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Implementing Reinforcement Learning via Markov Decision Process (MDP) for Wind Shelter Modelling: **A Precursor to the Dynamic Line Rating (DLR) Technology Trial in Queensland's Transmission Network**

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Outline of Presentation

- Introduction
- Methodology
 - Data Requirements
 - PQ Infrastructure – Built Section, Conductor Height, Ground Span
 - Vegetation
 - Wind
 - Aspect
 - Relative Topographic Position
 - Analytical Framework
 - Ground Span Level – Wind Shelter Scoring
 - Pixel Level – Finding Optimal Criticality
- Results
- Accuracy Assessment
- Challenges & Limitations
- Takeaway Message



Introduction

Powerlink QLD

- **Queensland Government owned corporation** – one of Australia's leading transmission network companies.
- We own, develop, operate and maintain the **high voltage transmission** network.
- We provide electricity to more than **five million Queenslanders** and **250,000 businesses**.
- Our network runs **1,700km** from north of Cairns to the New South Wales border.
- Comprises **16,500** circuit kilometres of transmission lines and **196** substations



Introduction

- Develop network-wide spatial modelling tool that will assist in identifying critical spans
- Real-Time Ratings Technology Trial Project
 - to identify critical locations of sensor technology and weather stations along transmission lines and corridors



Methodology

- Data Requirements

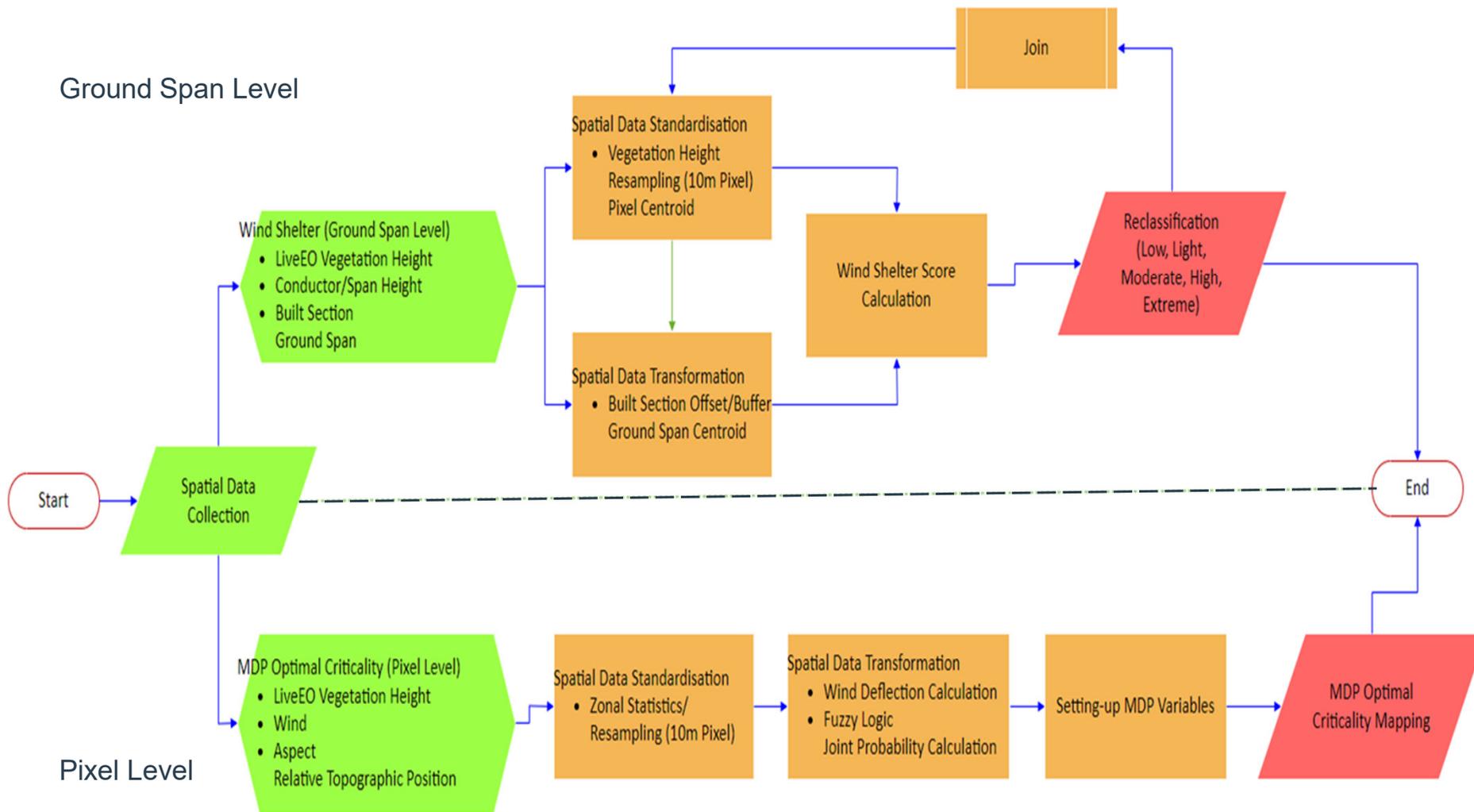
Table 1. Spatial data availability, resolution, and respective sources

Data/Factors	Associated Data	Source	Temporal Statistics	Spatial Resolution
PQ Infrastructure Data	Built Section, Span Height, Ground Span	PQ Enterprise Spatial Database		NA
Vegetation	Foliage Projective Cover	TERN QLD-Long Paddock	Annual (2021)	10m
	Vegetation Height	PQ/Live-EO	Annual (2023)	NA
Relative Topographic Position	Topographic Position	Geoscience Australia	(2018)	~90m
Elevation	DEM	Geoscience Australia	(2000)	1 Second Grid (~30m)
	Slope	Generated		1 Second Grid (~30m)
	Aspect	Generated		1 Second Grid (~30m)
Wind	Eastward Wind Speed	ECMWF*	36 years of monthly ERA5 (1985-2020)	0.25° x 0.25°
	Northward Wind Speed	ECMWF*	36 years of monthly ERA5 (1985-2020)	0.25° x 0.25°
	Wind Direction	Calculated		

*Bureau of Meteorology (BoM) has partnered with the European Centre for Medium-Range Weather Forecasts (ECMWF) to collaborate and share data, knowledge sharing and capabilities exchange (Source: [Australian Bureau of Meteorology partners with ECMWF | Meteorological Technology International](#)).

Methodology

- Overall Analytical Framework



Ground Span Level

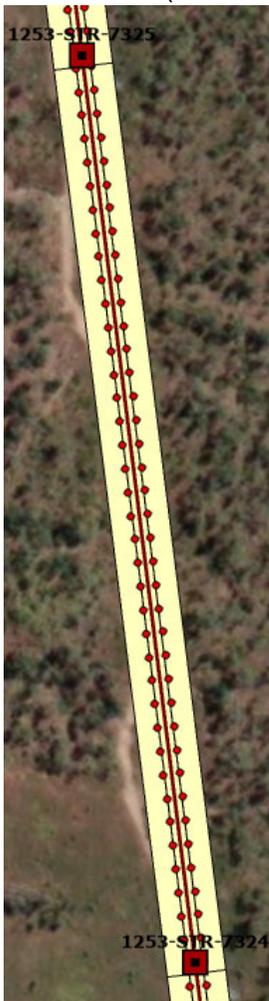
- Wind Shelter Scoring and Classification by Ground Span

