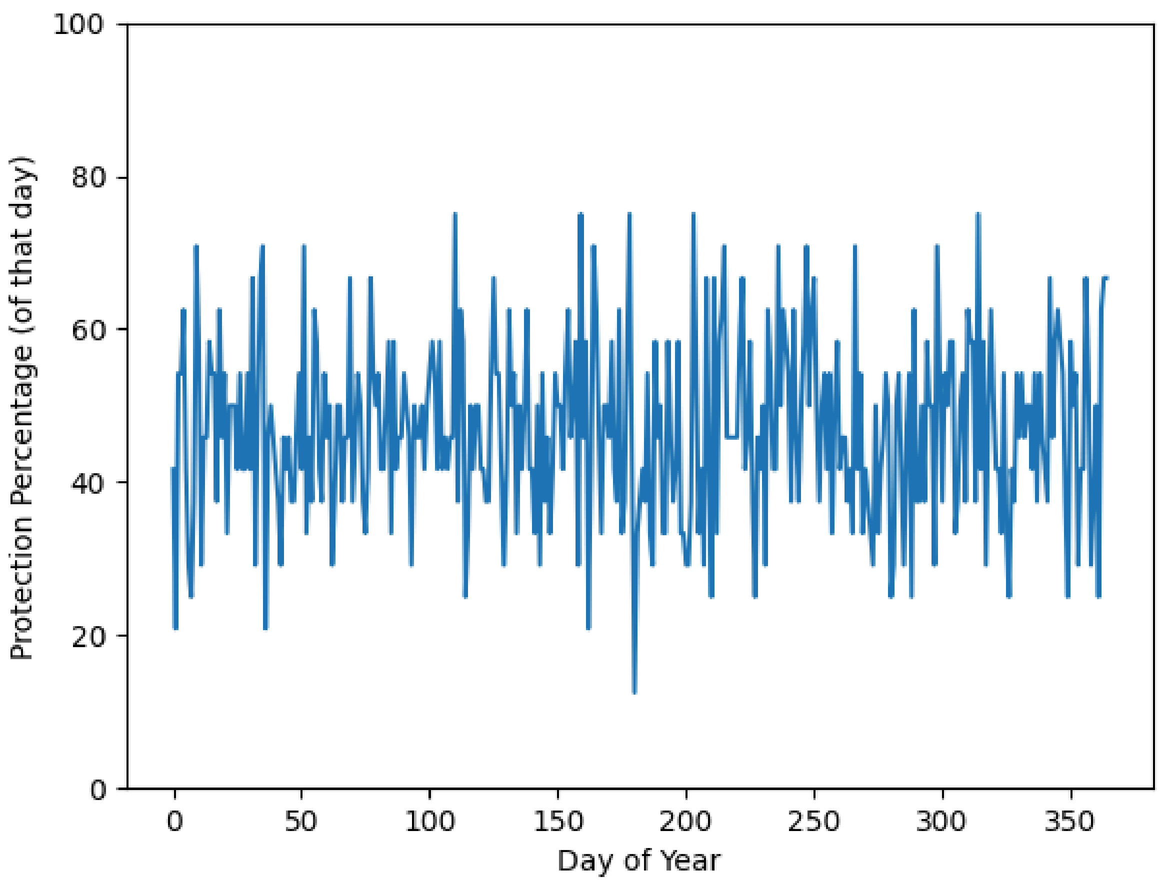
P(t) ≥ 60.0 for 94.25% of the time.

