Do Plants Grow Differently Around Leaky Weirs? An Observational Study in Eastern Australia.

I originally submitted this thesis to fulfil requirements for the degree of Bachelor of Science and Advanced Studies (Honours). It has since been edited. To the best of my knowledge, it is my own work, and I have credited all sources I used in its preparation.

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Do Plants Grow Differently Around Leaky Weirs? An Observational Study in South-Eastern Australia.

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0. Abstract and Abbreviations

0.1. Project Abstract

Degraded river systems lead to problems beyond poor water quality. Alluvial pastures along degraded rivers lose their resilience against floods and droughts, and aquatic animals are deprived of their breeding grounds when tributaries dry up too quickly. Conventional strategies to repair degraded rivers are costly, driving landscape managers to seek better solutions. In-stream structures such as leaky weirs, rock gabions, and Beaver Dam Analogues are gaining popularity due to their immediate hydrological impacts and their use of cheap, natural materials. Some policy makers, however, distrust these nature-based solutions, as they believe such methods rest on claims unsubstantiated by research.

Our study, conducted from 2023 to 2024, explored leaky weirs. These low, in-stream structures are thought to facilitate wetland recovery by altering local hydrology, but their effects on riparian plants have not been studied. Our study aimed to determine whether plant communities differed between sites with leaky weirs compared to sites without leaky weirs. We found that plant did grow differently around leaky weirs; however, this difference was only seen within 50m of the riverbank. In treatment sites, the abundance and richness of wetland plants along the inner riparian zone was significantly higher than in control sites. However, we saw no significant differences in pasture and canopy compositions. From this, we conclude that leaky weirs may have a positive impact on plant communities; however, this effect is only local in the short term and must be further tested through manipulative studies.

0.2. Terms and Abbreviations

0.2.1. General

BDA = Beaver Dam Analogues

Emergent Macrophytes = plants that are often submerged partially, but rarely submerged fully.

Floating Macrophytes = aquatic plants whose leaves float on the water's surface.

Forbs = non-graminoid herbaceous plants.

Least-Square Means = a method of quantifying differences between means under conditions of negligible interaction between explanatory variables. In cases where interactions are significant, Estimated Marginal Means analyses must be performed pairwise.

Lower Mulloon = northern section of the Mulloon Catchment, defined by a historical floodplain pocket. The term is used colloquially by local landholders. Its southernmost limit is approximately 400m south of the King's Highway, NSW (B52).

Macrophytes = Plants that are submerged, at least partially, during most times of the year. Classified as either emergent, floating, or submerged.

NSF = Natural Sequence Farming

PCA = Principal Component Analysis

Reeds = *Phragmites spp.*, *Typha spp.*

Rushes = plants in the family Juncaceae

Sedges = plants in the family Cyperaceae

Submerged Macrophytes = aquatic plants that are often fully submerged.

Survey Location *(terminology specific to section 2.3.)* = The collective term we used to describe adjacent upstream and downstream sites. Each survey location therefore contained two survey sites. We used this term in section 2.3., in reference to Figure 6.

Tinderbox drought = a 3-year period from 2017 to 2019, of abnormally low cool-season rainfall.

0.2.2. Plant Groups (Appendix Table 2A, Figures 8 & 9)

Acac = *Acacia spp.*

Carx = *Carex spp.*

Crcm = *Cirsium spp.*

Crtg = *Crataegus spp.*

Cypr = *Cyperus spp.*

Cyts = *Cytisus spp.*

Dock = *Rumex spp.*

Echm = *Echium spp.*

Elch = *Eleocharis spp.*

E_P = Exotic Pasture Grasses

Fncl = *Foeniculum spp.*

Frns = Ferns

Hypr = *Hypericum spp.*

Jncs = *Juncus spp.*

Lgst = *Ligustrum spp.*

Lmnd = *Lomandra spp.*

Lpts = *Leptospermum spp.*

Mals = *Malus spp.*

Mllc = *Melaleuca spp.*

Myrp = *Myriophyllum spp.*

Nymp = *Nymphoides spp.*

N_P = Native Pasture Grasses

Phrg = *Phragmites spp.*

Ppls = *Populus spp.*

Rosa = *Rosa spp.*

Rubs = *Rubus spp.*

Salx = *Salix spp.*

Schn = *Schoenoplectus spp.*

Typh = *Typha spp.*

Valls = *Vallisneria spp.*

Whln = *Wohlenbergia spp.*

1. Introduction

1.1. Background

Degraded river systems lead to problems beyond poor water quality. Grazing, desnagging, and land clearing practices create deep, unvegetated river channels that deprive their surrounding floodplains of water (Alexander et al., 2008; Brock, 2003; Lester and Boulton, 2008; Peel et al., 2022). Farmlands, which make up a substantial portion of Australia's land area, rely on water stored underground, both as soil moisture close to the surface and as groundwater in deep aquifers (Hazell et al., 2001; Lester and Boulton, 2008; Westoby, 1988). This is particularly the case in floodplain pastures, which rely on intermittent floods to replenish the water and nutrients in their soils. Moreover, freshwater ecosystems are some of the most biodiverse ecosystems in the world (Rusnák et al., 2022). Aquatic animals that breed in upland tributaries are deprived of their habitats when these tributaries dry up faster than they should.

Efforts to restore Australian river systems in the past have seen some success; but they have also come with unintended consequences. Willow plantings in the early to middle 20th century, an attempt to stabilise eroding stream banks, displaced many native plant communities (NSW Catchment Management Authority, Southern Rivers, 2011; Wright, 2018). Hard-engineering solutions, such as concrete flumes and industrial check dams, are costly to install and maintain – not to mention their impeding effects on migratory fish species (Gooden and Pritzlaff, 2021; Mallen-Cooper and Zampatti, 2020; NSW Catchment Management Authority, Southern Rivers, 2011; Palmer et al., 2005; Peter Hazell, personal communication, 2023; Salant et al., 2012).

In recent years, landscape managers have come to favour ecologically-based conservation strategies, also called nature-based solutions, which use biodegradable materials to imitate the natural hydrological and sedimentary processes present in healthy river systems (Burger, Reichand, & Cavagnaro, 2010; Hale et al., 2018; Lester and Boulton, 2008; Palmer et al., 2005; Peel et al., 2022). However, these strategies are so varied that no single study can document all their effects at once (Hale et al., 2018; Lester and Boulton, 2008). The aim of our study is to explore one strategy, called 'leaky weirs', which is a promising but controversial technique popularised by the Mulloon Institute (Peel et al., 2022; Peter Hazell, personal communication, 2023).

The controversy behind leaky weirs extends beyond the existence of the Mulloon Institute, but it is the Mulloon Institute that has long served as the strategy's most influential proponent (Peel et al., 2022; Peter Hazell, personal communication, 2023). Our study takes place in the Mulloon Catchment, where the Mulloon Institute has implemented a long-term monitoring initiative in the hopes of quantifying the ecological impacts of leaky weirs. Our study explores the relationship between leaky weirs and plant assemblage. Since plants are the main primary producers of most freshwater ecosystems, we reasoned they should be the subject of highest priority when assessing novel restoration methods such as leaky weirs (Burger, Reichand, & Cavagnaro, 2010; Hale et al., 2018; Zedler and Kercher, 2005).

1.2. Study Site

The Mulloon Catchment (Latitude: -35.200, Longitude: 149.633, WGS84, Figure 1) is an agriculturally modified hill-floodplain complex in Eastern Australia, and a sub-catchment of the Upper Shoalhaven River (Peel et al., 2022). It has a temperate, subhumid climate with a mean annual rainfall of 600-800 mm (Jenkins, 1996), and average maximum monthly temperatures ranging from 7 - 25^{o}C in January to 0 - 18^{o}C in July (Johnson and Brierley, 2006).

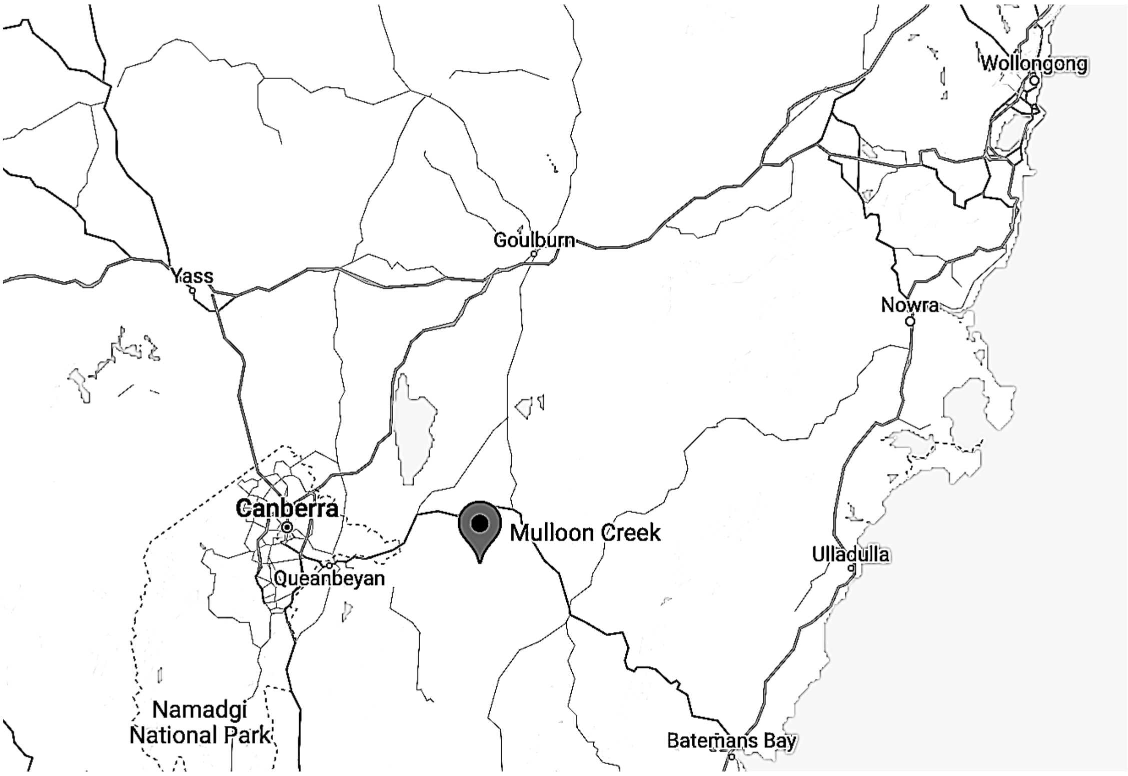

Figure 1: Location of Mulloon Creek, the longest continuous waterway in the Mulloon Catchment. Source: Google Maps.

During the middle to late Holocene Epoch (8000 BP ~ 1800 AD), this catchment contained ponds, swampy meadows, and ephemeral streams, the longest of which exists today as a continuous channel known as Mulloon Creek (Johnston and Brierley, 2006). It is joined downstream by Sandhills Creek and Shiel Creek to form the east-flowing Reedy Creek. All four waterways suffered from land clearing and overgrazing following European settlement (Peel et al., 2022).

Historically, three types of ecosystems dominated the catchment: grassy woodlands, swamps, and dry sclerophyll forests (Johnston and Brierley, 2006; NSW Dept of Planning and Environment, 2024). Of these, grassy woodlands were the most widespread, swamps were abundant but confined to narrow floodplains, and forests were sparse in the north but prevalent in the south (Johnston and Brierley, 2006; NSW Dept of Planning and Environment, 2024).

Today, most of the land is pastoral (Johnston and Brierley, 2006; NSW Dept of Planning and Environment, 2024; Peel et al., 2022; Peter Hazell , personal communication, 2024). A substantial patch of sclerophyll forest persists in the form of the 5285-hectare Tallaganda State Conservation Area south of Mulloon Creek's headwaters, but extensive patches of historical woodland no longer exist, and contemporary swamps are few and far between (NSW National Parks, 2018; Peel et al., 2022).

Leaky weirs were first installed in Mulloon Creek in 2006, under the instructions of independent thinker Peter Andrews, and funded by the National Landcare Programme (Peel et al., 2022). The operation expanded in 2018 and 2019 with Peter Hazell as the chief landscape manager of the Mulloon Institute and funded by the NSW Environment Trust (Peel et al., 2022). Leaky weirs are absent from Reedy Creek and Sandhills Creek at the time of our study (November 2023 - April 2024), though some have been planned for the coming years (Peter Hazell , personal communication, 2024).

1.3. Leaky Weir Design

Leaky weirs are low, in-stream barriers that raise upstream water levels to create ponds and prevent streambed incision (Peel et al., 2022). These ponds are effective sediment traps, and they collect plant debris and other organic materials washed from upstream (Peel et al., 2022). With enough sediments trapped behind each leaky weir, the ponds become miniature wetlands, which are believed to have a positive impact on local biodiversity.

Along with earthworks, tree planting, rotational grazing, and riparian fencing, leaky weirs are a key component of the Mulloon Institute's broader strategy known as 'landscape rehydration'. Proponents of this strategy believe leaky weirs can mitigate floods by spreading water across a wide area over a long period of time, which extends the duration of each flood but lowers their peak velocities (Gerry Carroll, personal communication, 2024; Peter Hazel, personal communication, 2023). They also claim that the chain-of-pond systems created by leaky weirs facilitate groundwater recharge (Gerry Carroll, personal communication, 2024; Peter Hazell, personal communication, 2024). If true, both claims have far-reaching implications for agriculture across Australia.

Structurally, leaky weirs are similar to rock flumes, beaver dam analogues, and one-rock dams – all of which are used in riparian conservation projects worldwide (Gooden and Pritzlaff, 2021; Government of Western Australia, 2021; Munir and Westbrook, 2020; Norman, 2020; Silverman et al., 2019). They are built from logs, rocks, and soil, and lie lower than the level of the stream bank, which allows water to pass continuously over them. At the same time, water also percolates through their porous substrate (Figures 2, 3, & 4), and with the compaction of this substrate and the growth of overtopping vegetation, a well-constructed leaky weir will transform into an elevated reed bed over time (Peel et al., 2022; Peter Hazel, personal communication, 2023). Vegetation then takes over the role of slowing stream flow, and forms a permanent, flexible barrier that protects the underlying streambed from incision (Peel et al., 2022; Peter Hazell, personal communication, 2023). Some leaky weirs are manually vegetated after construction, while others are left to recruit their own plant communities (Peter Hazel, personal communication, 2023).

