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Reliability, Resilience and Vulnerability (RRV) framework as a tool to assess vegetation water stress

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Abstract: Quantifying the vegetation response to water stress is crucial for understanding ecosystem condition under changing climate conditions and limited water availability. This study examines the possibility of applying Hashimoto's Reliability, Resilience and Vulnerability (RRV) framework as a quantitative composite indicator to assess vegetation water stress using a 21 -year dataset of monthly integrated remotely sensed vegetation indices and climate variables across 10 sites located in Southern Murray-Darling Basin, Australia. The analysis provides evidence of the applicability of the RRV for selected indices as an indicator of vegetation stress.

Keywords: *River red gum, Blackbox, Leaf area index, water resources, Evapotranspiration*

1. INTRODUCTION

Understanding how Murray-Darling Basin (MDB) native vegetation ecosystems respond to water stress is critical for assessing their long-term condition and adaptive capacity in response to water planning and for management purposes. Recent research efforts have significantly advanced our understanding of vegetation condition dynamics through multiple complementary approaches. A 26-year satellite data analysis across the entire MDB quantified vegetation greening and browning responses to floods and rainfall, revealing significant changes in vegetation-water relationships coinciding with Millennium Drought onset (Broich et al. 2018). State and transition modelling in the Macquarie Marshes demonstrated that floodplain vegetation communities exhibit predictable transitions driven by hydrological changes, with semi-permanent wetlands showing particular vulnerability to drying trends under river regulation. A recent 5-year study (2014–19) in the Macquarie Marshes tracking Water Couch grasslands and River Red Gum communities demonstrated that vegetation responses to water availability follow both linear and non-linear patterns (Mason, Honeysett et al. 2022). A 30-year NDVI study of River Red Gum and Black Box in the MDB used the adaptive cycle (panarchy) framework to show that vegetation trajectories shift with flood frequency, with multiple thresholds marking growth, stability, decline, and recovery phases; altered flooding changes the duration and character of these phases (Doody et al., 2024).

Hashimoto's Reliability, Resilience, and Vulnerability (RRV) framework provides three fundamental criteria for evaluating water resource system performance. The aim of this paper is to demonstrate that RRV is a successful indicator system for vegetation condition as a result of water stress. This ultimately might inform management strategies for environmental water.

2. METHODOLOGY AND RESULTS

This study is built on Hashimoto's Reliability, Resilience, and Vulnerability (RRV) framework (Hashimoto, 1982) to quantify water related stress impact on vegetation using site specific field and remote sensing data. Originally introduced for evaluating water resources system performance, this statistical index framework has found applications in broader sustainability analysis. Reliability (α) is the probability that system is in satisfactory state; $\alpha = \text{Prob}\,[\text{Xt} \in \text{S}]$. Resilience is (γ) how quickly system recovers from failure; $\gamma = p/(1-\alpha) = Prob\{Xt \in S\, and\, Xt+1 \in F\}/Prob\{Xt \in F\}$. Vulnerability (v) assesses the severity of failure when it occurs; $\nu = \Sigma\, sjej\ (j \in F)$. **Reliability** is the likelihood the system stays in a satisfactory state, **Resilience** is how quickly it recovers from failure, and **Vulnerability** is the expected severity of failure when it occurs. RRV metrics were calculated for 3 variables; LAI (leaf area index) using a threshold of $0.5 m^2/m^2$ (Doody et al., 2015), de-seasonalised AMLETT ET data (Doody et al. 2023) to remove radiation effect via linear regression, and similarly de-seasonalised CMRSET (Guerschman, 2022). For the ET variables, RRV was calculated using thresholds aligned with the LAI benchmark. RRV was analysed across 10 sites (Doody et al. 2023) and at individual sites based on 21 years of data. Across the 10 sites, River Red Gum (E. camaldulensis) was found at 4 sites; Booky, Calprrg, Ld, Lw, generally close to river channels or streams, while Black Box (E. largiflorens) occurred at 6 sites; Calps1-5, Mc, Mp2, typically associated with intermittent lakes, sand dunes, or saline/fresh groundwater environments (Doody et al. 2023).