Standard Deviation: 8.769367459158277

Sensitivity Analysis – Simulation

Time Intervals Between Events Differ

30 Minute Intervals



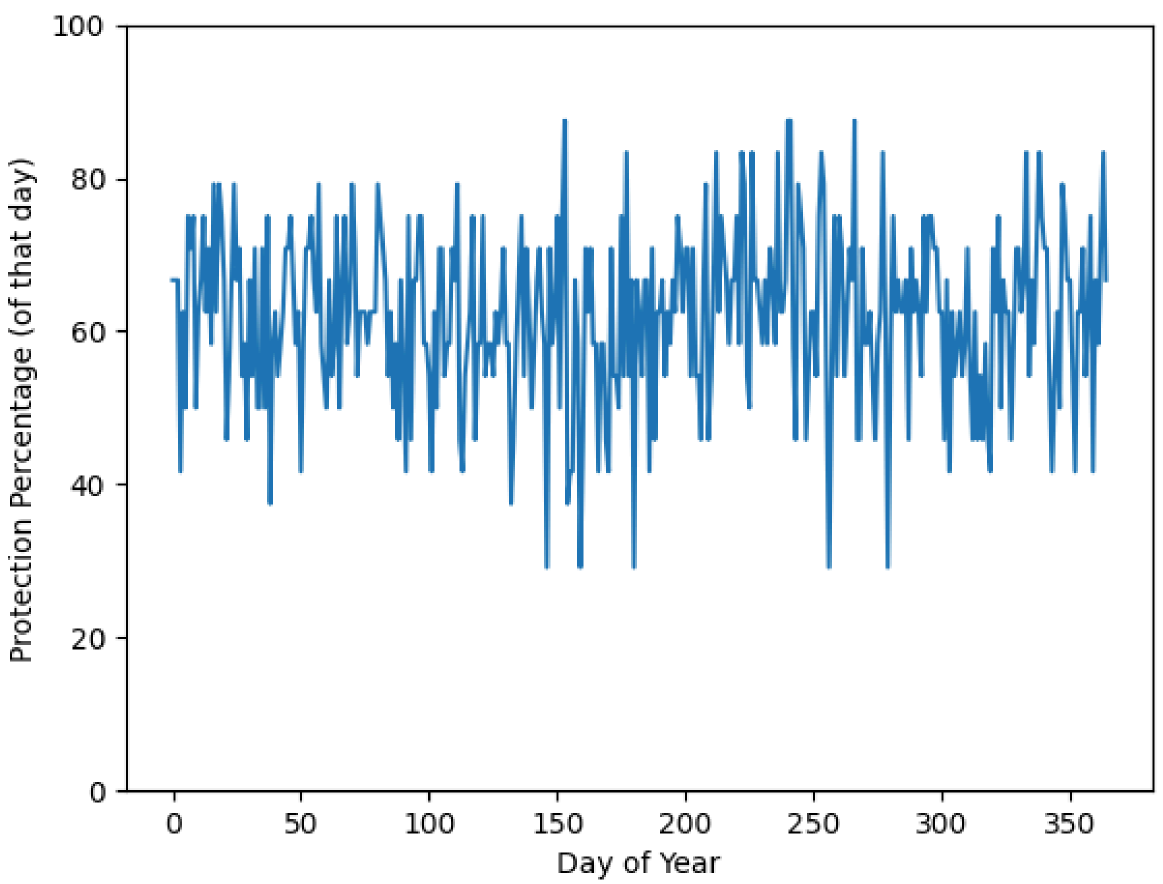
Average Protection Metric: **46.86%**

P(t) ≥ 40.0 for 72.88% of the time.

P(t) ≥ 30.0 for 90.68% of the time.

Standard Deviation: 11.630341809585198

40 Minute Intervals



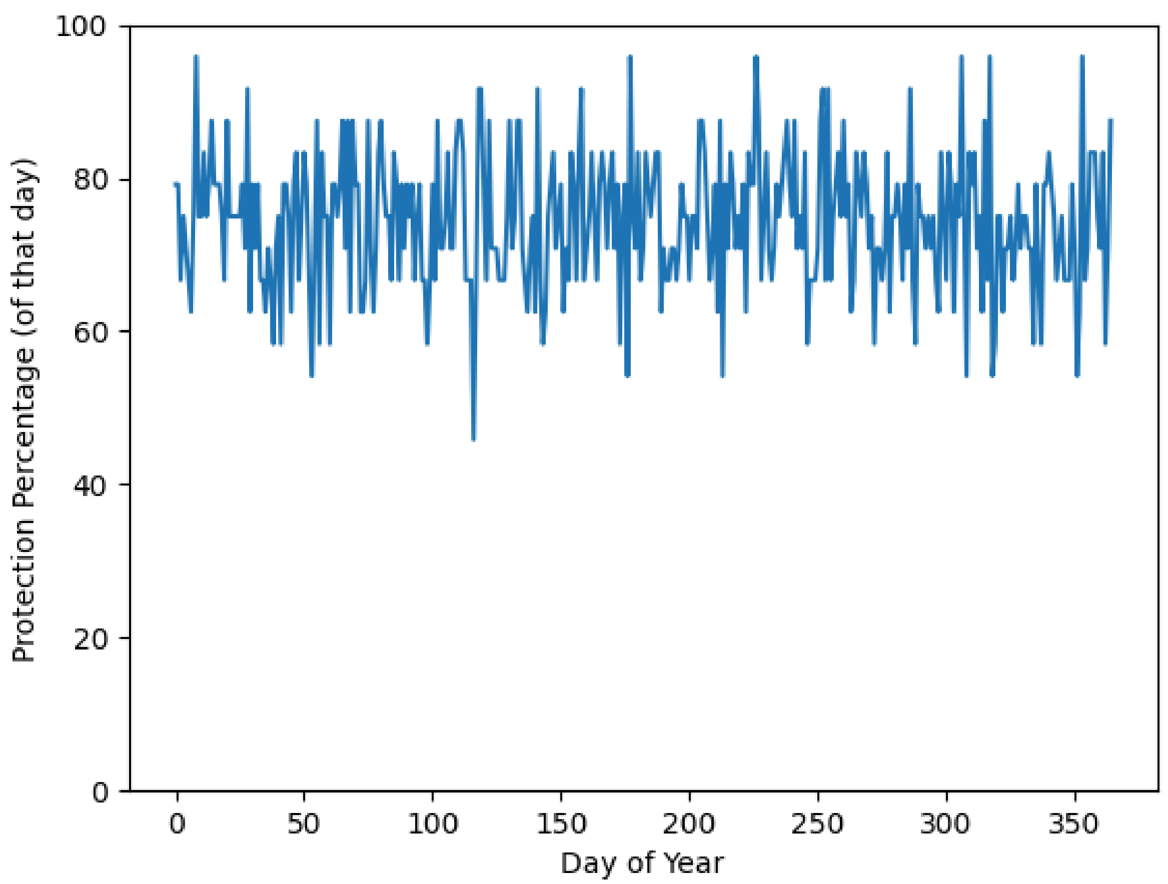
Average Protection Metric: **61.94%**

P(t) ≥ 60.0 for 57.81% of the time.

P(t) ≥ 50.0 for 87.12% of the time.