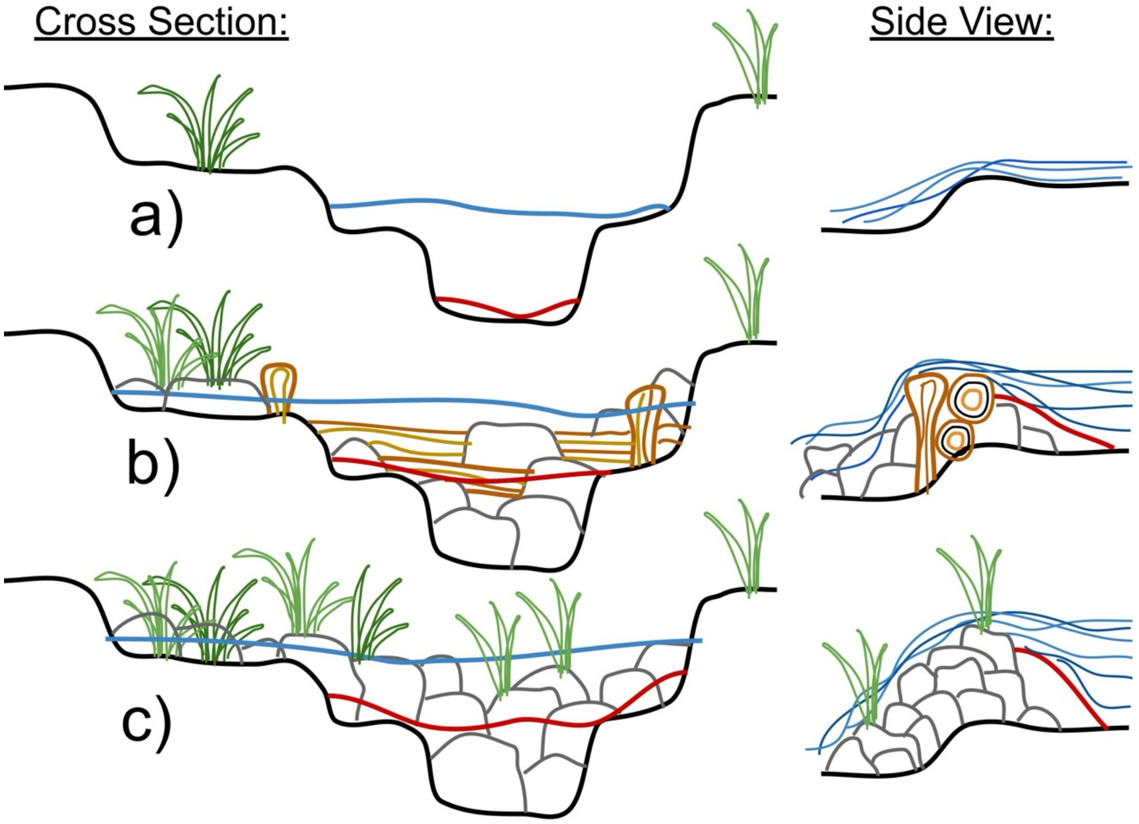

Figure 2: Main types of leaky weirs in the Mulloon Catchment. a) cross-section of the inner riparian zone of a river with no leaky weirs. b) 'woody' weirs (log sills, log-and-limestone weirs) have logs and wooden stakes as their main structural features. Woody weirs are often

short and gently sloping. c) 'rocky' weirs (rock sills, rock baffles, cobble bars, limestone weirs) are made of rocks and soil. They vary in height and are generally wedge-shaped. The roots of plants help stabilise leaky weirs over time. Blue lines indicate water levels; red lines show sedimentation. Based on personal observations, Peel et al. (2022), NSW Catchment Management Authority (2011), and Peter Hazell of the Mulloon Institute.

Figure 3: Leaky weir at 'Westview Farm'- a log sill (woody) weir built in 2019. The logs are hidden by a rocky baffle. This weir is considered by the Mulloon Institute as one of their most successful projects to date. Credit: Mulloon Institute, 2020.

Figure 4: Leaky weir at 'Peter's Pond'- a famous limestone (rocky) weir built in 2006. This weir was designed by Peter Andrews, and so bears his name. Credit: Mulloon Institute, 2020.

During prolonged drought, there is a risk of flow being severed from one leaky weir to the next, leading to lotic (still-water) conditions (Mallen-Cooper and Zampatti, 2020). This has yet to happen in Mulloon Creek, but does remain a possibility (Peter Hazell, personal communication, 2023). We need long-term studies in the future for a better idea of how leaky weirs respond to severe dry spells.

Despite their conceptual promise, and abundant testimonials from landholders (Peter Hazell, personal communication, 2023), there is little published evidence on the ecological effects of leaky weirs, as very few studies have directly compared sites with and without them. Due to the Mulloon Catchment's unique climate and land management practices, paired-catchment surveys are difficult to conduct, and within-catchment surveys in the past had no control sites (Bestow and Peel, 2021; NSW Catchment Management Authority, Southern Rivers, 2011). Our study is a within-catchment survey with an equal number of control sites and treatment sites.

1.4. Retention Structures, Debris, and Vegetation

While the use of leaky weirs may be a recent and poorly studied practice, the ecological effects of other in-stream structures have been documented worldwide for decades. In Canada and the United States of America, Beaver Dam Analogues (BDAs) are popular tools for wetland recovery (Czerepko et al., 2009; Połec et al., 2022; Silverman et al., 2019). In Northern Mexico, rock gabions and check-dams are used to similar ends (Norman et al., 2014). In Australia, irrigation weirs along the Murray River have unintentionally created wetland habitats (Blanch et al., 2000; Walker et al., 1994), and farm dams in Eastern NSW harbour diverse frog communities (Hazell et al., 2001).

Most studies on in-stream structures conclude that their ecological impacts depend on stream morphology. Channel of different width, grade, and substrate composition respond differently to human interventions. Positive consequences of in-stream structures include increases in the abundance and richness of wetland plants (Blanch et al., 2000; Czerepko et al., 2009; Kiraga et al., 2023; Połec et al., 2022; Silverman et al., 2019; Walker et al., 1994;), increases in plant growth (Bombino et al., 2008; Norman et al., 2014), and increases in local biodiversity (Kiraga et al., 2023; Silverman et al., 2019). Negative consequences include high rates of non-native colonisation downstream (Bombino et al., 2008; Greet et al., 2011), deviation of plant communities away from their initial states, (Bombino et al., 2008; Wollny et al., 2021), unfavourable changes in streambed substrate (Salant et al., 2012), and disruption of natural flow regimes (Greet et al., 2011). Negative consequences are most prominent in studies of impervious structures, such as diversion weirs, which create disparate up and downstream communities by impeding base flow, and reduce flow variability by removing large amounts of water for irrigation (Greet et al., 2011).

In addition to retaining water, leaky weirs are also sediment traps. Debris, particularly woody debris, are important for rivers (Lester and Boulton, 2008). Logs shelter aquatic insects and plant propagules from rapid currents, while smaller branches serve as food for macroinvertebrates (Lester and Boulton, 2008; O'Conner, 1992). In the 20th century, desnagging regimes removed tons of debris from Australian waterways, for reasons that varied from flood prevention to aesthetics (Lester and Boulton, 2008; Peel et al., 2022). In 2008, Lester and Boulton reviewed the effects of reintroducing woody material to these degraded streams, and found a positive response in plant, fish, and macroinvertebrate populations across numerous studies; only sites that were severely degraded or lacked colonising agents failed to recover (Lester and Boulton, 2008).

Living plants are even more important than debris, not only because they are the primary sources of debris to begin with, but also because standing vegetation traps nutrients, provides habitat for native animals, and facilitates groundwater recharge (Dunn et al., 2022). Roots alter channel flow resistance and bank strength, in some cases slowing flow by up to 84% (Huang and Nanson, 1997). Canopies provide shade, lower water temperatures, and decrease evaporation (Huang and Nanson, 1997; Lester and Boulton, 2008). Structural complexity and density of woody vegetation correlates with soil moisture levels (Burger, Reichand, & Cavagnaro, 2010). Grasses, sedges, and reeds reduce cutbank erosion and enhance floodplain development (Moody et al., 1999; Zlotina and Berkovich, 2012), and aquatic plants are home to fish and frogs (Hazell et al., 2001). Studying how leaky weirs affect plant communities will give us an indication of how they impact the other biotic components of riparian ecosystems.

1.5. Ecosystem Dynamics

Dynamics describe how an ecosystem's structure and function responds to changing environmental conditions (Figure 5). 'Threshold dynamics' refer to ecosystems that respond minimally to environmental change, only to suddenly shift to a different state once conditions reach a critical threshold (James et al., 2013). 'Linear dynamics', on the other hand, refer to systems that respond continuously to changes in the surrounding environment (James et al., 2013). In linear systems, change is roughly proportional to management effort (James et al., 2013). In threshold systems, however, management efforts may show very little sign of progress until a trigger event (fire, flood, etc.) occurs (James et al., 2013). A subset of threshold systems is described as having alternative stable states. These are known as non-reversible systems, as reverting the environment back to its historical condition may not restore the ecosystem, but instead produce a new set of structures and functions (James et al., 2013).

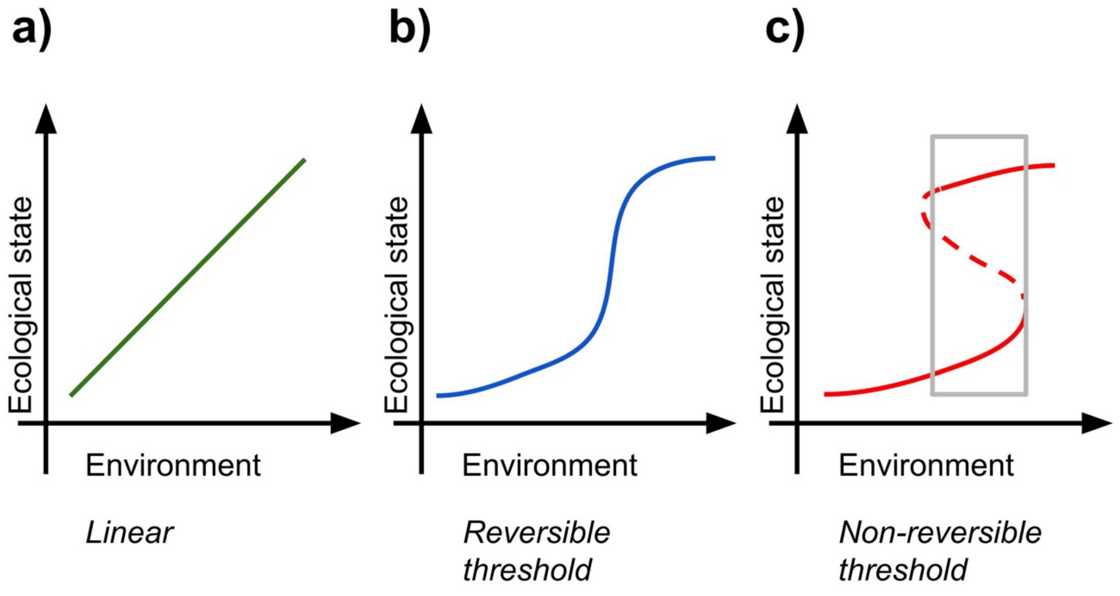

Figure 5: A diagram of ecosystem dynamics commonly recognised in literature. Each x-axis represents an environmental gradient (disturbance, temperature, soil moisture, etc.) and

each y-axis represents a variable (productivity, biodiversity, etc.) that indicates the ecological state of a system. a) linear dynamics: ecological change roughly proportional to environmental conditions; b) reversible threshold dynamics: limited response to a range of environmental conditions, then a sudden shift following a trigger event; c) non-reversible threshold dynamics: grey rectangle shows overlapping region where the same environmental conditions may result in two different stable ecological states. Adapted from James et al. (2013).

Degradation and restoration tend to progress linearly in wet, mesic biomes (James et al., 2013). In arid landscapes, especially those subjected to clearing practices, threshold dynamics are more common (James et al., 2013; Newbold et al., 2020).

The Mulloon Institute views the Mulloon Catchment as a reversible system that exhibits threshold dynamics. They reason that while the catchment is situated outside of Australia's arid centre and lacks an extended dry season, its climate is also not mesic (The Mulloon Catchment is of Köppen Climate Type Cfb - Temperate, oceanic climate). The Mulloon Institute sees leaky weirs as tools to help the Mulloon Catchment cross the threshold between its undesired state (stream and floodplain disconnected) and its desired state (stream and floodplain reconnected) (Peel et al., 2022). Degradation of the catchment began with the loss of ponds and wetland vegetation, so it is plausible that restoring these features will return the landscape to something resembling its pre-colonial form (Doble et al., 2012; Peel et al., 2022).

1.6. Criteria of Success

We think it is best to evaluate the effectiveness of restoration projects based on model systems (Palmer et al., 2005). In riparian ecology, model systems describe the ideal state of rivers and floodplains at a given site. What makes a river system 'ideal' will differ between catchments, and may depend on the underlying objectives of the project (ecological, economic, etc.). A project is successful if the resulting catchment closely resembles its model system, and maintains this resemblance with minimal follow-up maintenance (Palmer et al., 2005).

The model system of the Mulloon Catchment, as described by the Mulloon Institute, is based on its speculated pre-colonial form (Peel et al., 2022; Peter Hazell , personal communication, 2024). Johnston and Brierley (2006) found evidence of swamps, dells, and chains-of-ponds existing in the catchment prior to European settlement. These habitats were characterised by deep layers of fine-grained sediments and the presence of wetland plants (Johnston and Brierley, 2006). Based on this, we believe that changes in vegetation is a suitable indicator for the short-term effects of leaky weirs. Future studies may also wish to measure sedimentation rate, soil carbon content, and soil nitrogen levels (Hale et al., 2018; Peel et al., 2022).

1.7. Aims and Hypotheses

In this study, we aim to determine the relationship between leaky weirs and riparian vegetation. Specifically, we aim to see whether plant assemblages and habitat conditions differ between sites with leaky weirs and sites without leaky weirs.

Plant assemblage refers to the taxonomic composition of plants in a given area. In our study, we are concerned with relatively broad taxonomic groups- genera and family, rather than species. Habitat condition refers to vegetation structure, which is to the spatial arrangement of plants and plant debris. Canopy, shrubs, log hollows, litter, and groundcover are examples of structural categories. We also make a mention of ‘productivity’ throughout this study, which we define as a combination of biomass accumulation and drought resilience (section 0.2.1.). This is not the usual definition of the term, but it is the one that we think best reflects the concerns of local landholders. We hypothesise that both plant assemblages and habitat conditions will be different between sites with and without leaky weirs.

The following two chapters recount the methods that we used and the results we obtained; first regarding plant assemblage, and then habitat condition. The final two chapters make future recommendations and summarise our findings.

2. Plant Assemblages

2.1. Chapter Abstract

In this part of our study, we aimed to determine whether plant assemblages differed between sites with leaky weirs (treatment) and sites without (control). We hypothesised that assemblages would differ between treatment and control sites. We surveyed both upstream and downstream of existing and planned weirs, for a total of 24 survey sites (12 treatment and 12 control). We categorised common plant genera in the catchment into 31 artificial groups after consulting with local landholders and scientific advisory members of the Mulloon Institute. At each site, we measured abundances using a pseudocount with rank levels from 0 to 5. We performed a Principal Component Analysis (PCA) on the resulting data, rejecting principal components based on a square-root scree plot. We then performed a SIMPER analysis to see which groups contributed the most to assemblage differences between treatment and control sites. We tested for significance using a PERMANOVA analysis with the factors of treatment and stream position. We performed all analyses in R.

We found a significant difference in plant assemblages between treatment and control sites. Macrophytes contributed the most to these differences, along with actively managed taxa such as willows (*Salix spp.*) and blackberries (*Rubus spp.*). Sites with leaky weirs showed a higher rate of colonisation by tea trees (*Leptospermum spp.*). Pasture taxa made very little contribution, with the exception of thistles (*Cirsium spp.*). We did not find a significant difference between upstream and downstream sites. We conclude that leaky weirs may have a positive but localised effect on riparian plant assemblages. This effect appeared to be independent of stream position.