Buffer Offset/Instance



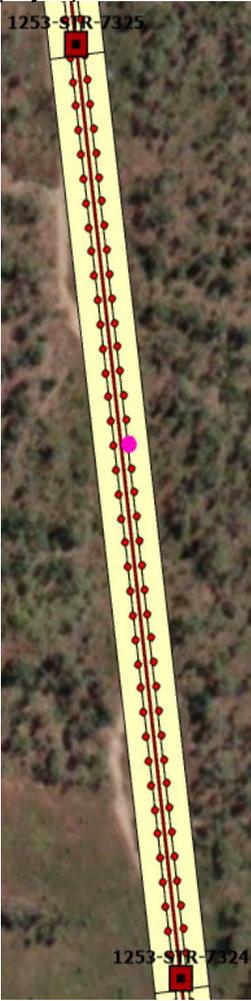
1 (Start)

Find the Min Vertical Clearance (Max Sag) by Span ID



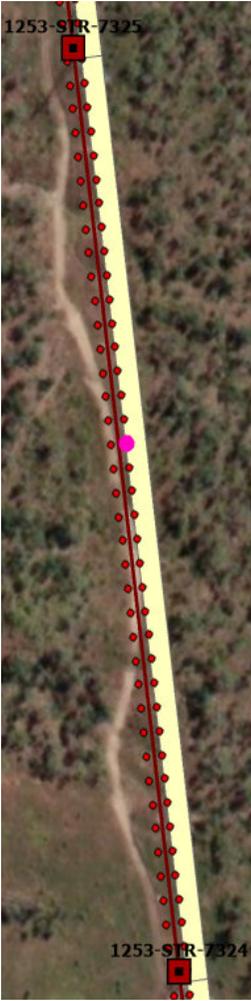
3a

Select the Instance



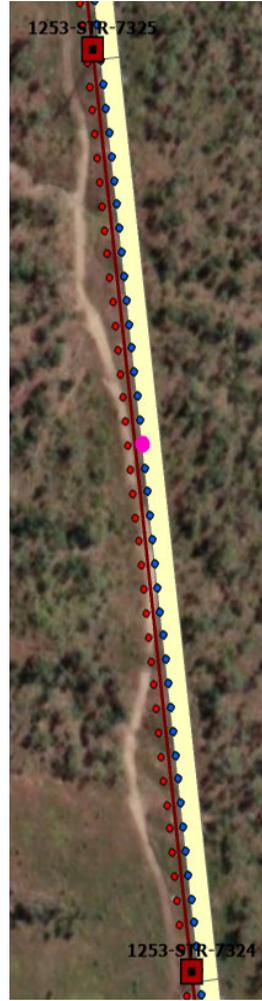
3b

Select the Instance



4

Select Conductor Heights Associated to Max Sag



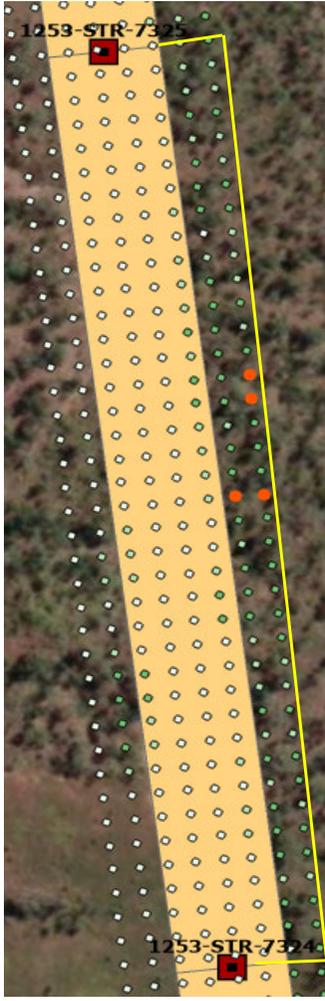
5

Calculate the Slope (Vegetation Height vs Conductor Height)



6

Count Slope < 0 & Calculate Score (%) by Ground Span ID



7 (End)



Ground Span Level

- Wind Shelter Scoring and Classification

WindShelterScore_by_GroundSpan

Wind Shelter Score (%/Class)

- 0 - 20 (Low)
- 21 - 40 (Light)
- 41 - 75 (Moderate)
- 76 - 95 (Heavy)
- > 95 (Extreme)

Tower

ConductorHeight_MinimumVerticalClearance_MaxSag

ConductorHeight_Associated_to_MaxSag

ConductorHeight

Vegetation_HigherThan_ConductorHeight

Vegetation_MaximumHeight (North)

MaxHeight (m)

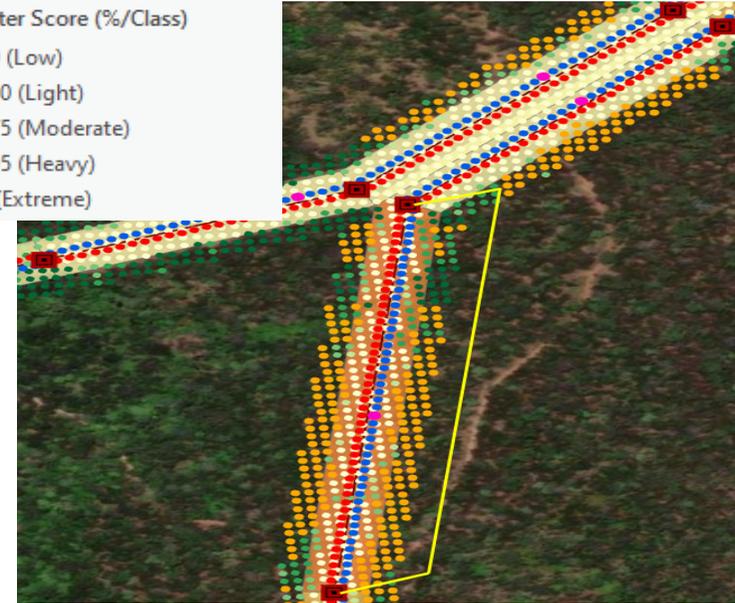
- 0 - 2
- 3 - 6
- 7 - 12
- 13 - 16
- 17 - 20

Vegetation_MaximumHeight (South)

MaxHeight (m)

- 0 - 2
- 3 - 6
- 7 - 10
- 11 - 14
- 15 - 20

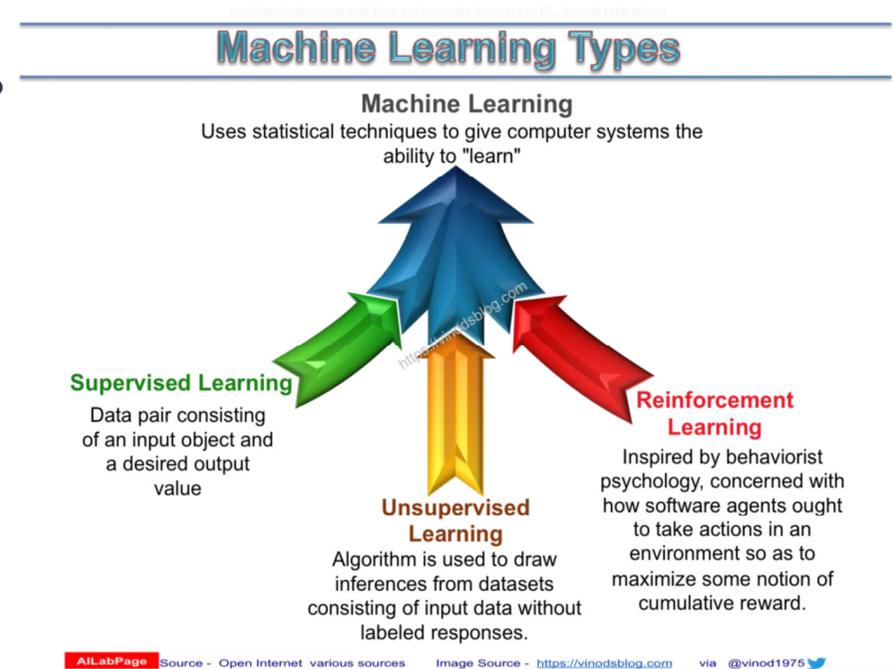
Built Section



Project is after heavy to extremely wind-sheltered ground spans

What's going on within & around Ground Span?