Standard Deviation: 11.232169020287882

(default) 60 Minute Intervals



Average Protection Metric: **74.34%**

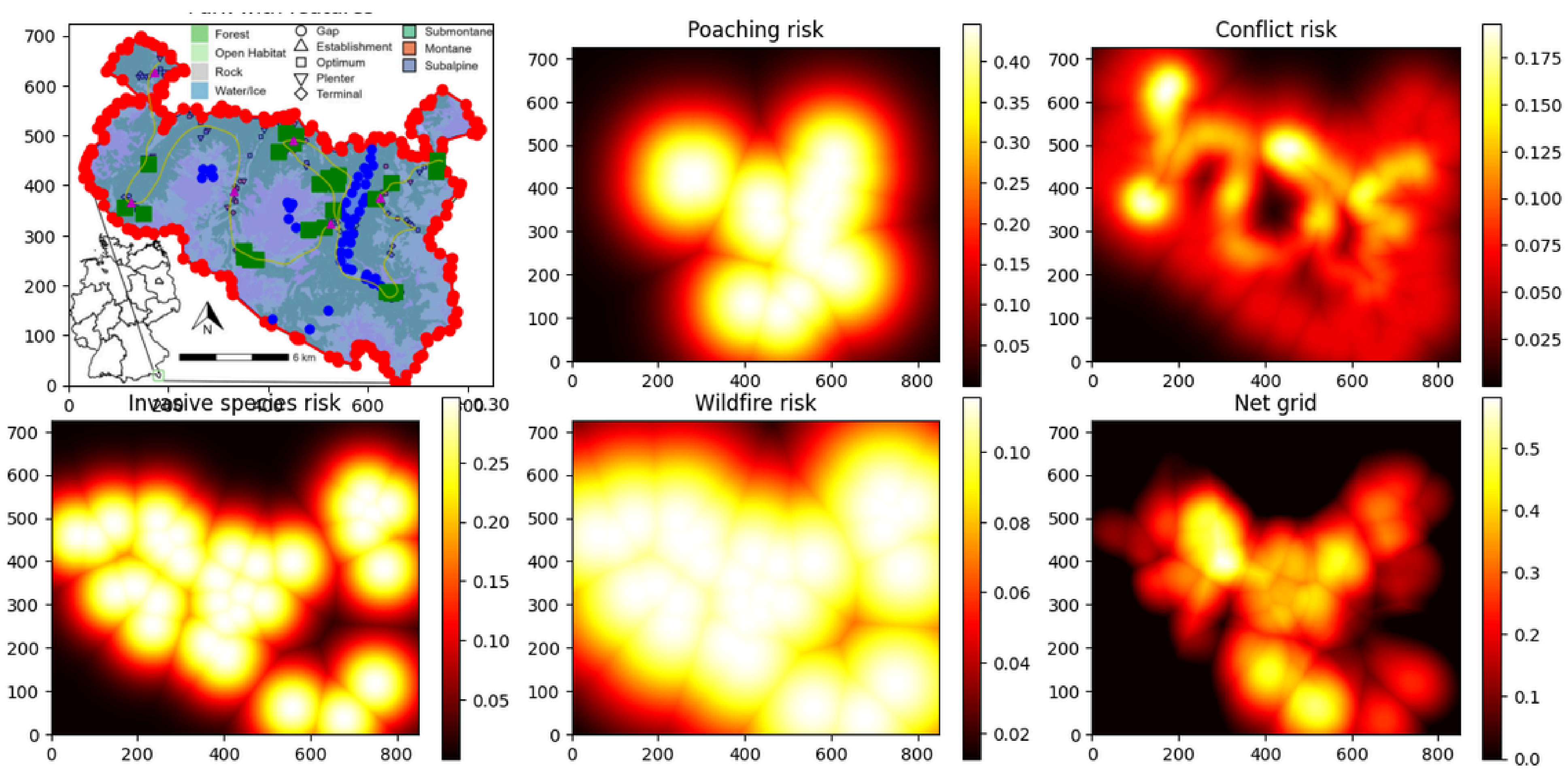
P(t) ≥ 70.0 for 72.60% of the time.

P(t) ≥ 60.0 for 94.25% of the time.