2.2. Introduction

Despite occupying a small percentage of earth’s land area, wetlands are highly biodiverse ecosystems that improve water quality, mitigate floods, and sequester carbon (Zedler and Kercher, 2005). The Mulloon Catchment, like many other floodplains in Australia, has lost many of its swamps to destructive land management practices during the 19th and 20th centuries (Brock, 2003; Finlayson and Rea, 1999; Johnston and Brierley, 2006; Peel et al., 2022). Leaky weirs can potentially restore wetlands by retaining floodwater and encouraging sedimentation (Peel at al., 2022).

Wetlands are characterised by unique floral communities. Flood-tolerant sedges, rushes, and reeds, which we hereafter refer to as emergent macrophytes (Section 0.2.2.), make up a large proportion of wetland vegetation along with submerged and floating macrophytes (Brock, 2003). An increase in these taxa around leaky weirs could be a sign of wetland recovery. Moreover, a major objective of the Mulloon Institute and local landholders is the restoration of native species (Peter Hazell , personal communication, 2024). Bombino et al. (2008) highlighted the potential for plant communities around retention structures to drift away from their native states; an undesirable outcome for restoration. Measuring plant assemblages around leaky weirs will help us evaluate whether they are contributing to or hindering the recovery of native plants.

Since the early 2000s, even before the construction of leaky weirs, the Mulloon Institute has been actively transplanting native trees and macrophytes from tube stocks in an effort to revegetate Mulloon Creek (NSW Catchment Management Authority, Southern Rivers, 2011; Peter Hazell , personal communication, 2024). However, not all of them survived; some died in drought, and others washed away in floods (Peter Hazell , personal communication, 2024). The Mulloon Institute uses leaky weirs as a complementary practice to revegetation. In theory, higher water levels improve habitats for wetland plants, and de-energised flows retain plant propagules that would otherwise be washed downstream (Carolyn Hall , personal communication, 2024; Peter Hazell , personal communication, 2024). Some plant taxa are managed more extensively than others; we will make a note of these in the form of a table (Appendix Table 2A). Leaky weirs should increase the success of revegetation efforts and facilitate natural succession, resulting in plant assemblages dominated by native wetland species.

Previous studies have shown that plant communities differ upstream and downstream of irrigation weirs and beaver dams (Blanch et al., 2000; Greet et al., 2011; Kiraga et al., 2023; Silverman et al., 2019; Walker et al., 1994). Sedges, rushes, and water milfoil (*Myriophyllum spp.*) prefer tailwater zones downstream, while cumbungi reeds (*Typha spp.*) and floating macrophytes dominate ponding zones upstream, where water is deeper and stream flow is less variable (Blanch et al., 2000; Greet et al., 2011; Walker et al., 1994). This may be true for leaky weirs too, and is a factor we will account for.

Although previous studies in the catchment have examined vegetation cover (Bestow and Peel, 2021), there have been no comparative studies of floral communities between sites with and without leaky weirs from a taxonomic standpoint. In this chapter, we aim to determine whether plant assemblages differ between sites with leaky weirs and those without. We hypothesise that plant assemblages are different between the two site types. If our hypothesis is supported, we will subsequently aim to identify the highest-contributing taxa.

2.3. Methods

We surveyed locations with leaky weirs (treatment) along Mulloon Creek (n = 6) and locations without leaky weirs (control) along Sandhills Creek (n = 3), Mulloon Creek (n = 1), and Reedy Creek (n = 2) for a total of 12 survey locations (Figure 6; and Appendix Table 1 A). We divided each location into two sites: upstream and downstream, for a total of 24 survey sites. We defined the boundary of each site as a 50m buffer zone from the water's edge, extending 50m upstream/downstream from existing weirs in treatment sites and planned weirs in control sites (Figure 7). We surveyed within these boundaries, including in-stream vegetation. Many potential survey locations were inaccessible to us due to a combination of high flow, landholder privacy demands, and extended travel times. We did not need to randomly select locations, as we surveyed all those accessible to us. All the weirs we surveyed were built in 2018-2019.

Previous research pointed to the effects of weirs on plant assemblages being largely confined to the ponding zones they create (Peel et al., 2022, Walker et al, 1994). Along Mulloon

Creek, these ponds rarely exceed 50m in length. Our survey locations were spaced at least 150m apart, so for the purposes of this study we assumed they were independent- even when they occurred along the same creek. Previous studies on vegetation-weir associations made similar assumptions in their methodology (Blanch et al., 2000; Walker et al, 1994). Future researchers should also consider spatial autocorrelation analyses to account for interactions between sites.

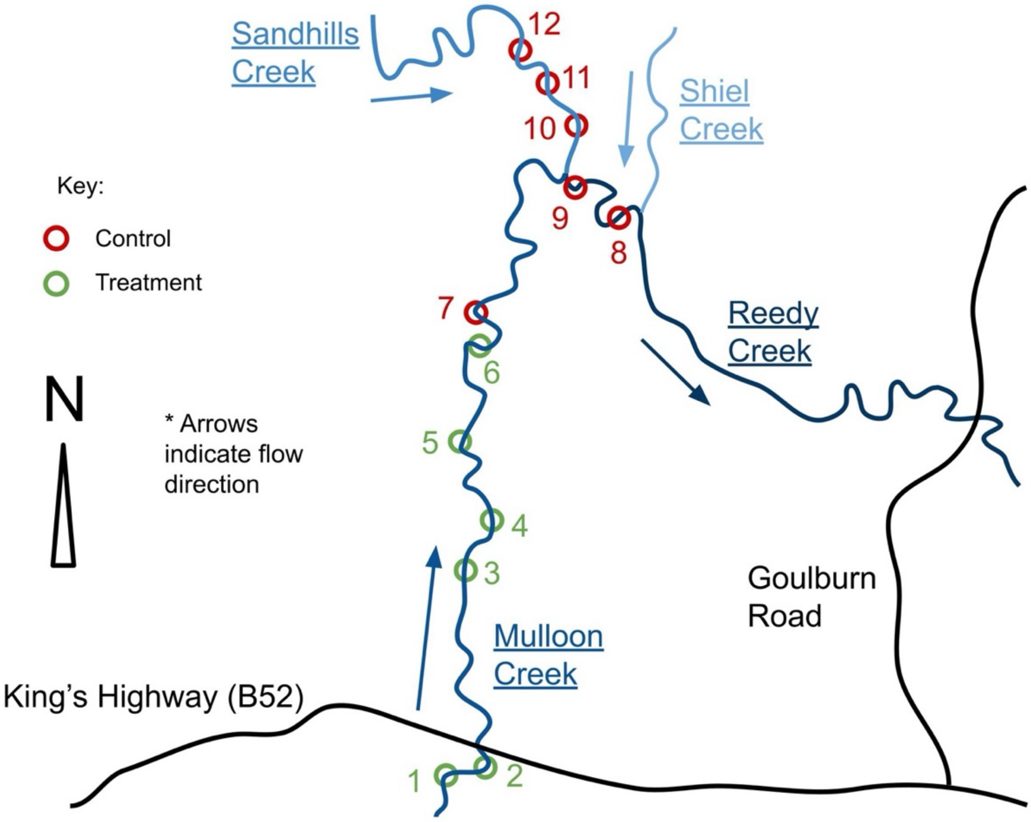

Figure 6: Treatment (green) and control (red) locations for vegetation surveys. Arrows show the direction of stream flow. Each location consisted of one upstream and one downstream site. Triangle points northward. Numbers correspond to survey locations (Appendix Table 1 A).

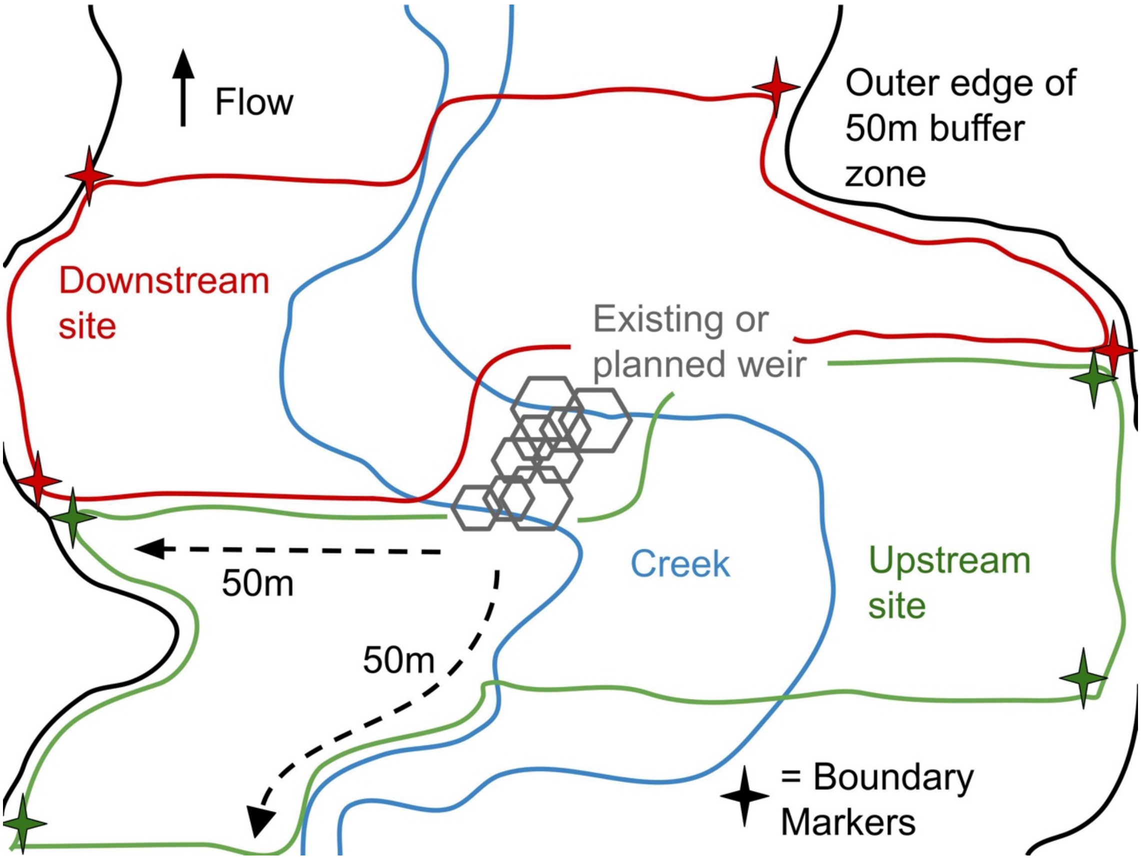

Figure 7: Sites at each survey location, bounded by 50m buffer zones. For each of the 6 treatment locations, we surveyed upstream and downstream of existing weirs. For each of the 6 control locations, we surveyed upstream and downstream of planned weirs. We used the general direction of stream flow to orientate our survey areas, and markers to indicate the outer boundaries of each site. Estimation was required, and sites were not exactly the same size. We found the margin of error difficult to judge. This should be revised and improved in future studies, perhaps with the aid of drone imagery.

Due to accessibility and time restrictions, we conducted observational surveys at a distance. We categorised plants into artificial groups that corresponded either to a single genus, a polyphyletic collection of genera, or a paraphyletic subset within a family (Appendix Tables 2A, 2B, and 3). We called these our 'groups of interest', and finalised them after consulting with local landholders, the Mulloon Institute, existing literature (Johnson and Brierley, 2006), and publicly available data from the NSW Department of Planning and Environment (NSW Dept of Planning and Environment, 2024).

In general, we prioritised taxa that were actively planted or removed, of high concern to local landholders, present in the area before European settlement, widespread in the area at the time of study, or known to provide habitat for fish, frogs, and macroinvertebrates. In total, we included 31 groups of interest (Appendix Table 2A). 28 were single-genus groups, and 3 included multiple genera. We surveyed the abundances of these groups at each of our 24 sites.

Instead of quadrat sampling, we used the method of pseudo-counting to estimate abundances (Blanch et al., 2000; Walker et al, 1994). Pseudo-counting uses rank-level scores (from 0 to 5, with 0 being absent and 5 being abundant) rather than total counts. We determined rank levels by individual counts for trees and cover for brambles and non-woody taxa (Jansen et al., 2005). As we wanted our survey methods to be reproducible, we specified semi-quantitative scoring criteria (Table 1). We did not have advanced field equipment, and our sampling time was limited by weather and logistics, so our scoring criteria contained large intervals between each rank level to accommodate for the inaccuracy in our estimates, as is typical of rapid surveys (Jansen et al., 2005; Blanch et al., 2000).

Table 1: Scoring criteria for rank levels. At every site, we assigned to each of our 31 groups an abundance score from 0 to 5. 'Individuals' refer to rametes whose above-ground portions are distinct, 'AND' means both stated criteria must be fulfilled, 'OR' means at least one stated criteria must be fulfilled. Brackets separate criteria in the cases where 'AND', 'OR' appear together. In the case of split channels (divergence and rejoining of stream braids), middle islands are categorised as continuations of the nearest bank (50m buffer zone is adjusted accordingly). Macrophytes in the middle of a channel are categorised under the closest bank.

Vegetation Type	**0**	**1**	**2**	**3**	**4**	**5**
Trees	Absent	1-5 individuals	5-10 individuals	10-25 individuals	15-20 individuals	20+ individuals
Brambles	Absent	Scattered individuals	Clumps present,	25-50% cover	50-75% cover	≥75% cover

			<25 cover			
Floating and Submerged Macrophytes	Absent	Scatter individuals	Isolated clumps	Abundant clumps	Continuous bands ≥5m long	Complete cover of the stream channel
Emergent Macrophytes	Absent	Scattered individuals	Isolated clumps along stream margins	Abundant clumping along stream margins	Continuous bands ≥5m long on one bank	Continuous bands ≥5m long on both banks
Pasture Grasses	Absent	Scattered individuals	Clumps present, <25 cover	25-50% cover	50-75% cover	≥75% cover
Forbes	Absent	Scattered individuals	Isolated clumps OR >10 individuals	Abundant Clumps OR >20 individuals	≥20 individuals AND <50% total site cover	≥50% cover

We used a Principal Component Analysis (PCA) to analyse our data, and rejected Principal Components based on a square-root scree plot (Del Giudice, 2022). We tested for significant differences in assemblages using a two-way PERMANOVA, with 9999 permutations and the factors of treatment (weir/no weir) and stream position (up/downstream) (Package: ‘vegan’). To determine which plant groups contributed most to the differences between sites, we used a SIMPER analysis with 999 permutations (Package: ‘vegan’). We analysed our data and generated our plots using R (Package: ‘ggbiplot’).

2.4. Results

We found a significant difference in plant assemblages between treatment and control sites (df = 1, p < 0.01, Figure 8). We found no significant difference in plant assemblages between upstream and downstream sites (df = 1, p = 0.67, Figure 9). We found no significant interaction between the factors of stream position and treatment (df = 1, p = 0.74).