- Ground span is a scene-level analysis
 - aimed at labelling each patch/ground span polygon with a semantic class based on its content (i.e. scoring & degree of sheltering)
- Can we further label each pixel with a class to refine our action/decision and find optimal policy?
- Implement Reinforcement Learning (RL) using Markov Decision Process (MDP)
 - stochastic dynamic programming to model sequential decision-making
 - applied in robotics, engineering, energy regulation, hydropower-reservoir operations, risk management, land-use planning, etc.



Source: per link above

Pixel Level (Solving Optimisation Problem)

- Finding Optimal Policy using Markov Decision Process (MDP)

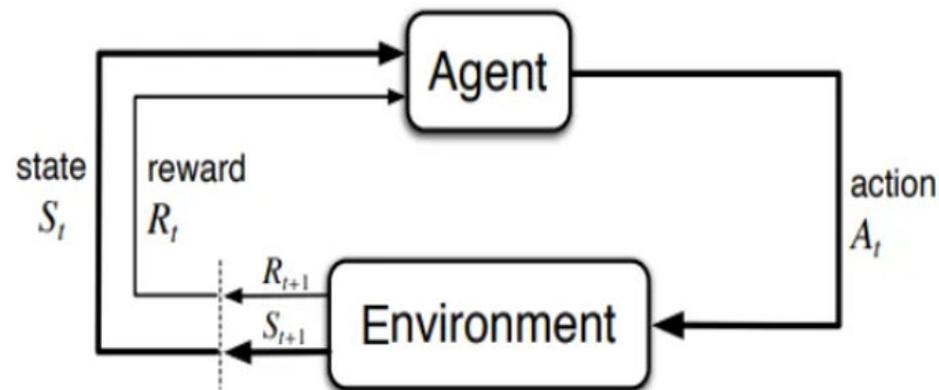


Figure 2. The agent-environment interaction characterizing the Markov Decision Processes (MDP)

Source: [Sutton and Barto \(2017\). Reinforcement Learning: An Introduction](#)

- MDP Variables (SATR)
 - a finite set of **states** $\mathbf{s} \in \mathbf{S}$.
 - a finite set of **actions** $\mathbf{a} \in \mathbf{A}$
 - a **transition** function $T(\mathbf{s}'|\mathbf{s},\mathbf{a})$ returning the probability of reaching state \mathbf{s}' , given the current state \mathbf{s} , the current action \mathbf{a}
 - a **reward** function $R(\mathbf{s},\mathbf{a},\mathbf{s}')$ returning a scalar reward based on reaching the new/next state \mathbf{s}' , after being in state \mathbf{s} , and taking action \mathbf{a} .

Pixel Level

Defining the MDP Variables

Wind Shelter Score

- Current and New State Variables
 - Wind shelter scores and classification as the **current State/Condition (s)**
 - Scoring was generally guided (not all) by EPRI's technical documentation
 - Classification from Debashis

Wind Shelter Score (%)	Classification
0 – 25	Low
26 – 40	Light
41 – 75	Moderate
76 – 95	Heavy
> 95	Extreme



Source/Acknowledgment: Debashis Paul

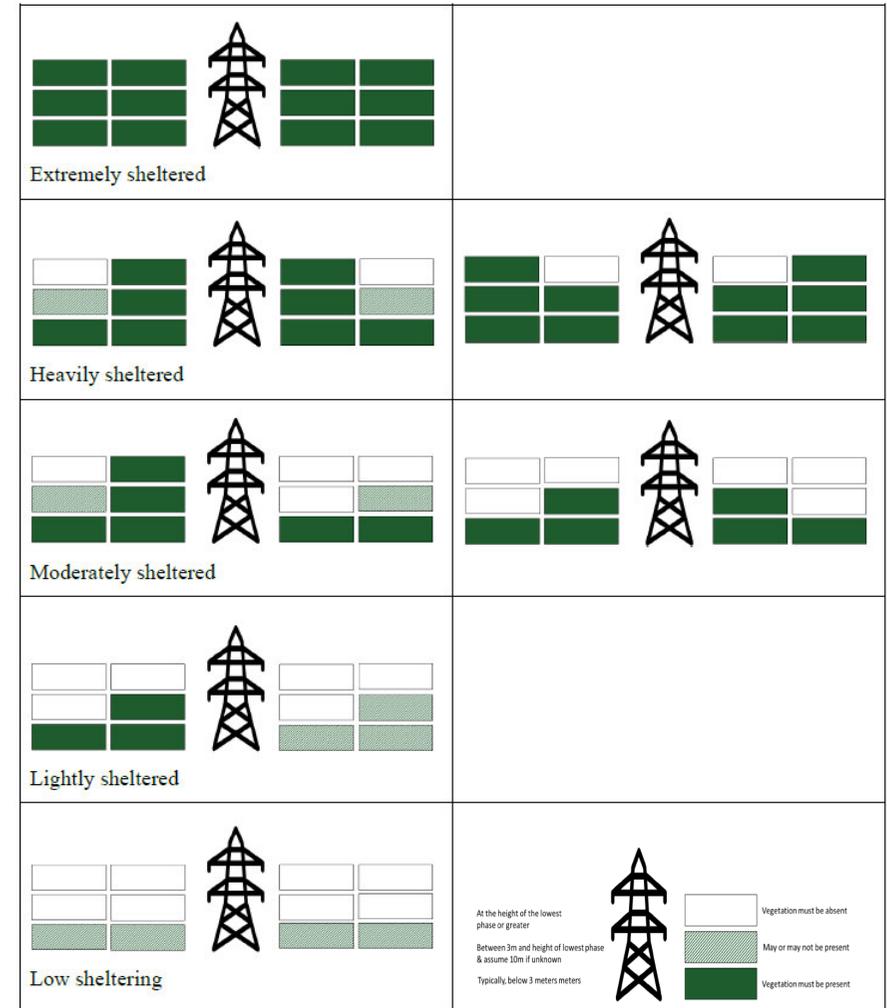


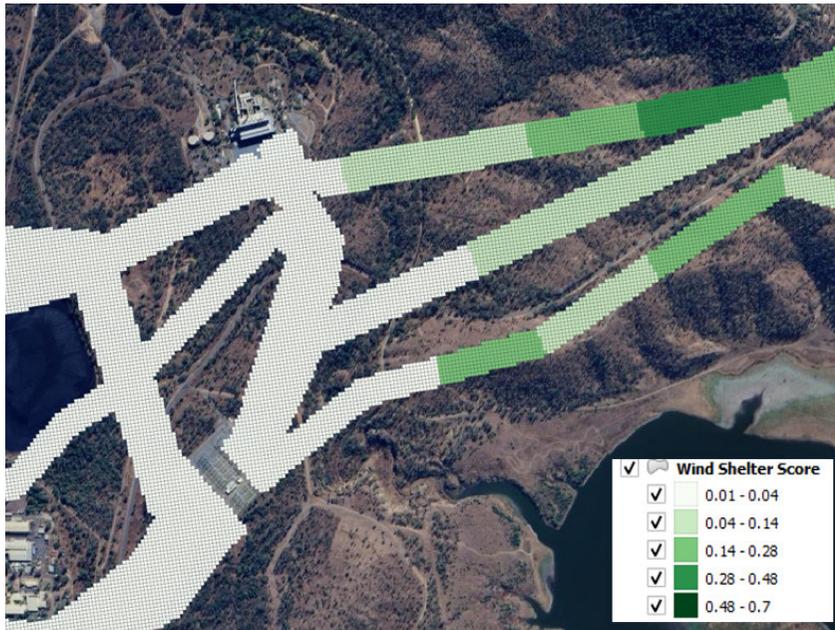
Figure 3. Obstruction based on vegetation height and radial distance (Adopted from EPRI Technical Update, 2023)