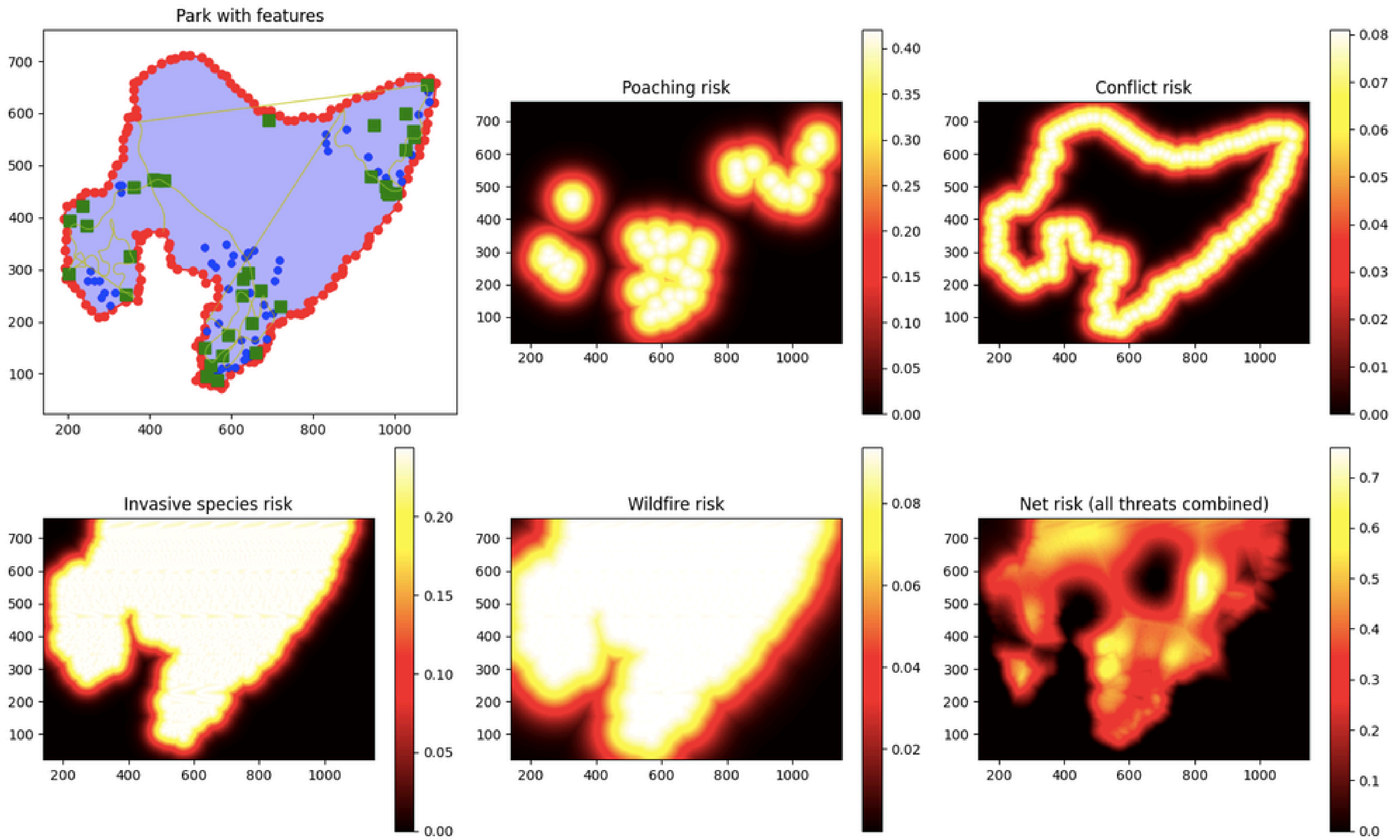
Standard Deviation: 8.769367459158277

Generalisation

Berchtesgaden National Park (Germany)



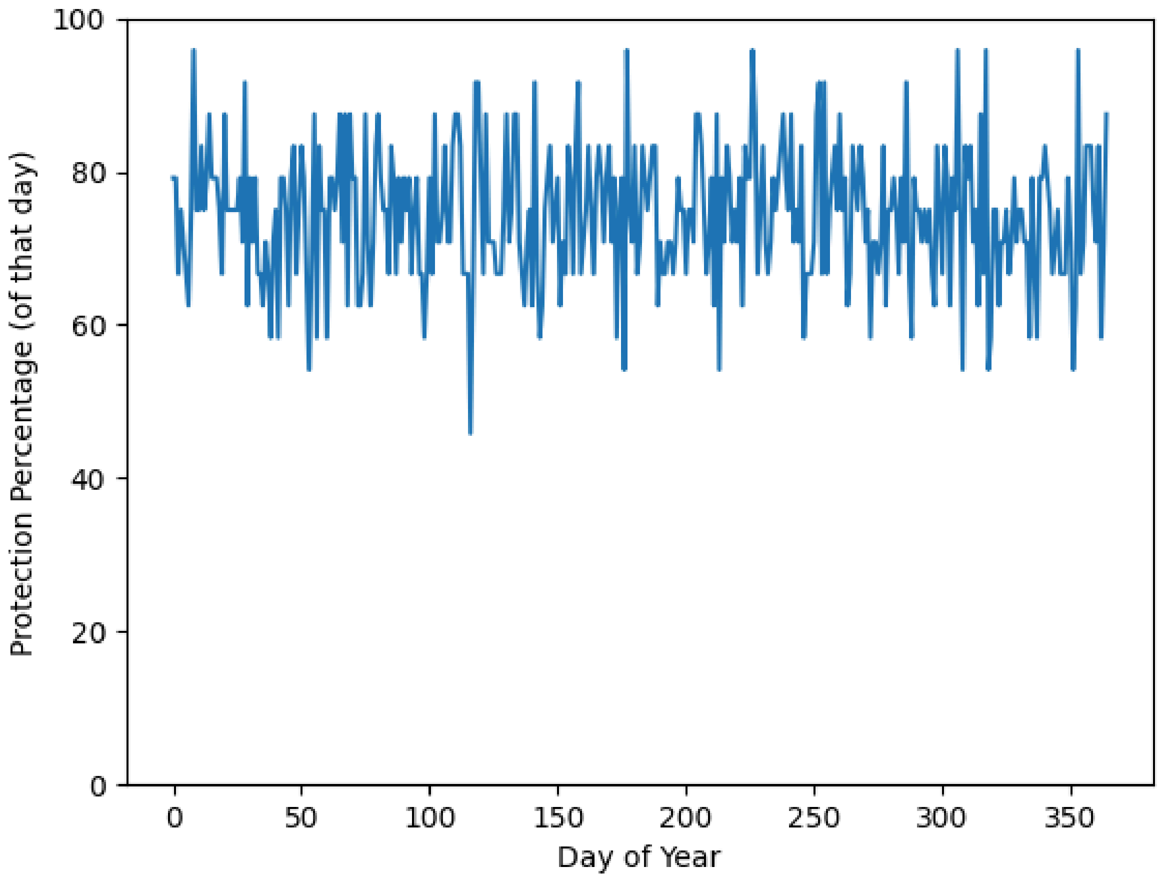
Yala National Park (Sri Lanka)



A brighter spot indicates a higher risk of threats occurring.