We interpreted our first principal component (PC1) as representing wetland plants. Treatment and control sites differed greatly along this component, which explained 42.8% of total variance (Figure 8). Main constituents of PC1 included *Typha, Eleocharis, Myriophyllum, Leptospermum, Salix,* and *Schoenoplectus*. Our second principal component (PC2) was difficult to interpret, and explained only 10.8% of total variance. Main constituents of PC2 included *Foeniculum, Typha, Vallisneria, Hypericum,* exotic pasture grasses, and *Schoenoplectus.* Across both PC1 and PC2, *Myriophyllum, Typha, Schoenoplectus* and *Eleocharis* had by far the highest contributions (Appendix Figure 1). Overall, macrophytes explained much of the variation between sites, while pasture and canopy plants explained very little. We considered no Principal Components beyond PC2 due to a sharp change in the slope of our square root scree plot (Appendix Figure 2).

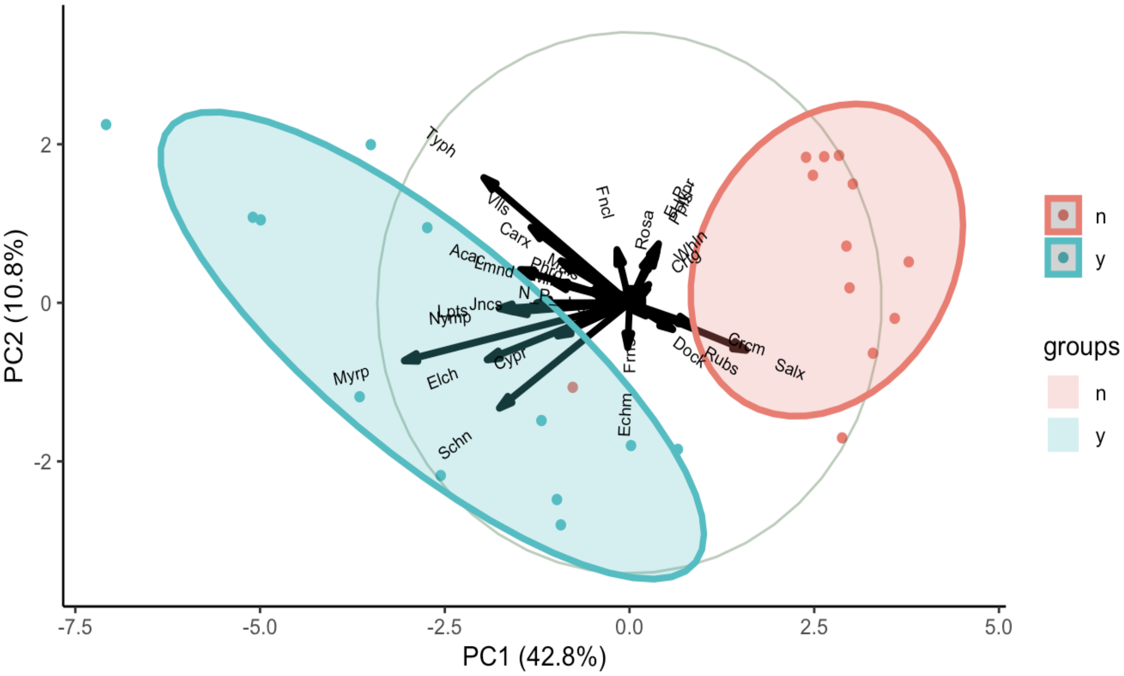

Figure 8: PCA biplot by treatment. n = control, y = treatment. Blue data points indicate treatment sites, while red data points indicate control sites. The two groups differ greatly along PC1, which appears to represent wetland plants. The meaning of PC2 is unclear. The first two principal components combined explain more than 50% of variation between sites. Each vector represents a different plant group. The greater the vector's magnitude, the more strongly that plant group contributes to differences between sites. Abbreviations defined in section 0.2.2.

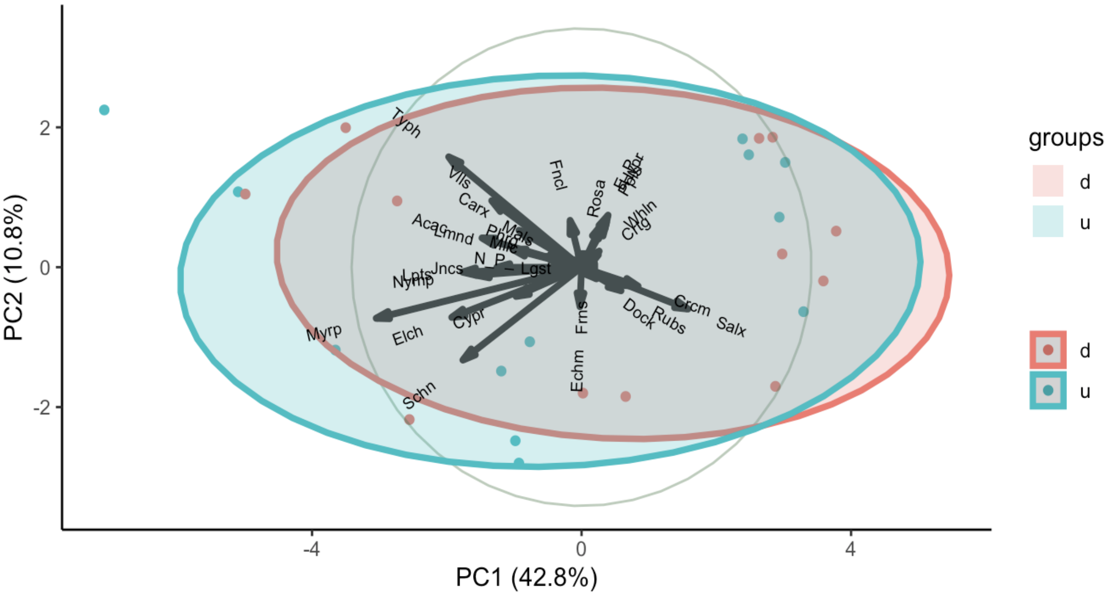

Figure 9: PCA biplot by stream position. d = downstream, u = upstream. Blue data points represent upstream sites, red data points represent downstream sites. The two groups do not appear to differ much, with upstream sites having a slightly greater (not statistically significant) abundance of macrophytes. Abbreviations defined in section 0.2.2.

Our SIMPER analysis showed that macrophytes contributed heavily to differences in assemblages between treatment and control sites (Table 2). Woody terrestrial plants also had high contributions, though most of these were actively managed taxa (Table 2).

Table 2: Top 13 plant groups (out of 31) with the highest contributions to differences between treatment and control sites, according to a SIMPER analysis with 999 permutations.

Genus	**Habit**	**SIMPER Contribution Score**	**Sites of Greater Abundance**	**Management Status**	**Native Status**
Vallisneria	Submerged macrophyte	0.7073926	Treatment sites	Unmanaged	Native
Rubus	Woody terrestrial	0.6772015	Control sites	Removal	Non-native
Acacia	Woody terrestrial	0.6433564	Treatment sites	Planting	Native
Cirsium	Herbaceous terrestrial	0.6058494	Control sites	Removal	Non-native
Cyperus	Emergent macrophyte	0.5647721	Treatment sites	Unmanaged	Native
Juncus	Emergent macrophyte	0.5236758	Treatment sites	Unmanaged	Native
Nymphoides	Floating macrophyte	0.4796222	Treatment sites	Unmanaged	Native
Typha	Emergent macrophyte	0.4320360	Treatment sites	Planting	Native
Salix	Woody terrestrial	0.3803661	Control sites	Currently unmanaged Historically planted	Non-native
Leptospermum	Woody terrestrial	0.3248645	Treatment sites	Unmanaged	Native
Eleocharis	Emergent	0.2561752	Treatment	Unmanaged	Native

	macrophyte		sites		
Schoenoplectus	Emergent macrophyte	0.1859301	Treatment sites	Unmanaged	Native
Myriophyllum	Submerged macrophyte	0.1027256	Treatment sites	Currently unmanaged Historically planted	Native

2.5. Discussion

In general, control sites lacked a diverse assemblage of macrophytes with the exception of location 7, which was situated in a natural ponding zone created by flood debris on Mulloon Creek, approximately 200m downstream from the northernmost weir of location 6. Perhaps due to its unique placement within the creek, amidst a log jam that seemed to act as a natural leaky weir, it contained a different plant assemblage to the other control locations (Figure 8). Control sites along Reedy Creek contained some macrophytes in the form of *Juncus, Carex,* and *Typha*, while those along Sandhills Creek were largely devoid of even these genera. Interestingly, macrophytes were present in sections of Sandhills Creek upstream of location 12, our northernmost survey site. We spotted particularly dense reed beds near culverts and road crossings. These populations should be studied more in the future. A high abundance of thistles (*Cirsium spp.*) at control sites was probably the result of a neglected pasture (near locations 11 and 12) serving as a source of colonising agents.

Treatment sites, on the other hand, contained high levels of in-stream vegetation. The most diverse assemblages occurred in locations 1 and 2, where all macrophyte groups were present. The Mulloon Institute plants reeds (*Typha spp.*, *Phragmites australis*) very close to or directly on top of leaky weirs to improve their structural stability (NSW Catchment Management Authority, Southern Rivers, 2011; Peter Hazell , personal communication, 2024), so it was unsurprising to find a high abundance of reeds around leaky weirs. More striking was the widespread proliferation of multiple other wetland taxa in treatment sites, even those that have not been extensively managed in recent years (Appendix Table 2A). This, we believe, can be attributed to the hydrological effects of the leaky weirs themselves.

Macrophytes thrive in rich, alluvial sediment (Higgisson et al., 2022). They also require periods of prolonged inundation throughout their growing seasons (Alexander et al., 2008; Higgisson et al., 2022). Leaky weirs can provide both of these conditions. By slowing flows, they encourage sedimentation and catch stray propagules (Bombino et al., 2008; Kiraga et al., 2023). Before leaky weirs were installed in Mulloon Creek, water levels would rise dramatically during floods and drop quickly thereafter. The inundation of stream terraces would be sudden and brief (Figure 10). After leaky weirs were installed, water levels would remain close to bankfull capacity for longer after each flood (Peel et al., 2022; Peter Hazell , personal communication). The prolonged submersion of sediment-rich stream terraces create ideal conditions for wetland plants (Alexander et al., 2008), and we think that the high abundance of them near culverts and road crossings can also be attributed to this. To further test this idea, researchers should perform intervention studies where an equal number of macrophyte seedlings are transplanted to sites both with and without leaky weirs, at a fixed distance from the wetted perimeter during low-flow periods. Measuring the subsequent growth rate, survival, and spread of these populations will give us a strong indication of whether leaky weirs create suitable conditions for wetland plants.

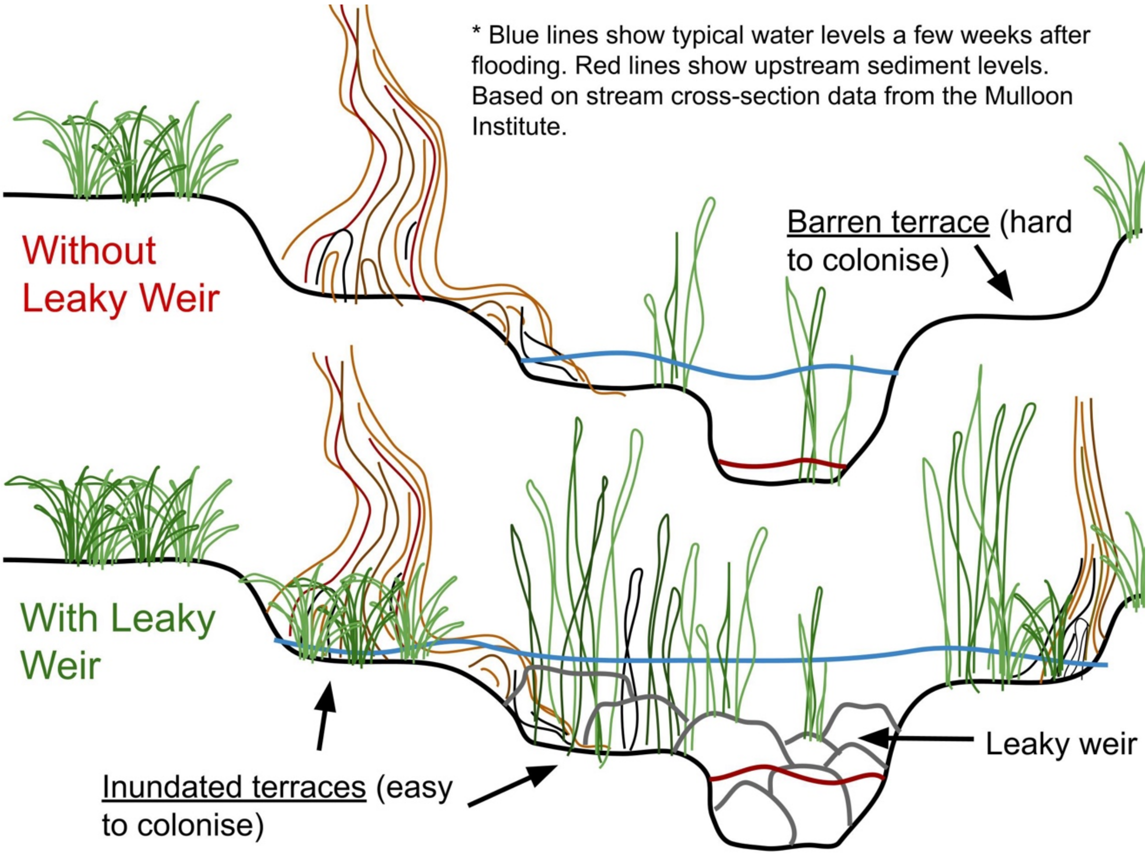

Figure 10: A possible cause for the high abundance of wetland plants in treatment sites. Leaky weirs sustain high water levels for longer after floods, inundating previously dry terraces. This creates favourable conditions for emergent macrophytes.

Along with macrophytes, actively managed woody plants such as willows (*Salix spp.*), wattles (*Acacia spp.*), and blackberries (*Rubus spp.*) also had high contributions to differences between treatment and control sites (Table 2). Willows are not currently managed by landholders, but were historically planted along all major waterways in the catchment (NSW Catchment Management Authority, Southern Rivers, 2011; Peter Hazell , personal communication, 2023; Wright, 2018). Most of them are approximately 40 years old at the time of writing. Their abundance, therefore, was largely determined before the existence of leaky weirs. Wattles, meanwhile, are being planted alongside the weirs as part of a revegetation initiative. Variation in willow and wattle abundances between sites was therefore unsurprising, and probably not related to leaky weirs. Blackberries are currently subject to various control measures, from slashing and goat grazing to chemical herbicides (Peter Hazell , personal communication, 2024). Methods differ from one property to the next, and likely is the main reason for variations in their abundance. We can say the same of actively managed forbs such as thistles.

Other widespread plant groups (e.g. *Foeniculum, Hypericum*, native and exotic pasture grasses) contributed very little to differences between treatment and control sites. Canopies in Lower Mulloon were almost exclusively dominated by willows and poplars, and most pastures were composed of the same few exotic taxa (*Eragrostis, Cenchrus, Cynodon*). A notable oddity were the tea trees- in particular, those of the genus *Leptospermum*; woody, flood-tolerant, subcanopy plants that were more abundant in treatment sites than control sites. Unlike willows and wattles, tea trees have not been extensively managed by landholders. It is possible that the backwater swamps created by leaky weirs have helped them recolonise riverbanks. Mature tea trees tolerate waterlogged soils, and their seedlings can survive submersion of up to 8 weeks (Zacks et al., 2018). An increase in swampy conditions around leaky weirs might favour them over their competitors, such as blackberries and grasses. Remnant patches of tea tree scrub are scattered throughout the Mulloon Catchment, and provide a constant supply of propagules (mostly in the form of seed capsules). Proximity to these patches probably played a role in their success.