Pixel Level

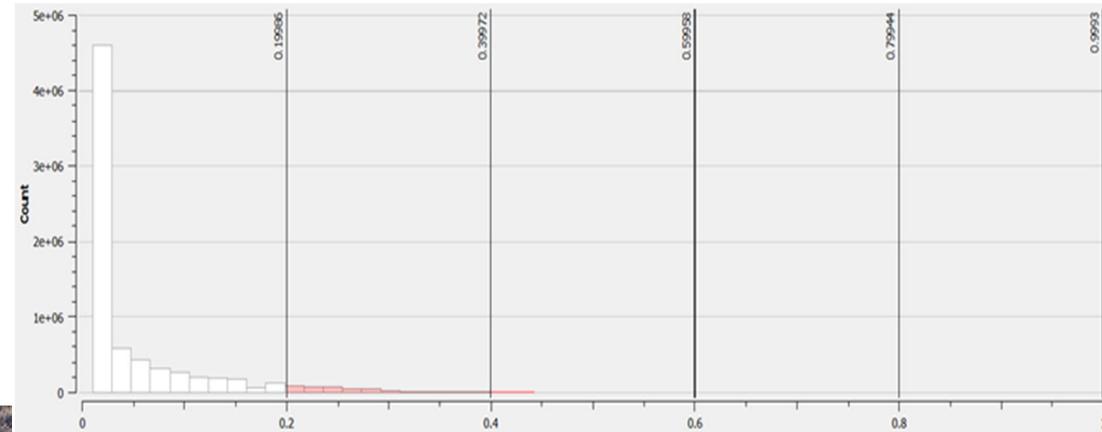
Defining the MDP Variables

Wind Shelter Score

- Current State Variable (s)
 - 5 current states/conditions
 - Low
 - Light
 - Moderate
 - High
 - Extreme



Wind shelter score histogram



Low Sheltering

Extreme Sheltering

Low Preference

High Preference

- Real-time rating sensor requires heavily sheltered or vegetated areas

Pixel Level

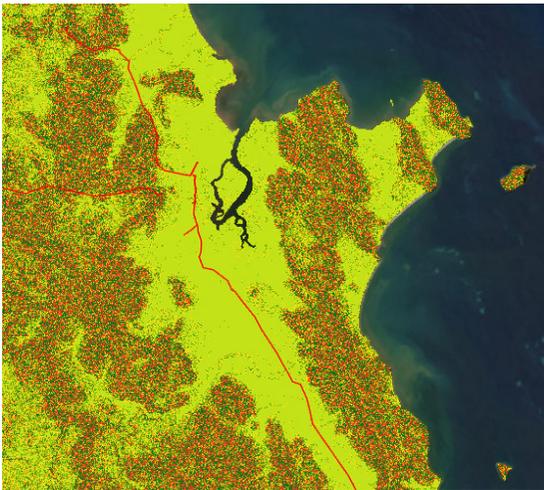
WAR Variables

- New State Variable (s')
- 5 new states/conditions
 - Low
 - Light
 - Moderate
 - High
 - Extreme

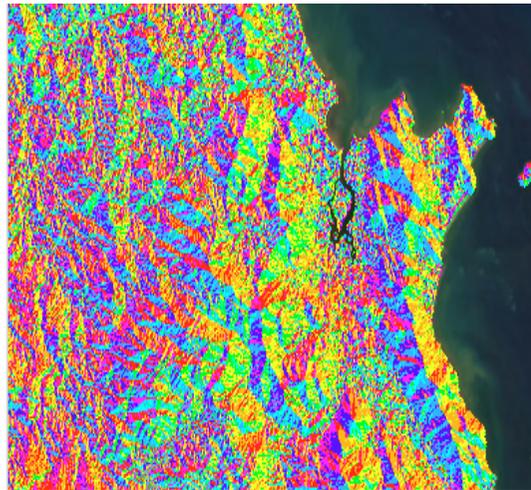
Defining the MDP Variables

Real-time rating sensor requires:

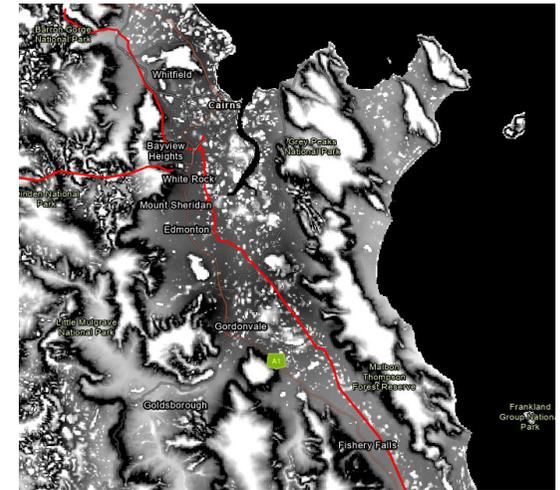
- Uneven topography
- Steep slopes & rough terrains (i.e. leeward/windward sides) – winds must deflect/flow freely.
- South-facing slopes with low influx of solar energy



Wind Deflection (W)



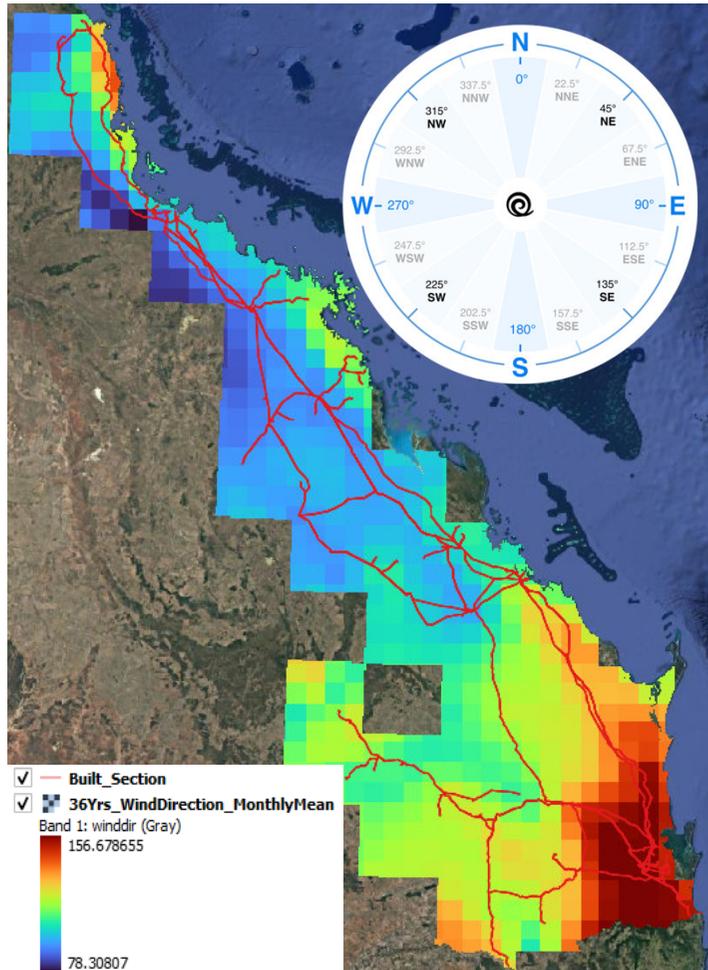
Aspect (A)