Prior to RRV calculation, cross-correlation analyses were performed between rainfall and the 3 variables (LAI, AMLETT ET and CMRSET ET residuals) to evaluate lagged associations. This analysis revealed that all sites show positive relationships between monthly rainfall and the 3 variables across sites with strength and varying consistency. ET residuals were generally more responsive to rainfall than LAI with site Mc consistently emerging as the most rainfall-responsive site. Site Mc and sites in the Calps group were consistently rainfall responsive, while sites Ld and Booky showed a weaker and variable relationship. The weakest correlation was shown by site Ld. Maximum correlations occur 1–3 months after rainfall events from Feb–May, representing the delayed response period. This supports water–limitation driving ecosystem dynamics with spring rainfall being the key predictor.

This comprehensive analysis of RRV metrics revealed clear differences across variables, sites, seasons, years and vegetation types in relation to their environmental context. The 3 variables show different response patterns at each site, however AMLETT and CMRSET residual variables revealed similar patterns across sites and vegetation types. There were few notable patterns. The 21-year long term analysis demonstrated ET variables are a more sensitive indicator with a greater range of RRV values. In contrast the range of indicators based on LAI was limited. This may indicate that ET processes are more robust to environmental stressors than vegetation leaf area dynamics. Further, RRV of ET residuals and LAI had opposite relationships across sites and vegetation type. The annual RRV analysis revealed strong inter- annual variation but relatively stable long-term performance for ET variables than LAI.

Seasonal analysis showed ET derived RRV variables show seasonal dependencies and variations (Refer to Figure 1). Results indicate that LAI reliability was generally high across sites, but resilience was lower during dry seasons, with vulnerability peaking in periods of prolonged water deficit. ET-based RRV reflected similar patterns, confirming that areas with reduced ET corresponded to higher stress, and de-seasonalised ET residuals captured subtle water-stress signals that were not apparent in raw ET time series. Vegetation type differences are strongest in CMRSET residuals, with Black Box showing higher RRV performance. These findings demonstrate that the combined use of RRV metrics and ET residuals provides a robust approach to assess vegetation water stress across temporal and spatial scales. This approach is likely to enable quantitative assessment of vegetation system performance under varying water availability conditions in semi-arid regulated river systems.

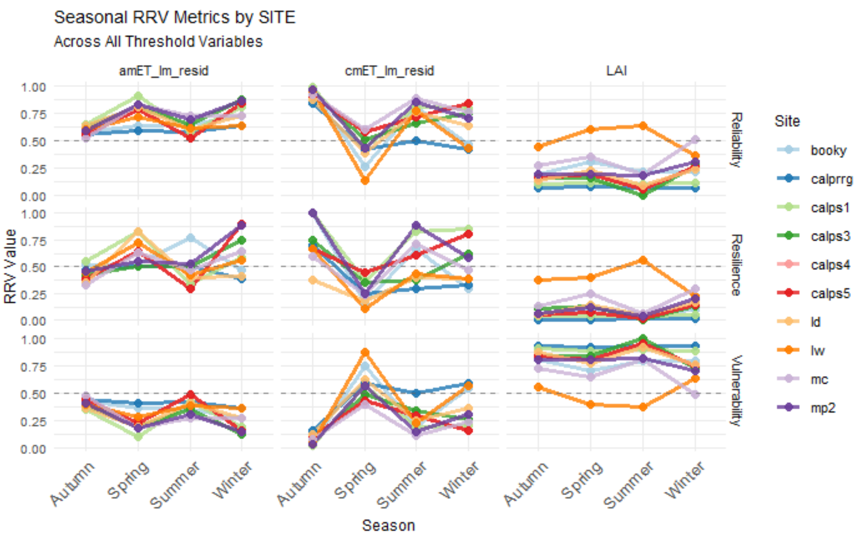

Figure 1 RRV by variable for each site & seasonal trend

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