Overall, our results showed a positive relationship between leaky weirs and vegetation. Native flood-tolerant plants such as tea trees and various sedges seem to enjoy the swampy conditions in newly-formed pools. Leaky weirs enhance revegetation projects, or at least do not hinder them, judging by the vigorous reed growth at treatment sites. Macrophytes are characteristic of wetlands, indicating a reversion of Mulloon Creek to its swampy, pre-colonial state (Peel et al., 2022). Reeds and rushes provide habitat for frogs, fish, and macroinvertebrates (Hazell et al., 2001; Higgisson et al., 2022), stabilise stream banks with their spreading rhizomes, and encourage sedimentation (Higgisson et al., 2022). Submerged macrophytes are food for wildlife and traps for pollutants (Thomaz, 2021). The proliferation of these plants around leaky weirs is a very promising sign.

Over the course of decades, leaky weirs may play a key role in wetland recovery by prolonging the inundation of berms and terraces (Alexander et al., 2008). At present, however, we have found that changes in plant assemblages were localised and not reflected in pasture and canopy vegetation. We conclude that leaky weirs may have a desirable effect on macrophytes and other flood-tolerant plants, but that in the short term this effect is restricted to the inner riparian zone. We recommend intervention studies in the future to determine the underlying mechanisms behind our observations.

3. Habitat Condition

3.1. Chapter Abstract

In this part of our study, we aimed to see whether habitat conditions differed between sites with leaky weirs (treatment) and sites without (control). We hypothesised that the condition of habitats will be better in treatment sites than control sites. We gathered Rapid Appraisal of Riparian Condition (RARC) survey scores for 13 locations with leaky weirs (treatment) and 36 locations without leaky weirs (control). Some of these sites were repeatedly surveyed in 2017, 2019, and 2021. In total, we collected scores from 45 surveys in treatment sites and 67 surveys in control sites across three years. We introduced site position as a random factor by categorising sites as either 'north' or 'south' depending on their geographic location with respect to historical floodplain pockets. We used a linear mixed model to account for repeated measurements across time. Our model had year and treatment as fixed factors, and site position as a random factor. We used the method of Estimated Marginal Means with Tukey-adjusted p-values as our post-hoc test. We analysed our data and generated our plots using R.

We did not find a significant difference in RARC scores between treatment and control sites, but we did find a significant difference in scores between years. There was no significant interaction between year and treatment. South sites, across all years and treatments, had higher average RARC scores than north sites. Preservation of native bushland and historical land management practices appeared to have a greater influence over vegetation structure than contemporary restoration efforts. We concluded that leaky weirs did not seem to influence habitat conditions in the short term.

3.2. Introduction

Vegetation structural complexity correlates with floral and faunal species richness, and so is an indicator of habitat condition (Jansen et al., 2005; Randlkofer et al., 2010; Remeš et al., 2022). Complex plant assemblages create a wide range of ecological niches, and make for healthy wildlife habitats (Randlkofer et al., 2010; Remeš et al., 2022). Mature trees, for instance, are rife with hollows and deadwood, providing shelter for birds (Randlkofer et al., 2010; Remeš et al., 2022). Of all historical human activities in the catchment, land clearing has been the most detrimental to wildlife habitat (Peel et al., 2022). Subsequent revegetation has not only been unable to reverse the damage, but has created a new set of problems. For instance, while historical willow plantings have increased structural complexity by introducing an overarching canopy, they have also decreased it by displacing native trees and creating unfavourable conditions for understorey taxa (NSW Catchment Management Authority, Southern Rivers, 2011; Peter Hazell , personal communication, 2024).

The Mulloon Institute conducted surveys of the catchment in 2017, 2019, and 2021 (Bestow and Peel, 2021) following the Rapid Appraisal of Riparian Condition guidelines (RARC) described by Jansen et al. (2005). RARC surveys quantify the structural complexity of vegetation in riparian zones, which serves as an indicator of habitat quality (Jansen et al., 2005). Canopy width, understorey cover, debris abundance, reed growth, and the presence of native species all contribute positively to RARC scores. Total scores are out of 50, with higher scores indicating better habitats. The RARC survey has been tested on the Murrumbidgee River, in Gippsland, and in the Goulburn-Broken Catchment (Jansen et al., 2005). In all three areas, RARC scores negatively correlated with grazing intensity (Jansen et al., 2005).

In Chapter 2, we found that leaky weirs increased macrophyte abundance, and hence increased the structural complexity of in-stream vegetation. However, we did not measure the structural complexity of the riparian zone systematically. We only considered particular plant groups of interest, and although we surveyed trees by count, we did not consider the width of their canopies. We grouped understorey plants taxonomically rather than structurally, and made no account of plant debris.

In this chapter, we aim to determine whether the habitat condition of vegetation differs between sites with leaky weirs (treatment) and those without (control). We will use RARC scores as indicators of habitat quality, and compare them between treatment and control sites. We hypothesise that habitat conditions will be better in treatment sites than control sites.

3.3. Methods

Using data collected in previous surveys of the Mulloon Catchment (Bestow and Peel, 2021), we gathered RARC scores from sites with leaky weirs and sites without (Figure 11). We termed these ‘treatment’ and ‘control’ sites respectively, using the same terminology as in section 2.3. We categorised sites as ‘north’ and ‘south’ based on their locations within the catchment. Historically, a continuous floodplain pocket stretched from the confluence of Sandhills Creek and Mulloon Creek to approximately three kilometres south of the King’s Highway (Figure 11). The 14 Property Management Areas (PMAs) dividing the catchment are numbered from south to north ascending (NSW Dept of Planning and Environment, 2024), and PMA5 (Westview) roughly coincides with the southern end of the historical woodland floodplain. We categorised all sites lying within PMAs 1- 4 as ‘south’ sites, and PMAs 5 -14 as ‘north’ sites. In their native states, south sites were probably more heavily forested than north sites (Johnson and Brierley, 2006; NSW Dept of Planning and Environment, 2024).

In total, we gathered 36 surveys of treatment sites and 61 surveys of control sites across 2017, 2019, and 2021, with repeated surveys of the same sites (13 treatment sites and 36 control sites) during these years (Appendix Table 4). We checked the normality of residuals by observing a Quartile-Quartile Plot (Pleil, 2016) and the homogeneity of variances by Levene’s Test (Wang et al., 2016), before testing for significance using a Linear Mixed Model accounting for repeated measures, with fixed factors of treatment (weir/no weir) and year (2017, 2019, 2021) and a random factor of site position (north/south) (Package: ‘nlme’). We calculated effect sizes (Cohen’s *d*) with a confidence level of 0.95 (Visentin et al., 2019). We analysed our data and generated our plots using R (Package: ‘ggplot2’).

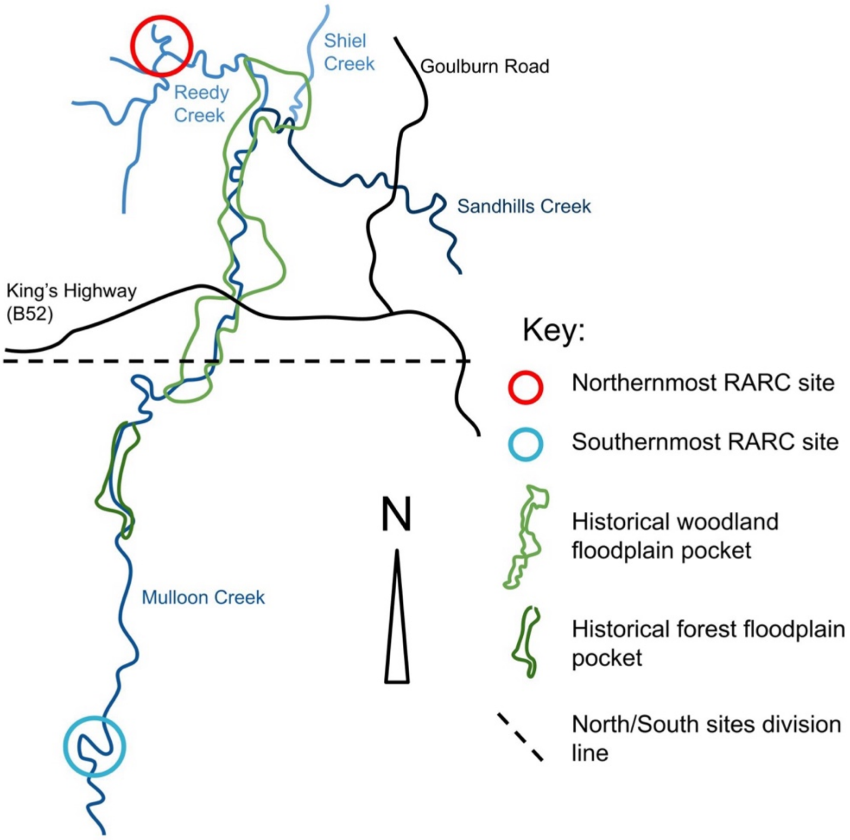

Figure 11: Map showing the division between north and south sites. Green regions outline historical floodplain pockets. Northern sites were initially dominated by woodlands, which have been cleared extensively for agriculture. Southern sites have not been cleared as heavily, and preserve some of their remnant forest vegetation.

3.4. Results

Our data met the assumptions of normally distributed residuals (Appendix Figure 3) and homogeneous variances after a square root transformation (Levene's Test, $p = 0.08$). We found no significant difference in average RARC scores between treatment and control sites ($F = 1.04$, $df = 1$, $p = 0.31$, Cohen's $d = 0.47$). We found a significant difference in average RARC scores between years ($F = 5.27$, $df = 2$, $p = 0.01$, Table 3), and we found no significant interaction between the factors of treatment and year ($F = 1.99$, $df = 2$, $p = 0.15$). Although south sites on average scored higher than north sites, both groups showed an improvement in scores over time (Figures 12 & 13). As there was no significant interaction between explanatory variables, we did not perform post-hoc tests.

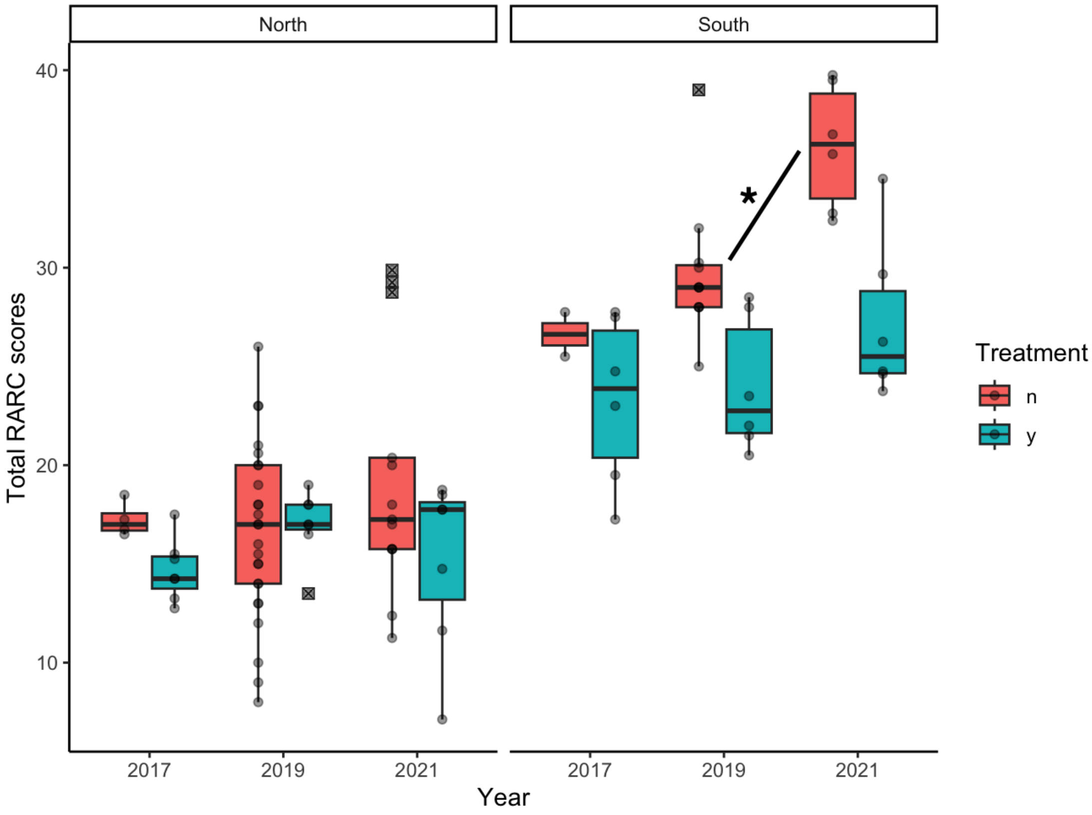

Figure 12: Total RARC scores, stratified by location. X- axis labels: n = control, y = treatment. Grey squares indicate outliers. Asterisk shows significance (p < 0.05).

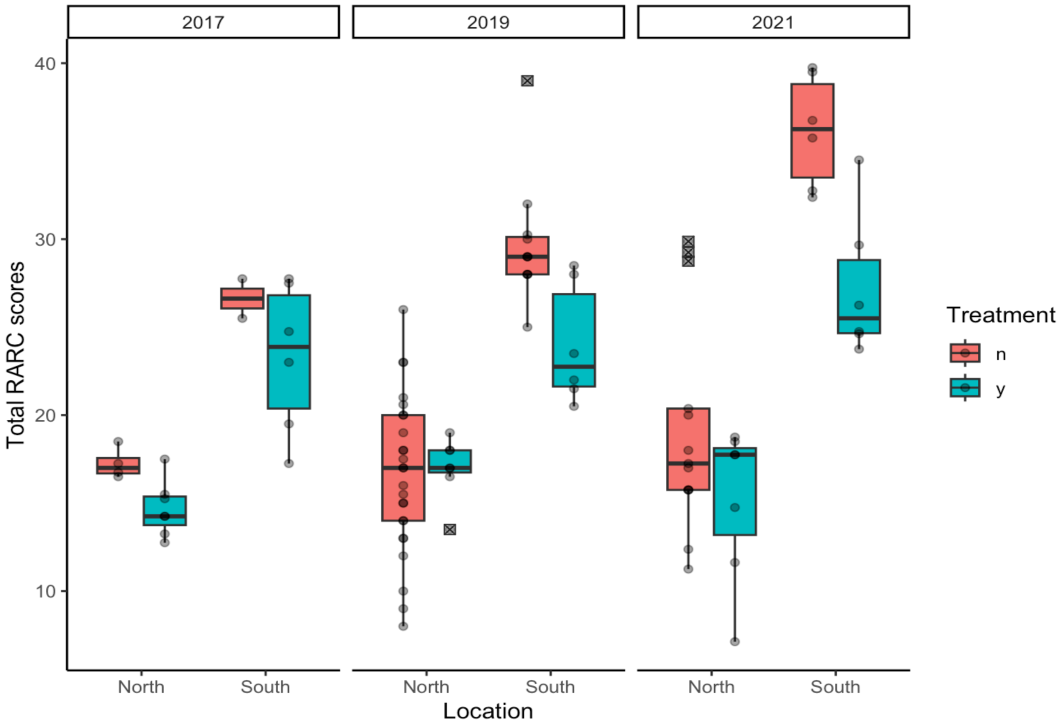

Figure 13: Total RARC scores, stratified by year. X-axis labels: n = control, y = treatment. Grey squares indicate outliers.