Relative Topographic Position (R)

Pixel Level

Wind Variable



Defining the MDP Variables

- BoM – ECMWF partnership
- ERA5 - 36 years

Date Coverage (1985-2020)

ECMWF ERA5 Monthly

Area of Interest

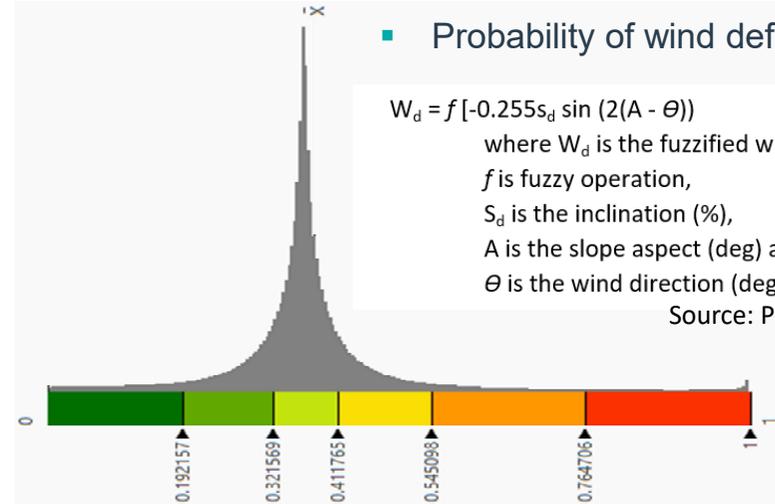
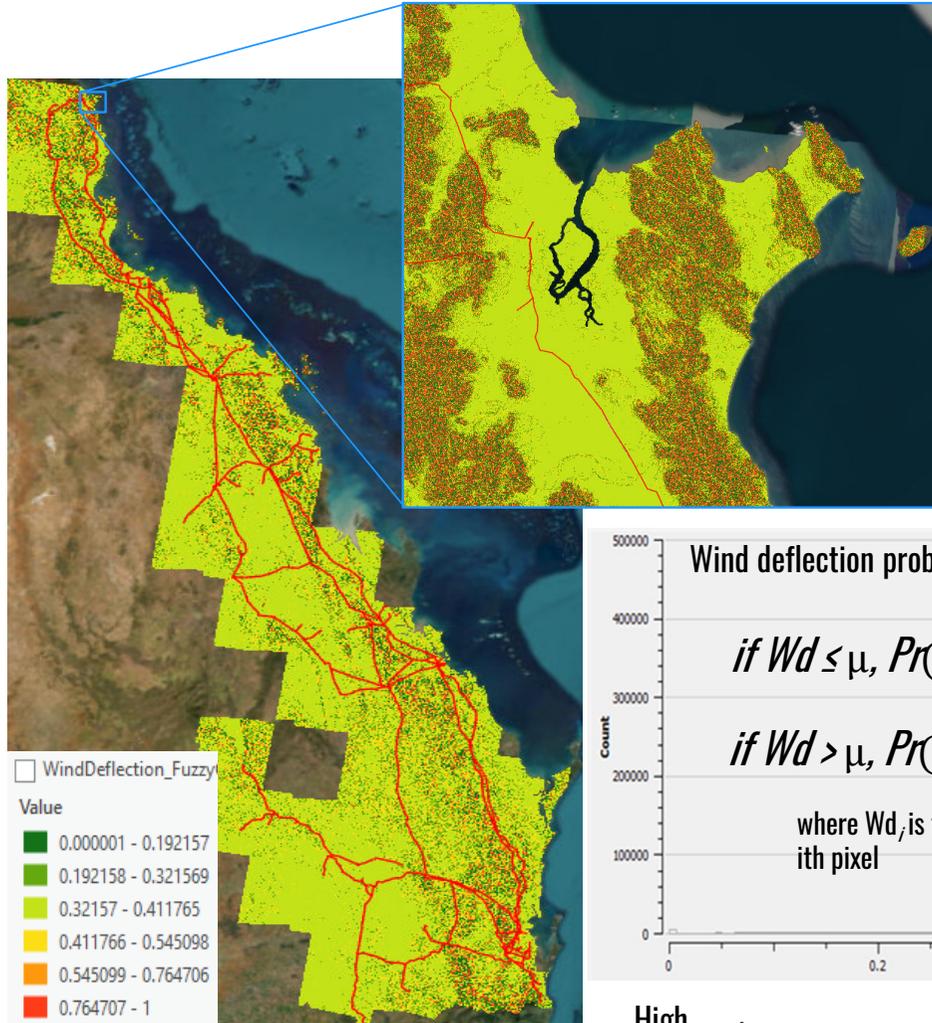
Calculate Wind Direction

- $u10$ component (m/s – 10m)
- $v10$ component (m/s – 10m)