Generalisation

Etosha National Park

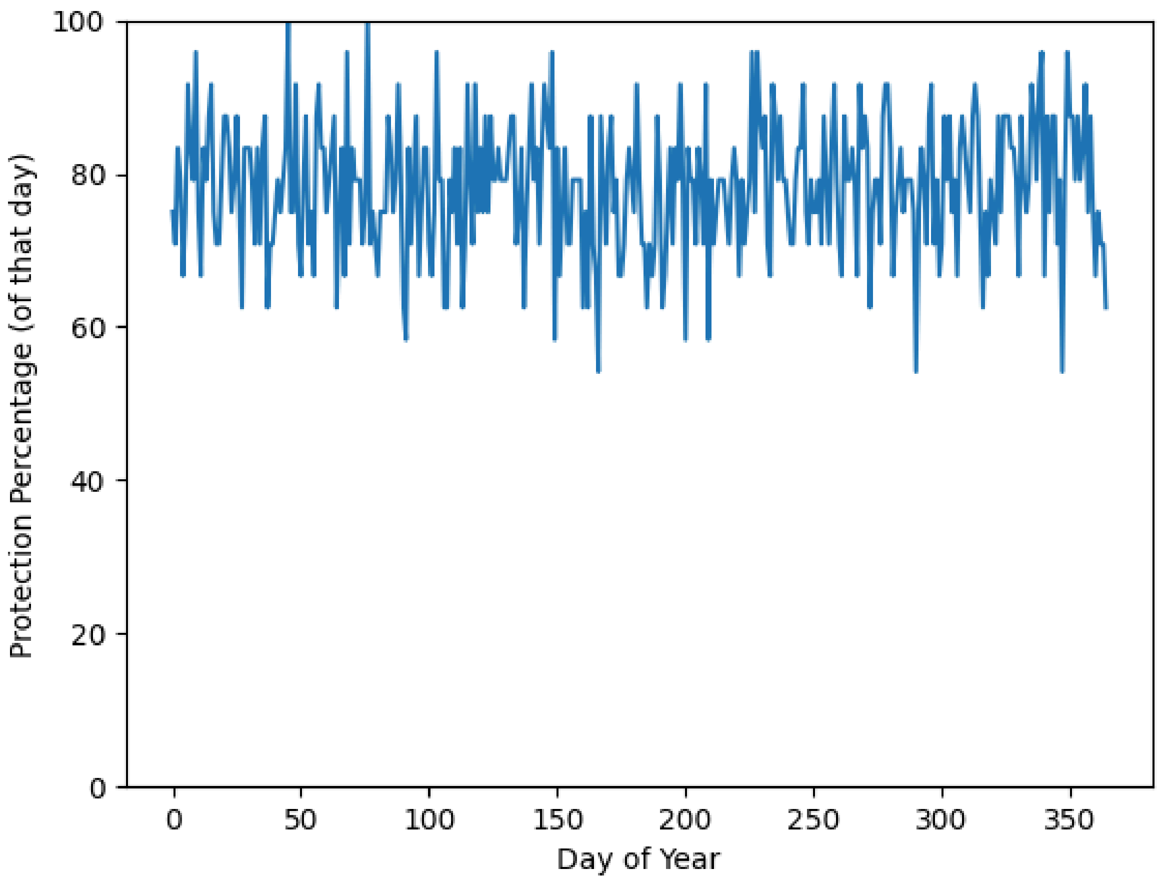


Average Protection Metric: **74.34%**

P(t) ≥ 70.0 for 72.60% of the time.

P(t) ≥ 60.0 for 94.25% of the time.