Table 3: pairwise effect sizes between years. We present absolute effect sizes, as we did not have a 'control' year.

Years compared	**Absolute value of effect size (|Cohen's *d*|)**
2017 and 2019	0.26
2017 and 2021	0.88
2019 and 2021	0.62

3.5. Discussion

Contrary to our hypothesis, we did not find a difference in habitat condition between treatment and control sites. Instead, we found that all sites grew more structurally complex over time, and that south sites were always in better condition than north sites. This suggests that historical management practices had a greater influence on habitat condition than the comparatively recent practice of building leaky weirs. In particular, we believe the protection of remnant native vegetation and the planting of willows were major factors that contributed to RARC score differences in the present day. We attribute increases in scores over time to high levels of rainfall in 2020 and 2021 (Figure 17).

Dry scrub forests, woodlands, and grassy wetlands were the most widespread plant communities in the Mulloon Catchment before colonisation (Johnson and Brierley, 2006; NSW Dept of Planning and Environment, 2024). Southern or Upper Mulloon harboured substantial patches of sclerophyll forest, while floodplains in Lower Mulloon consisted of woodlands and swamps with thin bands of alluvial ribbon gum forests (Johnson and Brierley, 2006; NSW Dept of Planning and Environment, 2024). Some of the uphill forests remain, but most of the floodplain woodlands have been lost to agricultural land clearing (Johnson and Brierley, 2006; NSW Dept of Planning and Environment, 2024). We believe that better preservation of bushlands in southern sites made them score better in RARC surveys, since native canopy vegetation contributes heavily to RARC scores (Jansen et al., 2005). Northern sites, in comparison, had less canopy cover in their natural states, and have also suffered greater subsequent degradation (Johnson and Brierley, 2006; NSW Dept of Planning and Environment, 2024).

As native canopies deteriorated throughout the catchment, a new canopy of willows took over (NSW Dept of Planning and Environment, 2024; Peter Hazell , personal communication, 2023; Wright, 2018). Basket willows (*Salix viminalis*) were introduced to the region in the middle to late 1900s, and have since become a dominant species, particularly in Lower Mulloon (NSW Catchment Management Authority, Southern Rivers, 2011). As a result, canopy cover in northern RARC sites were closely related to willow age and abundance. We cannot be sure if leaky weirs had a clear effect on either of these factors. Some landholders believe that prolonged inundation causes willow senescence, while others argue that an increase in local soil moisture helps them grow faster (NSW Catchment Management Authority, Southern Rivers, 2011; Peter Hazell , personal communication, 2023). Published studies on the subject show that willows can thrive just as well in flooded zones upstream of beaver dams as unflooded areas downstream, so leaky weirs may not have much influence over willow survival (Amlin and Rood, 2001). Even if they did have an effect, we cannot describe the underlying mechanisms. Instead, we think that an uneven initial distribution of willow seedlings and subsequent uprooting events (such as flooding, grazing, and manual removal) were more likely to have affected canopy cover, especially in Lower Mulloon (NSW Catchment Management Authority, Southern Rivers, 2011). We therefore attribute much of the variation we observed in RARC scores to factors unrelated to leaky weirs.

Whether leaky weirs will improve floodplain habitats in the long term is unclear. The preference of tea trees to colonise weir pools (section 2.5.) may result in increased native shrub cover, but this has yet to occur outside of the inner riparian zone. We think that future increases in vegetation complexity will be mostly due to the revegetation of streambanks at treatment sites, rather than the presence of leaky weirs.

We have a number of recommendations for future RARC surveys in the Mulloon Catchment. Firstly, we recommend different iterations of the survey to be used in different parts of the catchment. Jansen et al. (2005) gives technical guidelines for the RARC survey version 2, which is suitable for sites that naturally have > 60% canopy cover. This was the version used by the Mulloon Institute in all their previous surveys, and we believe it should continue to be used in southern sites, which were historically forested and relatively well-preserved (Johnston and Brierley, 2006; NSW Dept of Planning and Environment, 2024). On the other hand, Jansen et al. (2006) gives technical guidelines for the RARC survey adapted to the mid north of Southern Australia, which is suitable for sites with small or ephemeral waterways and < 30% canopy cover. We think this version should be used for northern sites, especially those that lie within historical floodplain pockets (Jansen et al., 2006; Johnston and Brierley, 2006). Both survey methods yield a total score out of 50, with the same contributing subcategories, so they are standardised with respect to one another. The main differences between them lie in their scoring criteria, which assume different historical conditions (Jansen et al., 2006; Johnston and Brierley, 2006). Using different survey methods for different sites will result in a bias towards higher scores in northern sites, but we believe such bias is necessary to account for their poor ecological condition prior to restoration. Degraded sites with low initial canopy cover respond differently to management efforts compared to intact sites with extensive canopies, and their scores should be weighed accordingly (James et al., 2013).

Secondly, we recommend modifying the scoring criteria for the ‘features’ subsection of all RARC surveys. Native canopy species regeneration, native understorey regeneration, large native tussock grasses, and reeds contribute 2 points each to this subsection (Jansen et al., 2005). We think reeds should contribute at least 4 points, because of how important they are for combating erosion and providing wildlife habitat in agriculturally modified river systems (Hazell et al., 2001; Higgisson et al., 2022). We also believe that RARC surveys should create an additional subsection for floating macrophytes, though we understand this may be difficult as the ecological benefits provided by macrophytes can vary from one river to the next (Thomaz, 2021). A high abundance of them is not always desirable, and species composition is a key consideration (Thomaz, 2021).

Finally, we suggest that the Mulloon Institute review the ‘habitat’ subsection of its previous RARC survey projects. In the technical outline by Jansen et al. (2005), continuity and width of riparian vegetation contribute 4 points each to this subsection, while proximity to intact native vegetation contributes 3 points. In the RARC operational sheets by the Mulloon Institute, ‘continuity and width of riparian vegetation’ is mistranscribed as ‘continuity and width of riparian *canopy* vegetation’. Jansen et al. (2005) gives little indication of how riparian vegetation is to be distinguished from pasture vegetation in the first place, and insertion of the word ‘canopy’ into the scoring criteria has no doubt led to underscoring in many sites. We recommend a disambiguation of the term ‘riparian vegetation’, as well as a revision of the Mulloon Institute’s operational sheets.

4. Future recommendations

Our study had many limitations. The most important ones are as follows:

- Sandhills Creek and Mulloon Creek differ in underlying geology and land use history.
- Downstream succession may be affected by upstream vegetation.
- Contemporary land use varies throughout the catchment.
- Estimating vegetation cover from a distance entails large error margins.

To address them, we make the following recommendations. First, future researchers should conduct paired-catchment studies if possible, and nested-design studies if not. Paired-catchment studies are especially difficult given Mulloon Creek's unique climate and biogeography, but opportunities for them should be pursued. Alternatively, more control sites should be surveyed on Mulloon Creek and more treatment sites (once they are established) should be surveyed on Sandhills Creek and Reedy Creek. This will account for the confounding factors of underlying geology and downstream succession.

Second, future researchers should compare our method for assessing plant assemblages (described in section 2.3.) with established methods in literature, particularly those using rank-levels and pseudocounts. Future studies should test whether our scoring criteria yields consistent results in the hands of different surveyors. If it does not, it should be reviewed and modified.

Finally, future researchers should conduct Before-After Control-Impact studies on leaky weirs (Conner et al., 2016). The timeframe of our study meant we could not implement a Before-After Control-Impact study design, but future researchers may have the chance to do so.

In addition, we note the following topics as potential research avenues in the future:

4.1. Floodplain productivity

As leaky weirs retain water during floods, they may increase the productivity of surrounding pastures through base flow and lateral percolation (Peel et al., 2022). Conceptually, higher in-stream water levels lead to more surface area through which water can soak into the surrounding soil (Figure 14). This is thought to increase biomass accumulation and decrease drought stress (Peel et al., 2022; Peter Hazell , personal communication, 2023). Local landholders believe such effects will increase over time as multiple drought-flood cycles 'pulse' water through the floodplain (Figure 14), allowing them to cultivate water-intensive crops that have not been commercially grown in the catchment for decades, such as cotton and potatoes (Gerry Carroll, personal communication, 2024). If true, this could have important ramifications for Australian agriculture.

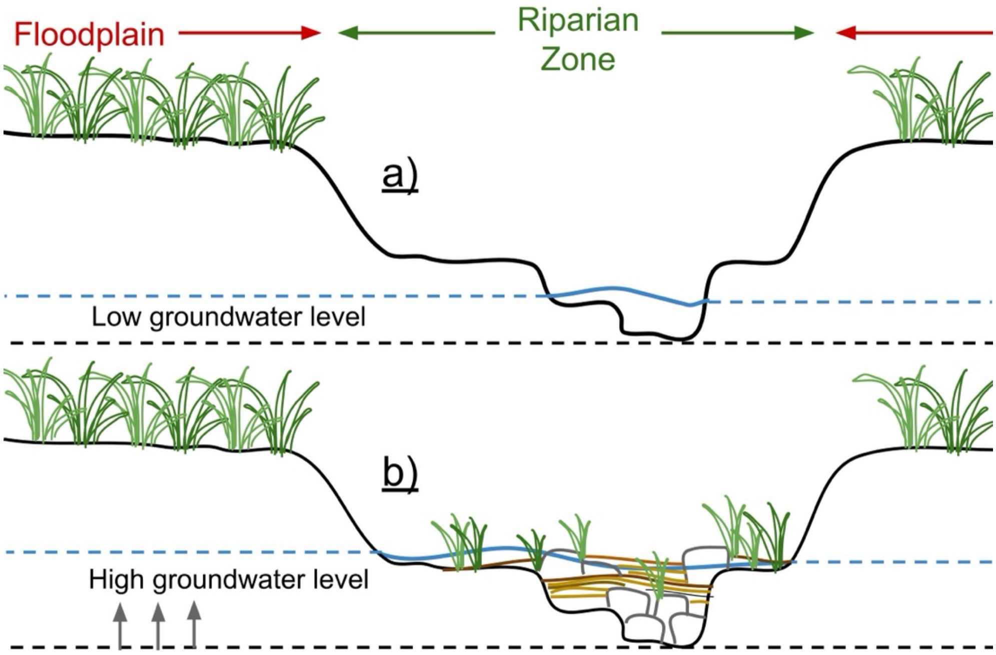

Figure 14: conceptual mechanism behind landscape rehydration by leaky weirs. a) Cross-section of a degraded creek and floodplain without leaky weirs. b) The same creek and floodplain with a leaky weir installed. The weir keeps water at bankfull capacity for longer, and 'pulses' moisture through the surrounding soils. This process is believed to increase water availability for pastures. Sketch depicts typical water levels a few weeks after heavy rain. Based on Peel et al. (2022), Peter Hazell of the Mulloon Institute, and landholder Gerry Carroll.

Previous studies indicate that while plant growth in the riparian zone responds quickly to revegetation efforts (Hale et al., 2018), productivity in the wider floodplain may take longer to change (Norman et al., 2014). If weirs have a positive effect on biomass accumulation and help alleviate drought stress, we should see these effects more clearly in older weirs than newer ones. Normalised Difference Vegetation Index (NDVI) correlates with leaf area, vegetation cover, and biomass, making it a convenient measurement of productivity (Carlson and Ripley, 1997; Norman, 2020). A second index, the Normalised Difference Water Index (NDWI) is used to measure drought stress in foliage (Gao, 1996). Future studies could use both NDVI and NDWI values to determine the effects of leaky weirs on floodplain productivity (Figure 15).

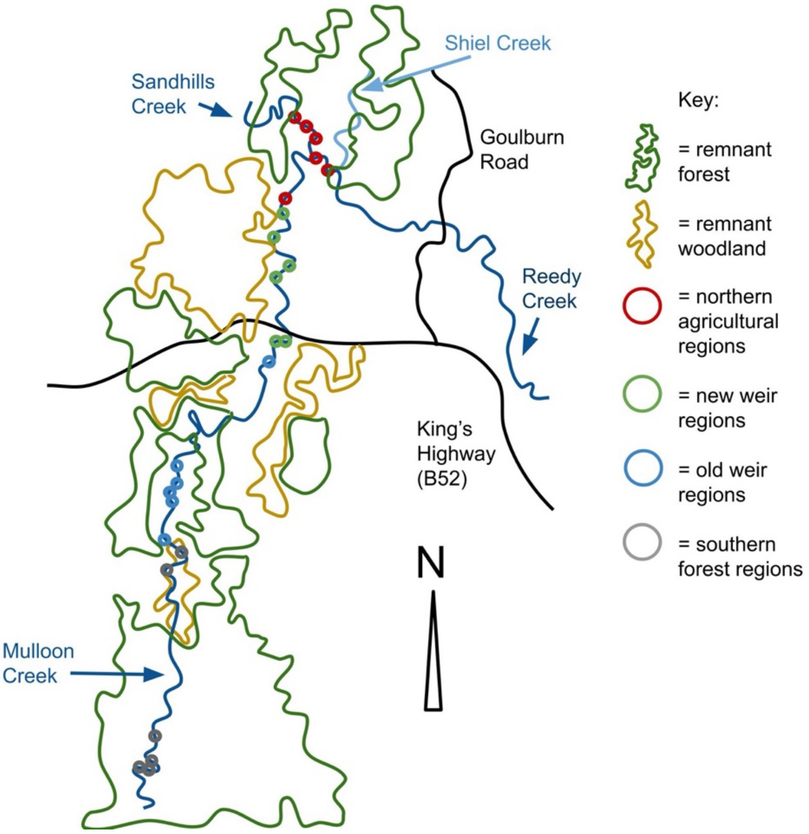

Figure 15: A map of possible survey regions for floodplain productivity. Ideal locations for comparison include agricultural regions without leaky weirs, agricultural regions with newly built leaky weirs, agricultural regions with pre-existing leaky weirs, and forested regions. Adapted from NSW Dept of Planning and Environment, 2024.

To account for the effects of climate, researchers can use rainfall data gathered from Braidwood weather station to inform predictive NDVI and NDWI models. This is particularly useful in highlighting the effects of leaky weirs during dry spells, such as the tinderbox drought- a 3-year period (2017, 2018, 2019) during which cool-season precipitation was 50% lower than average (Devanand et al., 2024, Figure 16).