Get the Monthly Mean

Pixel Level Defining the MDP Variables

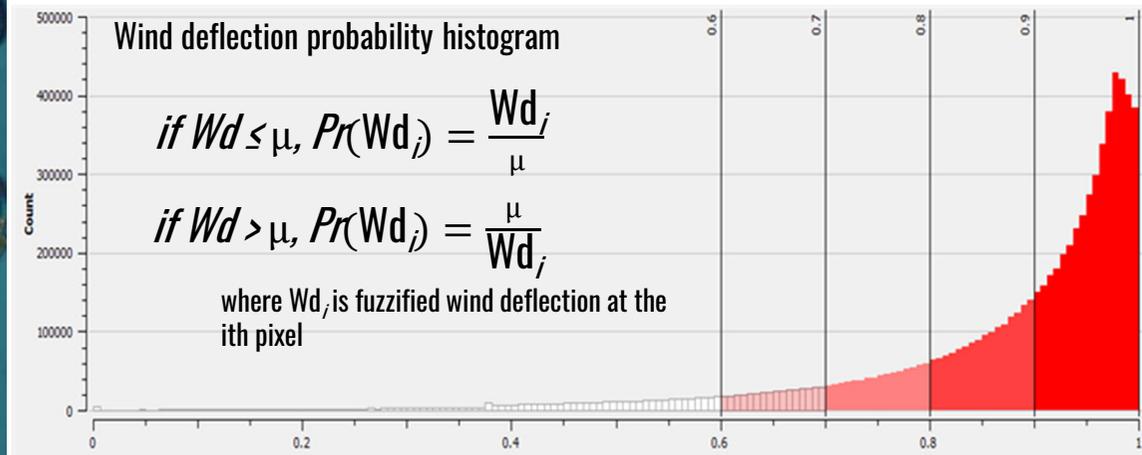
Wind Variable



- Fuzzy Gaussian of wind deflection
- Probability of wind deflection

$$W_d = f[-0.255s_d \sin(2(A - \theta))]$$

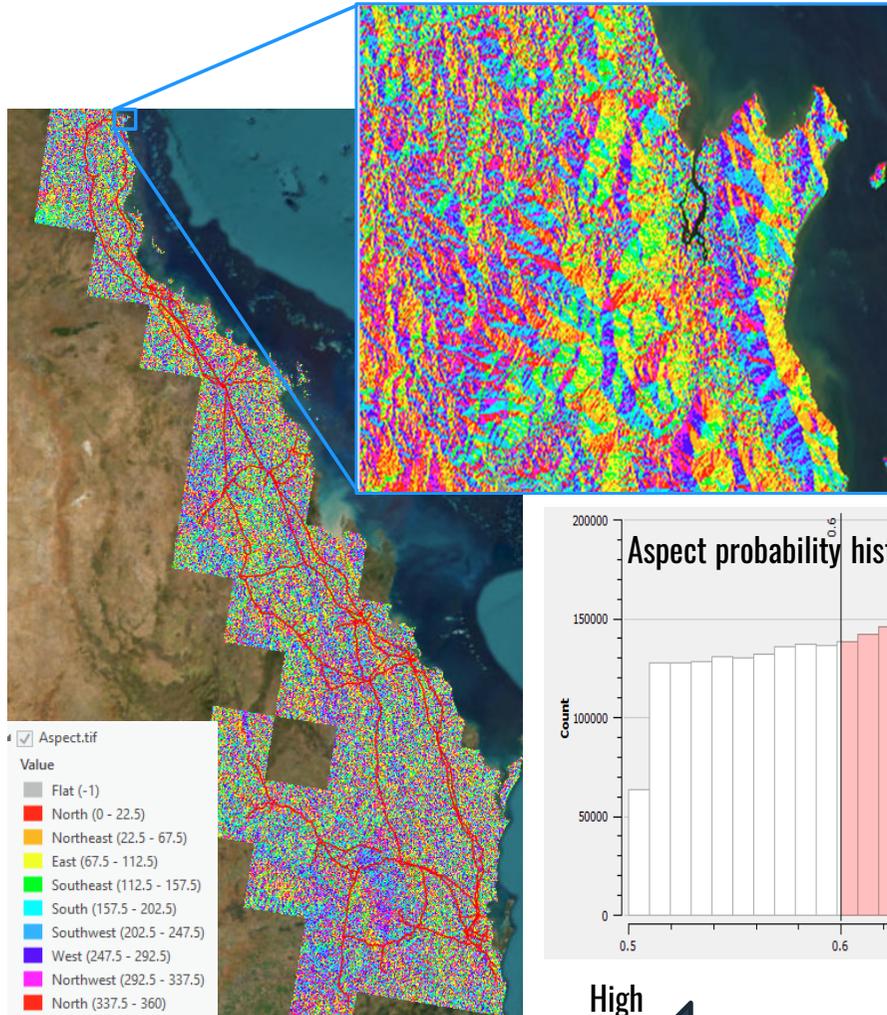
where W_d is the fuzzified wind deflection value,
 f is fuzzy operation,
 S_d is the inclination (%),
 A is the slope aspect (deg) and
 θ is the wind direction (deg)]
 Source: Purves *et al.* 1998