Yala National Park

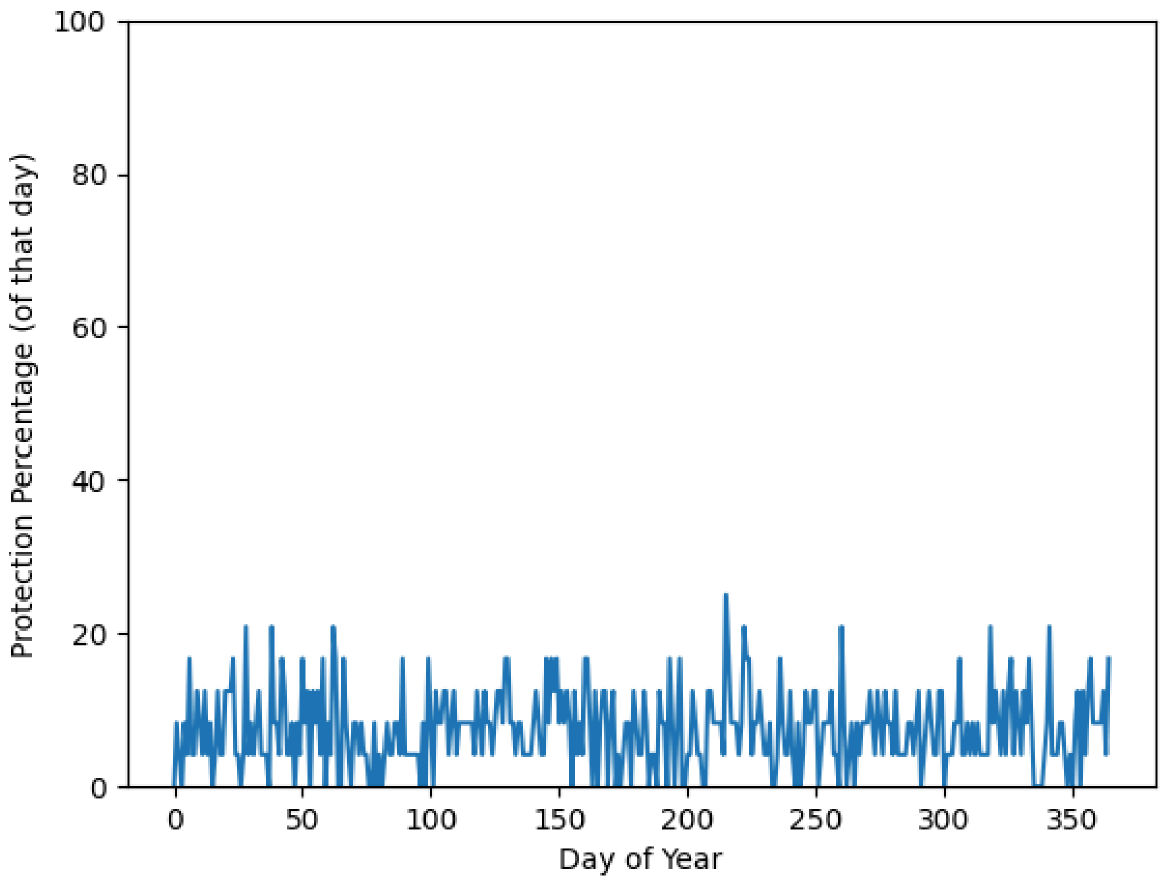


Average Protection Metric: **78.33%**

P(t) ≥ 70.0 for 87.12% of the time.

P(t) ≥ 60.0 for 98.08% of the time.

Berchtesgaden National Park



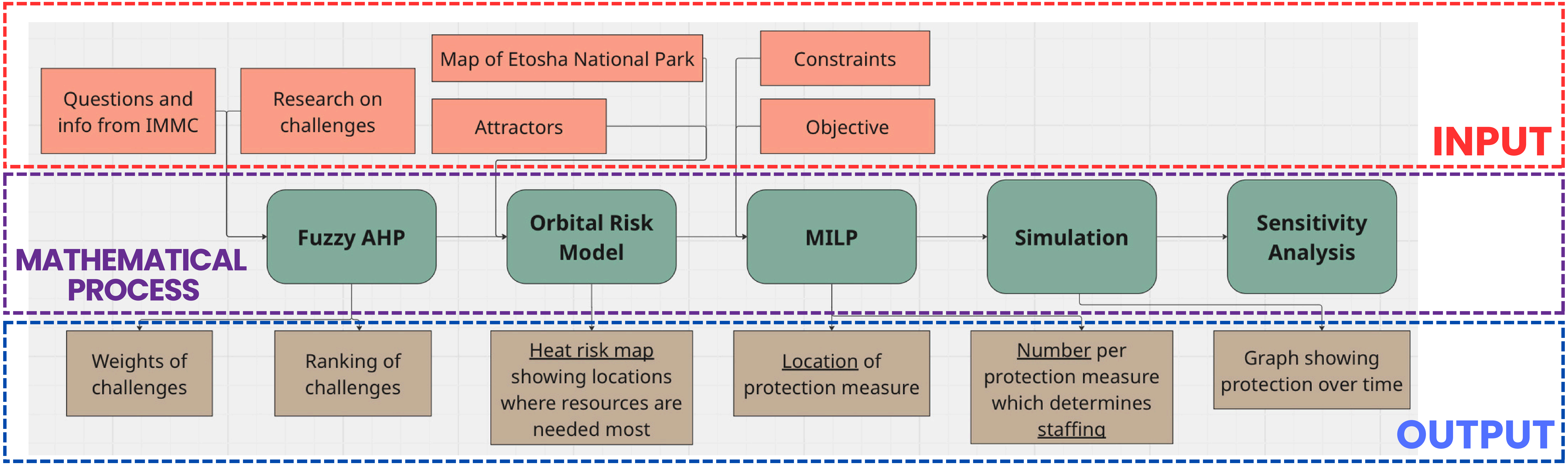
Average Protection Metric: **7.48%**

P(t) ≥ 10.0 for 25.21% of the time.

P(t) ≥ 5.0 for 55.89% of the time.

Conclusion

- Strengths
  - Adaptability
  - Scalability
  - Integration of multiple challenges within a single framework
- Limitation: Accuracy is highly dependent on availability of data
- Future work: Incorporate satellite data and real-time patrol routing


INPUT
Questions and info from IMMC
Research on challenges
Map of Etosha National Park
Attractors
Constraints
Objective
MATHEMATICAL PROCESS
Fuzzy AHP
Orbital Risk Model
MILP
Simulation
Sensitivity Analysis
OUTPUT
Weights of challenges
Ranking of challenges
Heat risk map showing locations where resources are needed most
Location of protection measure
Number per protection measure which determines staffing
Graph showing protection over time

Thank you!