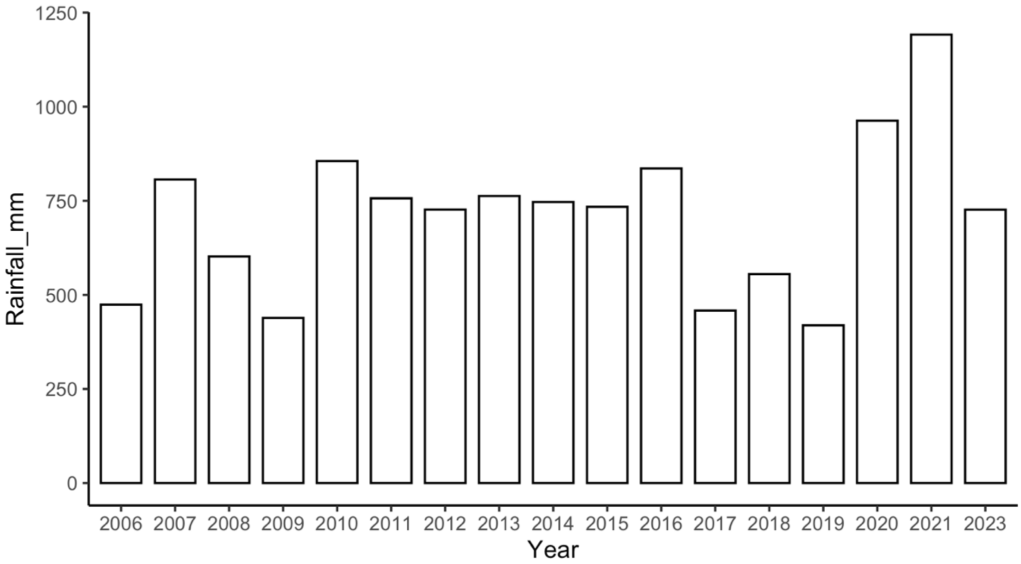

Figure 16: rainfall data for Braidwood, ~25 km from Mulloon Creek. 2017, 2018, and 2019 are markedly drier than previous years. 2020 and 2021, on the other hand, are much wetter. Data source: Bureau of Meteorology (2024). Generated using R (Package: 'ggplot2').

4.2. Indigenous Knowledge

The Mulloon Catchment is situated on the intersection of multiple Aboriginal Countries (Carolyn Hall , personal communication, 2024; Peter Hazell, personal communication, 2023). At the time of writing, elders of Yuin Country are the most involved in the Mulloon Institute's projects (Carolyn Hall, personal communication, 2024; Peter Hazell, personal communication, 2023).

In our study, we described our plant groups of interest based on discussions with local landholders and members of the Mulloon Institute (section 2.3.), but we did not communicate with elders of Yuin Country. We recommend that future researchers consult Indigenous Elders on common plants and animals in their study regions, how floral and faunal communities have changed over time, and how the geomorphology of rivers and streams have changed over time.

The perspective of Indigenous Peoples on these issues is vital to both environmental and cultural preservation.

4.3. State-transition Models

Peel et al. (2022) defines 3 main states of riparian ecosystems in the catchment: pre-colonial, current, and desired. They also mentioned the possibility of intermediate states but did not describe these. We recommend a conceptual model that includes at least 5 states:

1. Pre-colonial: chain of ponds, wetlands, and other speculated historical features
2. Degraded: barren, incised, lacking vegetation, low water levels
3. Weir present: barren, but with leaky weirs present and higher water levels
4. Weir vegetated: leaky weirs are covered in vegetation, surrounding landscapes may still be barren
5. Desired: well-vegetated banks, abundant in-stream vegetation, high water levels

We think these definitions suitably account for the possibility of structural failure in leaky weirs (transition from 3 to 2), as well as unsuccessful revegetation efforts (transitions from 4 to 3, and 5 to 4). To involve local landholders in restoration projects, we can ask them to evaluate waterways on their properties periodically (on a weekly basis, for instance), based on this 5-stage model. We can do this through online surveys, questionnaires, or interviews. Over the course of many years, we can form a probabilistic model using Markov Chains to predict how systems in the catchment will behave in the future. This will help identify the most challenging stages in restoration efforts, so land managers can better direct funding and monitoring efforts. Markov Chains have been used to model plant succession (Samuels, 2001), and they may be suitable for predicting revegetation processes as well. Rigorous, consistent data collection and a clear description of each transition state are necessary prerequisites for the success of this method.

5. Project Summary

We found different plant assemblages growing around leaky weirs than in other sections of the creeks we surveyed. In particular, we saw a marked increase in wetland plants in sites with leaky weirs, both upstream and downstream, when compared to sites without leaky weirs. We attribute this in part to revegetation efforts, and in part to improved hydrological conditions created by the weirs.

On the other hand, we saw no significant improvement in habitat condition around leaky weirs. We think that vegetation structural complexity is influenced more by historical management and land use than by recent policies and interventions. We think that any effects leaky weirs might have on it will only be seen many years into the future.

Though our study so far has painted leaky weirs in a positive light, we will conclude it with words of caution. Low replication at the catchment level means that our results may not hold for all, or even most, creeks and rivers in Eastern Australia. To better understand how these structures affect riparian ecosystems, we need more landscape rehydration trial projects in different catchments under different climate conditions. While we have shown that leaky weirs can create favourable conditions for wetland plants, we do not know how they impact animal communities, and have only a basic understanding of how they influence geomorphological processes. We think that a higher abundance of macrophytes is beneficial to fish and macroinvertebrates, but studies in the past have found that retention structures can negatively affect sediment transport and decrease the number of natural riffle pool habitats in a river system (Salant et al., 2012). Depending on channel morphology and underlying geology, leaky weirs may even worsen downstream erosion and create homogeneous, clay-filled streambeds (Salant et al., 2012). Though we see no signs of this in Mulloon Creek, it is a topic that requires further study and a risk to be considered when planning to build retention structures in other waterways.

Finally, we emphasise that leaky weirs alone cannot bring back wetlands. Their influence on plant assemblages, though positive, is localised and limited. Responsible grazing regimes, riparian zone fencing, contour work, and tree planting efforts should occur in conjunction with the use of leaky weirs. Underlying economic and political factors such as rural development and the increasing demand for agricultural products also need to be addressed (Finlayson and Rea, 1999). Leaky weirs may benefit riparian vegetation, but they will not solve all our problems.

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6.1. General

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7. Appendix

Appendix Table 1 A: 12 survey locations referred to in chapters 2 and 4. When surveying plant assemblages (chapter 2), each of these 12 locations contained one upstream and one downstream survey site, making for a total of 24 survey sites. When surveying NDVI and NDWI values (chapter 4), we defined survey regions by a 92m buffer centred at an existing or planned leaky weir in each of these 12 locations, and included additional survey locations to represent older weirs, which are listed in Table 1B.

Survey Location (numbered from South to North, ascending)	**Transect number (from previous RARC surveys)**	**Treatment (weir/no weir)**	**Creek (Mulloon/ Sandhills/ Reedy)**	**Latitude**	**Longitude**
1	T18	weir	Mulloon	-35.243694	149.619205
2	T19	weir	Mulloon	-35.243553	149.621191
3	T21	weir	Mulloon	-35.228312	149.620263
4	T22	weir	Mulloon	-35.224654	149.622632
5	T23	weir	Mulloon	-35.219005	149.619395
6	T24	weir	Mulloon	-35.212024	149.621240
7	T25	no weir	Mulloon	-35.209580	149.621607
8	T28	no weir	Reedy	-35.202373	149.634033
9	T27	no weir	Reedy	-35.199993	149.630196
10	T44	no weir	Sandhills	-35.195451	149.629718

11	T43	no weir	Sandhills	-35.192303	149.627446
12	T42	no weir	Sandhills	-35.190820	149.625303

Appendix Table 1 B: An additional 12 survey locations, each marking the centre of a survey region for NDVI and NDWI surveys (chapter 4). We used these locations to represent older weirs and control sites in the south of the catchment.

Location name (as of 2024)	**Treatment (weir/no weir)**	**Creek (Mulloon/ Sandhills/ Reedy)**	**Latitude**	**Longitude**
Object 80	weir	Mulloon	-35.272637	149.591452
Object 12	weir	Mulloon	-35.276463	149.590218
Willy’s Ripl	weir	Mulloon	-35.289234	149.588271
Goldney’s Gate	weir	Mulloon	-35.278373	149.589032
Object 8	weir	Mulloon	-35.247302	149.616895
Triple Ponds	weir	Mulloon	-35.280886	149.589317
Object 83	no weir	Mulloon	-35.296969	149.589953
Object 98	no weir	Mulloon	-35.293501	149.591885
LM5.0	no weir	Mulloon	-35.335936	149.585656
LM10.0	no weir	Mulloon	-35.341663	149.585289
LM13.0	no weir	Mulloon	-35.344453	149.583921
Object 140	no weir	Mulloon	-35.344075	149.582129

Appendix Table 2 A: Rationale for the formation and inclusion of plant groups (chapter 2), with the main constituent genera of each.

Group name	**Main Constituent Genera**	**Reasons for Inclusion**
Acacia	*Acacia*	Indigenous to site; native woodland genera; currently widespread; actively managed
Leptospermum	*Leptospermum*	Indigenous to site; native woodland genera; currently widespread
Phragmites	*Phragmites*	Native wetland genera; currently widespread; indicative of swampy conditions; combats erosion; provides habitat for fish, frogs, and macroinvertebrates
Typha	*Typha*	Currently widespread; actively managed; indicative of swampy conditions; combats erosion; provides habitat for fish, frogs, and macroinvertebrates
Native Pasture Grasses	*Poa, Themeda, Eragrostis*	Indigenous to site; native woodland genera; currently

		widespread; actively managed
Ferns	*Pteridium, Blechnum*	Indigenous to site
Melaleuca	*Melaleuca*	Indigenous to site; native woodland genera
Wahlenbergia	*Wahlenbergia*	Indigenous to site; native woodland genera
Lomandra	*Lomandra*	Indigenous to site; native woodland genera, actively managed
Juncus	*Juncus*	Indigenous to site; native wetland genera; currently widespread; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Carex	*Carex*	Indigenous to site; native wetland genera; currently widespread; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Schoenoplectus	*Schoenoplectus*	Native wetland genera; currently widespread; indicative of swampy conditions; combats erosion; provides habitat for fish, frogs, and macroinvertebrates
Eleocharis	*Eleocharis*	Native wetland genera;

		indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Nymphoides	*Nymphoides*	Native wetland genera; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Cyperus	*Cyperus*	Indigenous to site; native wetland genera; currently widespread; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Rubus	*Rubus*	Currently widespread; actively managed
Salix	*Salix*	Currently widespread; actively managed; of high importance to local stakeholders
Populus	*Populus*	Currently widespread; actively managed
Ligustrum	*Ligustrum*	Actively managed; of high importance to local stakeholders
Rumex	*Rumex*	Currently widespread
Exotic pasture grasses	*Poa, Paspalum, Cenchrus,*	Currently widespread;

	Cynodon, Lonium	actively managed
Cytisus	*Cytisus*	Actively managed; of high importance to local stakeholders
Cirsium	*Cirsium*	Currently widespread; actively managed; of high importance to local stakeholders
Hypericum	*Hypericum*	Currently widespread
Echium	*Echium*	Currently widespread
Crataegus	*Crataegus*	Currently widespread; actively managed
Rosa	*Rosa*	Currently widespread
Malus	*Malus*	Currently widespread
Foeniculum	*Foeniculum*	Currently widespread
Myriophyllum	*Myriophyllum*	Indigenous to site; native wetland genera; currently widespread; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates
Vallisneria	*Vallisneria*	Indigenous to site; native wetland genera; indicative of swampy conditions; provides habitat for fish, frogs, and macroinvertebrates

Appendix Table 2 B: Notable exclusions from table A

Genera	**Reasons for exclusion**
Eucalyptus	Not currently widespread in survey sites
Casuarina	Not currently widespread in survey sites
Lantana	Not currently widespread in survey sites; very little management effort directed towards this genus

Appendix Table 3: Further information on key genera. Location labels are structured as (Label in our study; Label in previous RARC surveys). E.g. location 2 corresponds to the Mulloon Baseline RARC survey transect 19, and so is labelled (2; T19).

Genus	**Native Status (native/non-native)**	**Identification Confidence Level**	**Possibly Confused With**	**Locations Present (As labelled in this study; as labelled in previous RARC surveys)**
Acacia	Native	Very High	Other genera in the family Fabaceae	(3; T21), (5; T23), (6; T24), (7; T25), (1; T18), (2; T19)

Leptospermum	Native	High	*Melaleuca*	(9; T27), (4; T22), (3; T21), (6; T24), (5; T23), (1; T18), (2; T19), (7; T25)
Phragmites	Native	Very High	Other reeds	(4; T22), (1; T18), (2; T19)
Typha	Both native and non-native species present	Very High	Other reeds	(9; T27), (10; T44), (; T43), (; T21), (; T42), (; T24), (; T18), (; T19)
Poa	Both native and non-native species present	Low	Other genera in the family Poaceae	All sites
Ferns	N/A	N/A	N/A	None
Melaleuca	Native	Medium	*Leptospermum, Callistemon*	(9; T27), (3; T21), (4; T22), (7; T25), (1; T18), (2; T19)
Themeda	Native	High	Other genera in the family Poaceae	(1; T18), (2; T19), (6; T24), (11; T43)
Wahlenbergia	Native	Very High	Other forbs	(9; T27), (11; T43), (12; T42), (7; T25)
Lomandra	Native	High	Genera in the	(7; T25), (3;

			families Juncaceae, Liliaceae, and Cyperaceae	T21), (12; T42), (1; T18), (2; T19)
Juncus	Native	Medium	*Eleocharis, Schoenus, Schoenoplectus, Ficinia*	(1; T18), (2; T19), (3; T21), (4; T22), (5; T23), (6; T24), (7; T25), (9; T27), (8; T28), (12; T42)
Carex	Native	High	Other genera in the family Cyperaceae	(1; T18), (2; T19), (3; T21), (4; T22), (5; T23), (6; T24), (9; T27), (8; T28), (12; T42), (11; T43), (10; T44)
Schoenoplectus	Native	Medium	*Schoenus, Bolboschoenus, Eleocharis, Ficinia*	(1; T18), (2; T19), (3; T21), (4; T22), (5; T23), (6; T24), (7; T25)
Eleocharis	Native	Medium	*Juncus, Schoenus, Ficinia, Bolboschoenus, Schoenoplectus*	(10; T44), (1; T18), (2; T19), (3; T21), (4; T22), (5; T23), (6; T24), (7; T25)

Nymphoides	Native	Medium	Genera in the families Nymphaeaceae and Menyanthaceae	(1; T18), (2; T19), (3; T21), (4; T22), (5; T23), (6; T24), (7; T25)
Cyperus	Native	Very High	Other genera in the family Cyperaceae	All sites
Rubus	Non-Native	Very High	Genera in the families Rosaceae and Grossulariaceae	All sites
Salix	Non-native	Very High	Other deciduous trees	All sites
Populus	Non-native	High	Other deciduous trees	(9; T27), (11; T43), (3; T21)
Ligustrum	N/A	N/A	N/A	None
Rumex	Non-native	High	Other forbs	(9; T27), (8; T28), (3; T21), (6; T24), (12; T42), (5; T23)
Eragrostis	Both native and non-native species present	Low	Other genera in the family Poaceae	(12; T42), (11; T43), (6; T24), (12; T42)
Paspalum	Non-native	High	Other genera in the family Poaceae	All sites
Cenchrus	Non-native	Medium	Other genera in	All sites