Pixel Level

Defining the MDP Variables

Aspect Variable

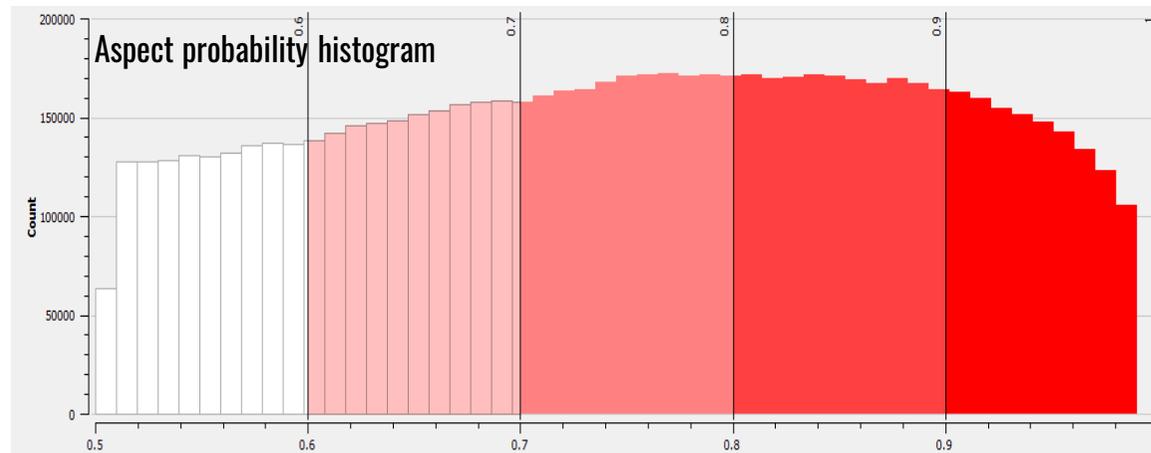


- Aspect probability

$$\text{if } Aspect < 180, Pr(A_i) = 1 - \frac{A_i}{360}$$

$$\text{if } Aspect \geq 180, Pr(A_i) = \frac{A_i}{360}$$

where A_i is the aspect value at the i th pixel



High Preference

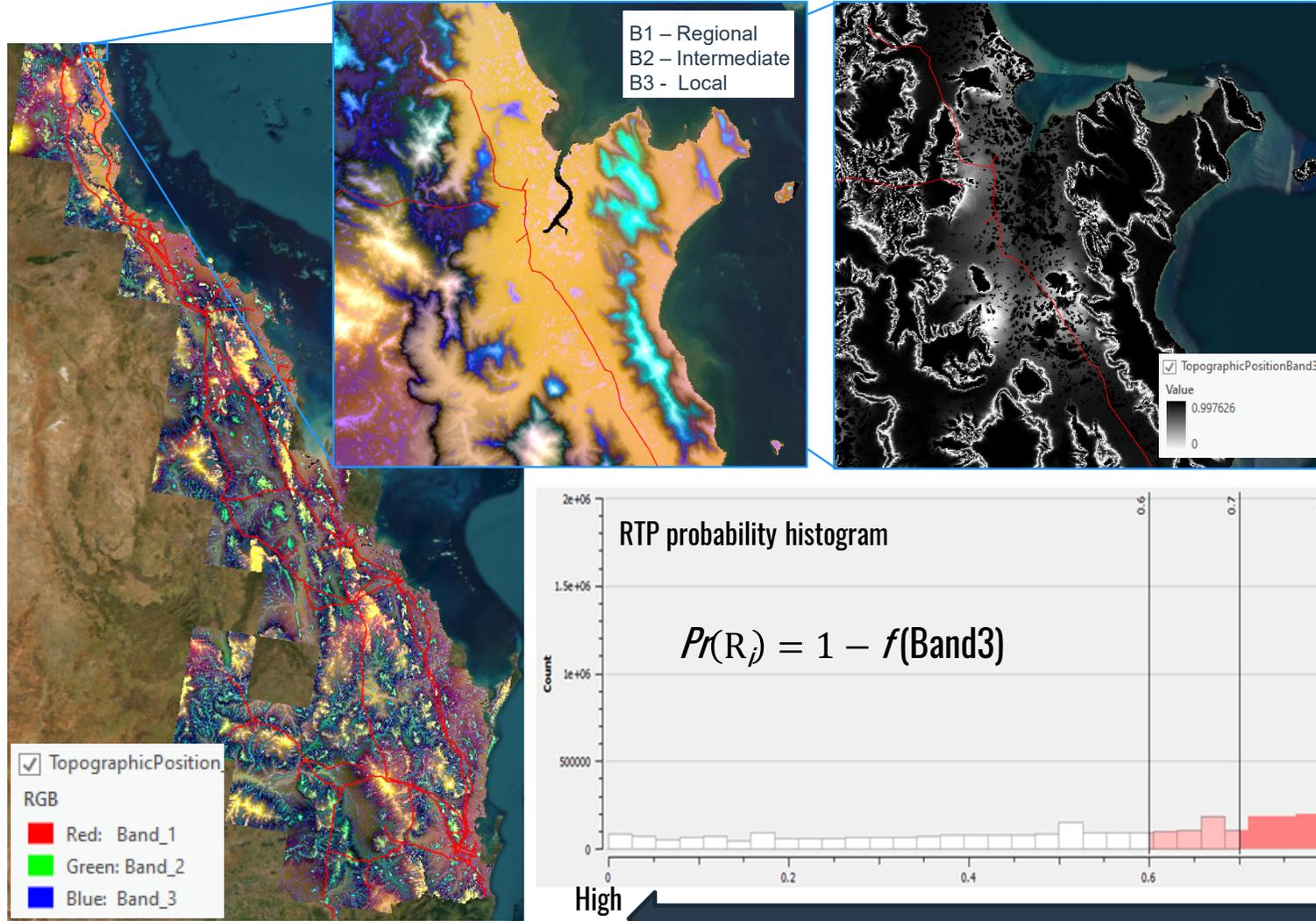


Low Preference

Pixel Level

Defining the MDP Variables

Relative Topographic Position (RTP) Variable



- Local scale position of landforms
- RTP probability

Pixel Level

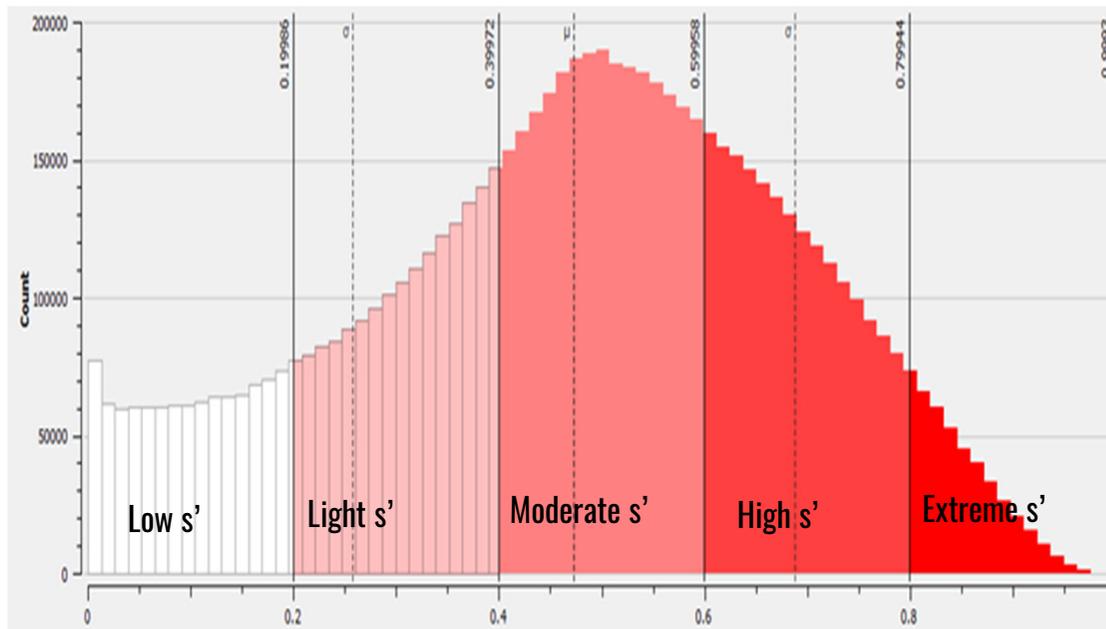
Defining the MDP Variables

- Transition Probability [T(s,a,s')]

$$T_i(s_{i,a} | s_i) = [1 - WS_i] \cap [Pr(WAR_i)]$$

where

WS_i is current state wind shelter score at the i th pixel
 $Pr(WAR_i) = Pr(Wd_i) \cap Pr(A_i) \cap Pr(R_i)$ at the i th pixel



Transition probability histogram

What to do with WAR probabilities and preferences?

New State/ Condition (s')	Description
Low	Low WS, Wd, even RTP & north-facing aspect
Light	Light WS, Wd, RTP & NE/NW-facing aspect
Moderate	Moderate WS, Wd, RTP & E/W-facing aspect
High	High WS, WD, RTP & SE/SW-facing aspect
Extreme	Extreme WS, Wd, RTP & south-facing aspect

Pixel Level

Defining the MDP Variables

- Actions (a_j) and Rewards ($R(s_j, a_j, s'_j)$)
- Discounting Factor [$\gamma \in [0, 1]$] = 0.9

- Organised & processed the MDP matrix in R
- Value iteration
- Finding optimal policy/criticality

New State/ Condition (s')	Description	Reward ($R(s_j, a_j, s'_j)$)	Actions/ Assigned Criticality (a_j)
Low	Low WS, Wd, even RTP and north-facing aspect	-10	Low-Critical
Light	Light WS, Wd, RTP and NE/NW-facing aspect	-5	Lightly Critical
Moderate	Moderate WS, Wd, RTP and E/W-facing aspect	0	Moderately Critical
High	High WS, WD, RTP and SE/SW-facing aspect	+5	High-Critical
Extreme	Extreme WS, Wd, RTP and south-facing aspect	+10	Extremely Critical

▪ Bellman Equation

Initialize $V(s)$ arbitrarily, for all $s \in \mathcal{S}$
 Initialize θ to a small positive value

Loop:

$\Delta \leftarrow 0$ *For every state*
 Loop for each $s \in \mathcal{S}$: *For every available action*
 $v \leftarrow V(s)$ *For every resulting next state after taking a in s*
 $V(s) \leftarrow \max_a \sum_{s',r} p(s', r | s, a) [r + \gamma V(s')]$
 $\Delta \leftarrow \max(\Delta, |v - V(s)|)$

Until $\Delta < \theta$

Output a deterministic policy, $\pi \approx \pi^*$, such that
 $\pi(s) \leftarrow \operatorname{argmax}_a \sum_{s',r} p(s', r | s, a) [r + \gamma V(s')]$

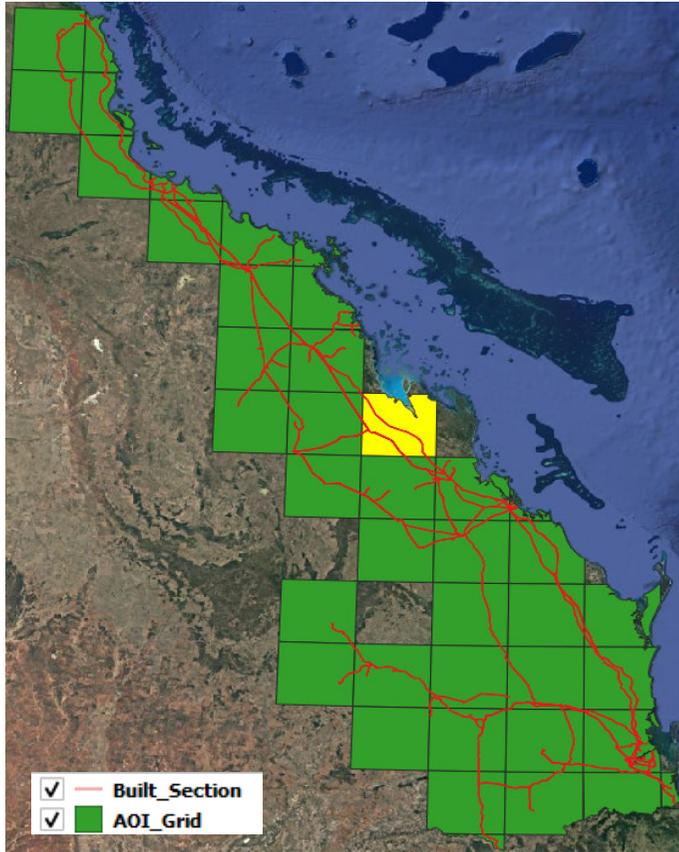
Source: Bettosi (2023)