Practical Assumptions
#1: There is no corruption that significantly compromises the protection provided by the national park. National parks are government-designated protected areas, and the government has a stated commitment to conservation. While isolated incidents may occur, assuming systemic corruption would introduce unpredictable dynamics that cannot be modelled reliably without data. This assumption allows us to focus on optimal allocation without having to account for deliberate sabotage.
#2: Poachers are more likely to target areas with higher likelihood of animals being present. Poachers seek to maximise their chance of encountering valuable wildlife, so areas, such as waterholes, with greater chances of finding the animals are more attractive targets.
#3: Road networks are the same routes used by patrollers and poachers. Roads provide the most direct and practical routes for movement within and around the park. Since both patrollers and poachers aim to move efficiently within the shortest time, it is reasonable to assume that they rely on similar accessible routes.
#4: Equipment and workforce capacity remains constant. This means equipment remains undamaged, and staff work 8-hour shifts everyday with constant effectiveness. This allows for simplification of staffing determination and equipment availability. An excess budget is in place should there be a need to hire more staff or purchase more equipment.
#5: Communication between all parties happens instantaneously. This means that we do not have to worry about communication issues caused by poor connection or being entirely disconnected from the internet, which would cause resources to be distributed incorrectly in an unpredictable manner.

Mathematical Assumptions
#5: The terrain in a national park is flat, unless previously indicated or substantial. Etosha National Park comprises mostly savannahs [6] which are flat. This simplifies distance and travel time calculations by allowing movement to be modeled using planar distance.
#6: It is only necessary to consider the initial state of the park when applying our mathematical model. The state of the park and the areas that need more attention will change due to the application of the model, but tracking this would overcomplicate the model while not making very significant contributions to its effectiveness.
#7: The flow of tourism, and hence the number of people in a national park, is constant. This allows for simplification of frequency of human-wildlife conflicts by considering only the location, and not the time of the year. This is because detailed data on visitor arrival patterns are unavailable.
#8: All protection measures (drones, jeeps, etc.) travel at a constant speed at all times Assuming constant travel speed simplifies the simulation while providing a reasonable estimate of average response times, as short-term variations have negligible impact on long-term staffing needs.

3.3.1 Seasonal Dynamics

We define a dry season index $S(\tau) \in [0, 1]$ that peaks in the late dry season (July) and is low in the wet season (February) [7]. A smooth sinusoidal model can thus represent this annual cycle:

$$S(\tau) = \frac{1}{2}\left[1 + cos\left(2\pi\frac{\tau - \tau_{peak}}{365}\right)\right]$$

, where $\tau_{peak} = 182$ for Etosha Park (July 1 is the 182th day in a year)

This index is used to scale challenges that are driven by animal concentration at different times of the year (i.e., poaching, human-wildlife conflict). For the wildfire risk, we define a fire danger index $F(\tau)$ that rises sharply in the dry season, as this reflects the accumulated dryness during that time:

$$F(\tau) = (S(\tau))^p$$

, where $p = 2$ to give a narrower peak

In this long-term model, the effect of night and day remains constant, as each diurnal cycle would still comprise a day and night period, and the number of poachers in the general vicinity would remain constant with tiny fluctuations.

Poaching: The attractors involved when poaching are waterholes (51 points from the park map). Poachers target animals, and animals gather at waterholes, especially during the dry season.
For a point (x, y), time τ and a waterhole w, the influence of the attractor is:

$$\phi_{poach,w}(x,\ y,\ \tau)\ =\ W_{poach} \times S(\tau) \times e^{-\frac{d_w(x,y)^2}{2\sigma_{poach}(\tau)^2}}$$

As such, the poachers follow: $\sigma_{poach}(\tau) = \sigma_{poach,0} \times (1 + \alpha_{poach} S(\tau))$

Where:

- $\sigma_{\text{poach},0}$ is the baseline distance between an animal and the water source, which is 2km [10]
- α_{poach} is the maximum fractional increase in challenge radius from baseline during peak seasons, with $\alpha_{\text{poach}} = 0.5$ representing the radius expands by 50% during peak season [8]

This tracks the changes in the influence radius of poaching throughout the day.

The total poaching risk is the sum of poaching risks at all waterholes:

$$\phi_{poach}(x,\ y,\ \tau)\ =\ \sum_{w \in waterholes} \phi_{poach,w}(x,\ y,\ \tau)$$

4.7 Objective and Constraints

We use Multi-Integer Linear Programming (MILP) to maximise the total reduction, with our objective being to maximise the total risk reduction over the park:

$$max \sum_{i=1}^{N} \sum_{c=1}^{5} y_{i,c} \triangle A_i$$

1. **Budget constraint**

$$\sum_{w} 3_{yw} \cdot c_{camera\ trap} + \sum_{j} z_{j} \cdot c_{laser\ camera} + \sum_{C} x_{C} \cdot c_{jeep} + \sum_{d} u_{d} \cdot c_{drone} \leq budget$$

2. **Forced constraints (to guarantee a baseline level of protection):**

- **At least one jeep per camp: $x_C \geq 1$ for all C**

Justification: Each ranger camp must have at least one vehicle to enable rapid response to incidents. Without this, response times would be unacceptable.

- **At least 20 waterholes equipped:** $\sum y_w \geq 20$

Justification: Waterholes are critical wildlife attractors; equipping a minimum number ensures coverage of the most important high-risk areas, even if the budget is tight.

- **At least 50 laser cameras placed:** $\sum z_r \geq 50$

Justification: A baseline coverage of the road network is essential for monitoring vehicle movement and detecting illegal activities.

- **Total drones are limited to 50:** $\sum u_d \leq 50$

Justification: Operational constraints (available pilots, maintenance capacity) and the diminishing returns of additional drones justify a maximum fleet size.

3. **Integrality Constraints:**

$$y_w \in \{0, 1\}, \quad z_j \in \{0, 1\}, \quad x_c, u_d \in Z \geq 0.$$

The above integrality constraints are to restrict decision variables to integers as factional numbers of cameras, jeeps or drones cannot be deployed.

5.3 Incident Generation

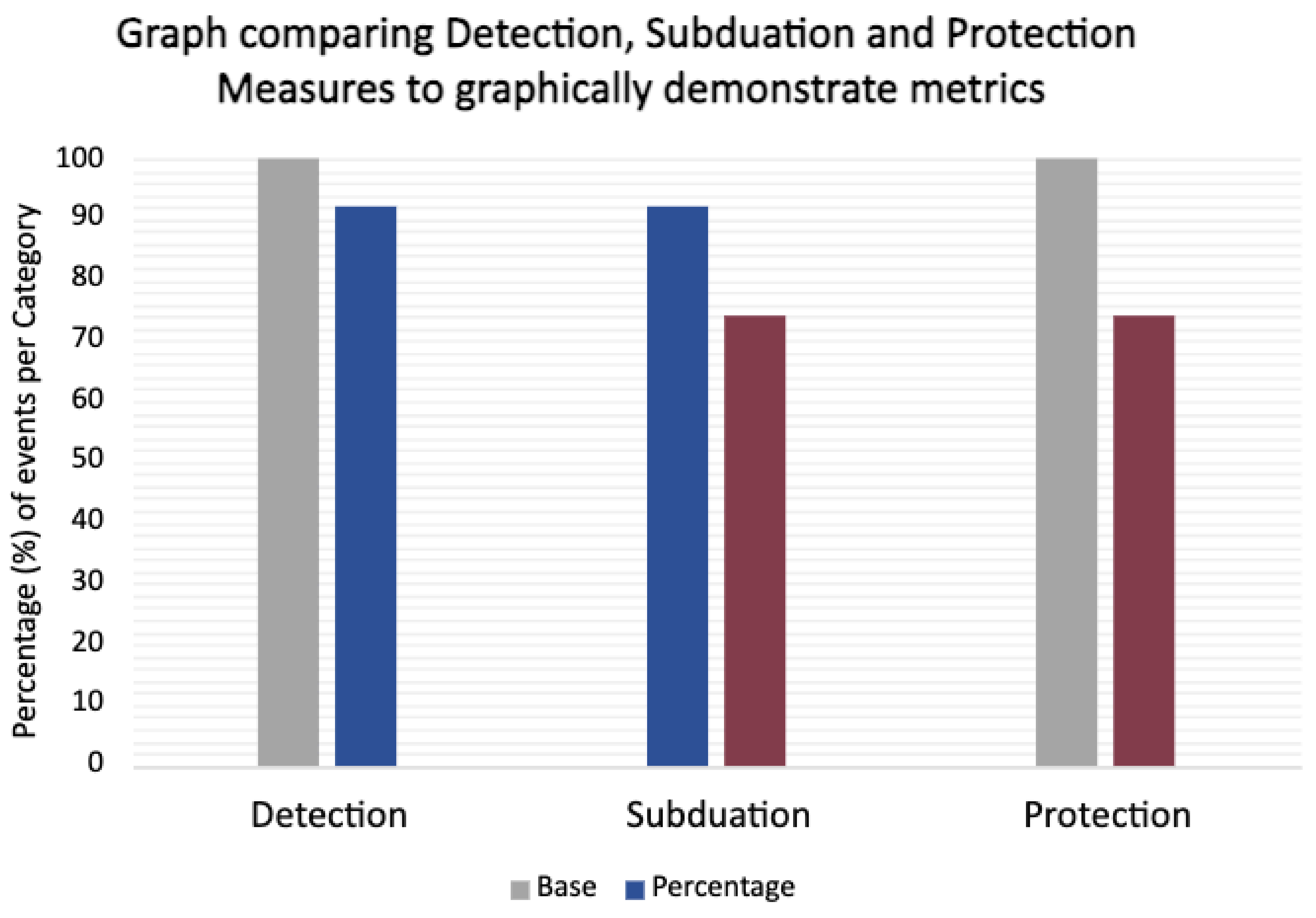
We define the probability that an event occurs in an individual cell in a given hour is the risk of the cell over that total risk of all the cells in the day: $p_{i,c}(\tau) = \frac{R_{i,c}(\tau)}{\int R(\tau)}$

We define the probability of the event type being: $p_c = \frac{p_{i,hwc}(\tau)+p_{i,extract}(\tau)+p_{i,fire}(\tau)+p_{i,invasive}(\tau)+p_{i,poach}(\tau)}{p_{i,c}(\tau)}$

The effective incident probability is reduced in cells where protection measures are present. We define a deterrence factor $\delta_{i,c} \in [0, 1]$ that multiplies the baseline probability. The factor depends on:

- **Continuous monitoring:** If the cell is within coverage radius (0.1km for cameras, 0.8km for laser cameras), then $\delta_{camera} = 0.7$ (i.e., 30% reduction)
- **Active patrol presence:** If a ranger camp is currently within eyesight vision (5km) of the cell, then $\delta_{patrol} = 0.6$ (i.e., 40% reduction)

If both conditions hold, the combined factor is $\delta_{i,c} = \delta_{camera} \times \delta_{patrol} = 0.28$. If none, $\delta = 1$



Protection evaluates the performance overall.

Detection and Subduation isolate those phases, to show where the allocations fails. This helps for further improvement to system.