Completed MDP Matrix



Pixel Level

- Solving MDP Optimal Criticality
 - 41 MDP grids



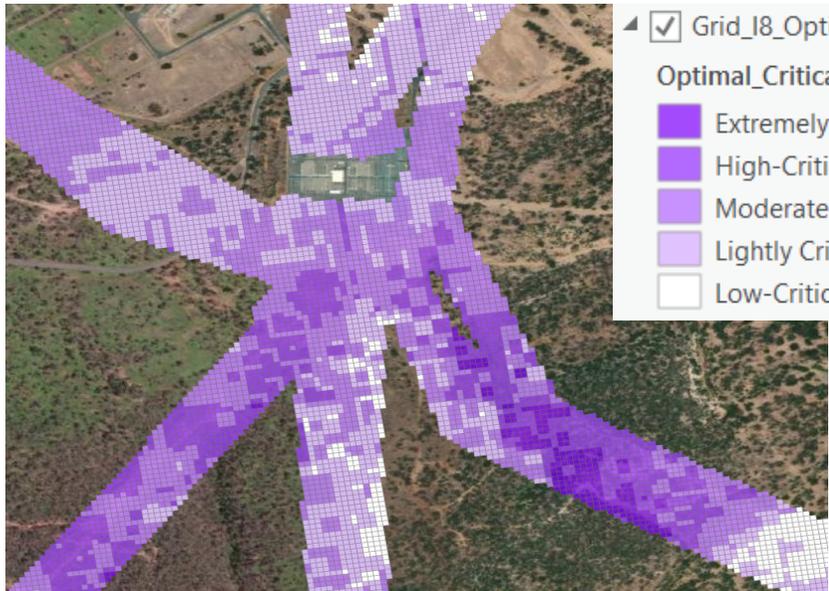
Wind Shelter Web Map

```

Console Terminal Background Jobs
R - R 4.4.2 - Z:/Spatial/GIS_FME/Topic/Easement_Maintenance/WORK/20240507_SM_WindShelter/MDP_Optimal_Criticality/
> #Load the data
I8_data <- ZonalStat_Grid_I8
# Group data by unique ID
I8_grouped_data <- I8_data %>% group_by(pointid)
# Function to create the transition and reward matrices
I8_create_matrices <- function(I8_grouped_data) {
  states <- unique(c(I8_grouped_data$curState, I8_grouped_data$newState))
  actions <- unique(I8_grouped_data$Crit_Level)
  # Initialize transition and reward matrices
  P <- array(0, dim = c(length(states), length(states), length(actions))) # 3D matrix
  for transitions
  R <- matrix(0, nrow = length(states), ncol = length(actions)) # 2D matrix for
  rewards
  for (i in 1:nrow(I8_grouped_data)) {
    current_state <- I8_grouped_data$curState[i]
    action <- I8_grouped_data$Crit_Level[i]
    new_state <- I8_grouped_data$newState[i]
    reward <- I8_grouped_data$Reward[i]
    trans_prob <- I8_grouped_data$Trans_Pr[i]
    # Map states and actions/criticalities to indices
    state_idx <- which(states == current_state)
    new_state_idx <- which(states == new_state)
    action_idx <- which(actions == action)
    # Populate transition matrix and reward matrix
    P[state_idx, new_state_idx, action_idx] <- trans_prob
    R[state_idx, action_idx] <- reward
  }
  return(list(P = P, R = R, states = states, actions = actions))
}
# Function to perform value iteration for a given ID
I8_value_iteration <- function(P, R, discount = 0.9, tol = 1e-6) {
  num_states <- dim(P)[1]
  num_actions <- dim(P)[3]
  V <- rep(0, num_states) # Initialize value function
  Q <- matrix(0, nrow = num_states, ncol = num_actions) # Initialize Q values (state
  -action/criticality values)
  delta <- tol + 1
  
```

Environment	History	Connections	Tutorial
ZonalStat_Grid_G7	74382 obs. of 15 variables		
ZonalStat_Grid_H6	191134 obs. of 15 variables		
ZonalStat_Grid_H7	444250 obs. of 15 variables		
ZonalStat_Grid_I6	44635 obs. of 15 variables		
ZonalStat_Grid_I7	347745 obs. of 15 variables		
ZonalStat_Grid_I8	304760 obs. of 15 variables		

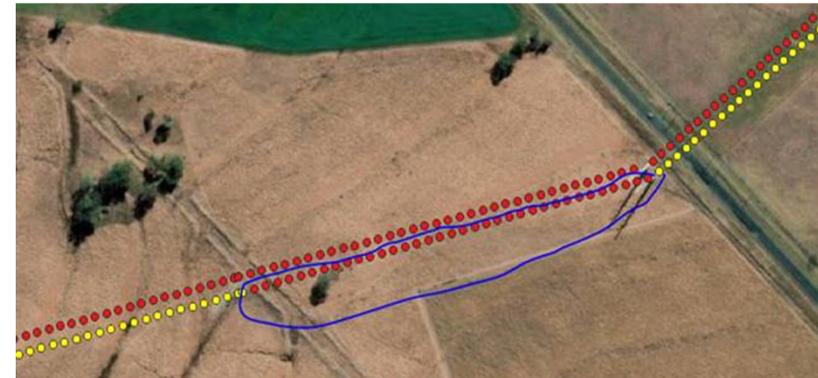
Files	Plots	Packages	Help	Viewer	Presentation
<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Install	Update				
Name	Description				
<input type="checkbox"/> crayon	Colored Terminal Output				
<input type="checkbox"/> curl	A Modern and Flexible Web Client for R				
<input checked="" type="checkbox"/> dplyr	A Grammar of Data Manipulation				
<input type="checkbox"/> fansi	ANSI Control Sequence Aware String Functions				
<input type="checkbox"/> farver	High Performance Colour Space Manipulation				
<input type="checkbox"/> generics	Common S3 Generics not Provided by Base R Method Related to Model Fitting				
<input type="checkbox"/> ggplot2	Create Elegant Data Visualisations Using the Grammar of Graphics				



Project is after extremely critical pixels (areas)

Accuracy Assessment

- Ground Span Level
 - missed 180 out of 27,001 spans (99.33% capture ratio)
 - manual corrections



Before manual correction



After manual correction

- Pixel Level
 - 1:1 match/correspondence between pre-defined actions and the resulting optimal criticalities
 - Subject to interpretation and decision appetite



Challenges & Limitations

- Complex process and computationally intensive
- Up-to-date availability of spatial data
- Use of variable spatial data resolution
 - Data were resampled to 10m pixel size
- LiveEO's vegetation height
 - maximum value of the data range was used as the height of pixel centroid
- MDP action-reward pairing and optimal criticality are subject to interpretation.



Takeaways

- Integral part of project policy and decision-making (where, how many sensors, how much \$\$\$)
- Strengthened collaboration between Spatial and Transmission Line Strategies



Thank you!