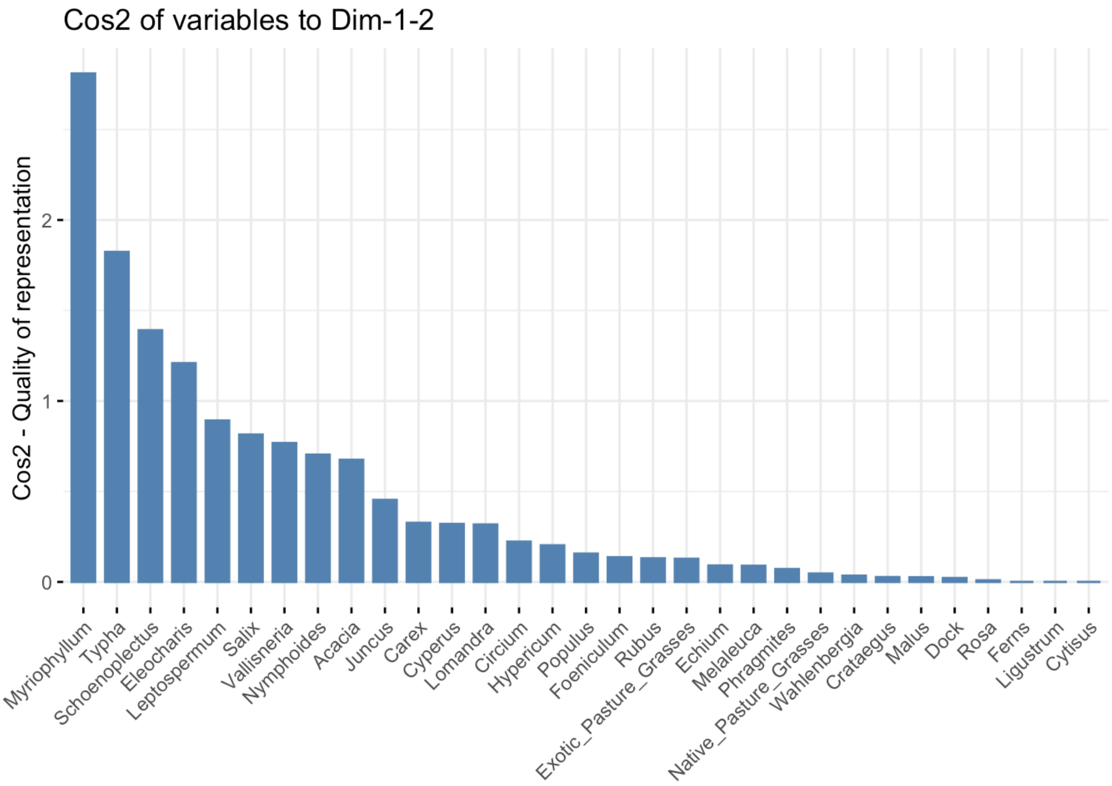
			the family Poaceae	
Cynodon	Non-native	Medium	Other genera in the family Poaceae	All sites
Lonium	Non-native	Medium	Other genera in the family Poaceae	All sites
Cytisus	N/A	N/A	N/A	None
Cirsium	Non-native	Very High	Other genera in the family Asteraceae	(9; T27), (10; T44), (11; T43), (3; T21), (4; T22), (12; T42), (5; T23), (6; T24), (7; T25)
Hypericum	Non-native	High	Other forbs	(10; T44), (11; T43), (12; T42), (2; T19)
Echium	Non-native	Very Low	Other genera in the family Boraginaceae	(4; T22), (5; T23), (6; T24), (7; T25)
Crataegus	Non-native	High	Other deciduous trees	(11; T43), (8; T28), (12; T42), (2; T19)
Rosa	Non-native	Medium	*Rubus*, *Crataegus*	(11; T43), (12; T42), (7; T25), (1; T18)
Malus	Non-native	Medium	Other deciduous	(3; T21), (2;

			trees	T19)
Foeniculum	Non-native	Very High	Genera in the families Apiaceae and Asteraceae	(9; T27), (10; T44), (3; T21), (12; T42), (2; T19), (1; T18)
Myriophyllum	Native	Very High	*Vallisneria, Hydrilla*	(9; T27), (8; T28), (3; T21), (4; T22), (7; T25), (6; T24), (5; T23), (1; T18), (2; T19)
Vallisneria	Native	Low	*Myriophyllum, Hydrilla*	(11; T43), (1; T18), (2; T19), (5; T23)

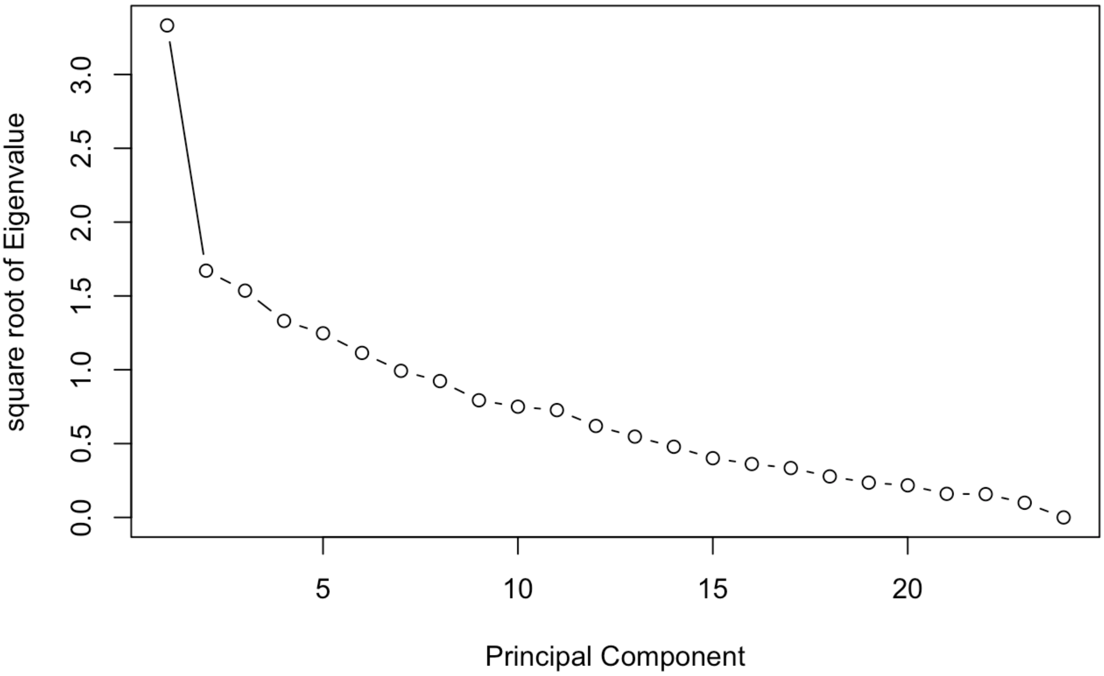
Appendix Table 4: The number of treatment and control RARC sites surveyed in the years 2017, 2019, 2021, 2024. Many of these sites were repeatedly surveyed. We used a mixed linear model to account for repeated measurements.

Year	**Number of Treatment RARC Sites Surveyed**	**Number of control RARC sites Surveyed**
2017	13	6
2019	13	36
2021	13	19

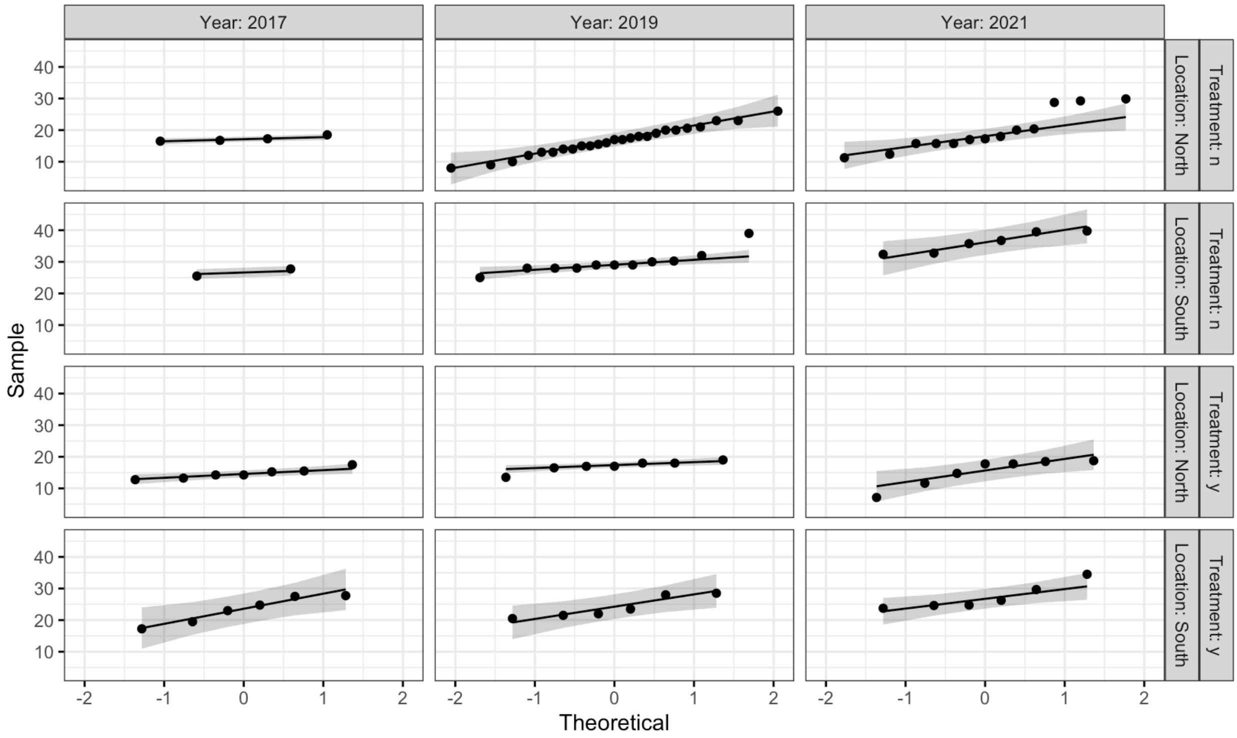
Total	39	61



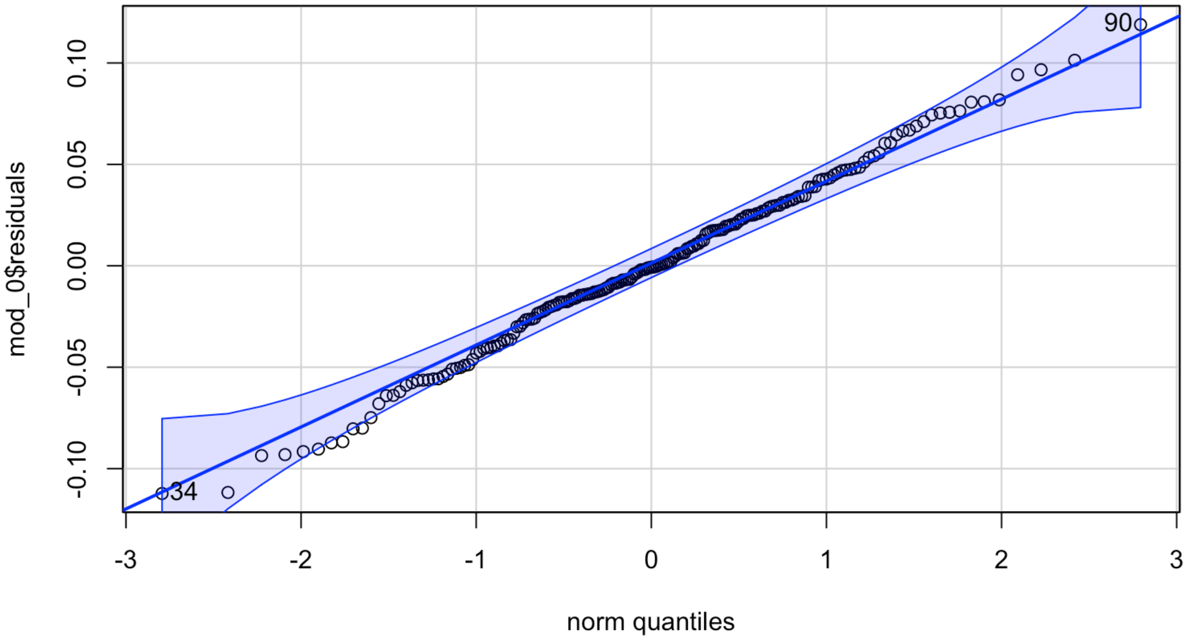
Appendix Figure 1: Contribution of plant groups to the first and second Principal Components. Myriophyllum, Typha, Eleocharis, *and* Schoenoplectus *were the highest contributors.*



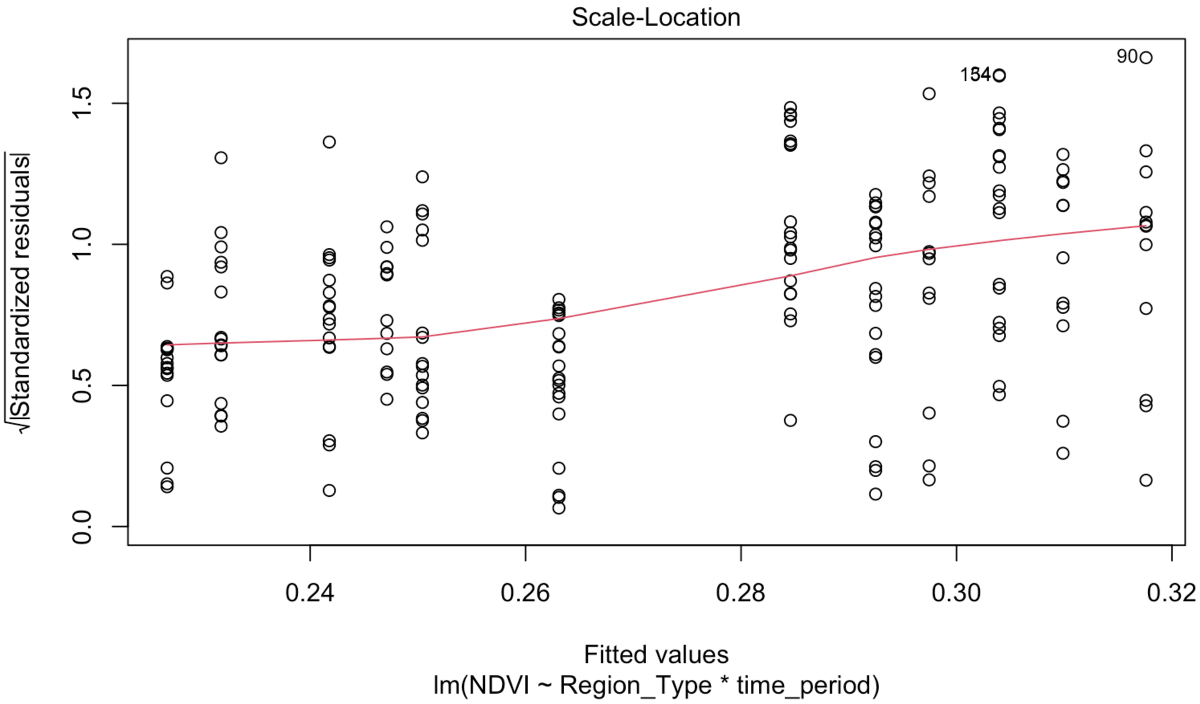
Appendix Figure 2: Square-root scree plot of Principal Components. We see a dramatic change in slope beginning at PC2. We disregarded subsequent principal components.



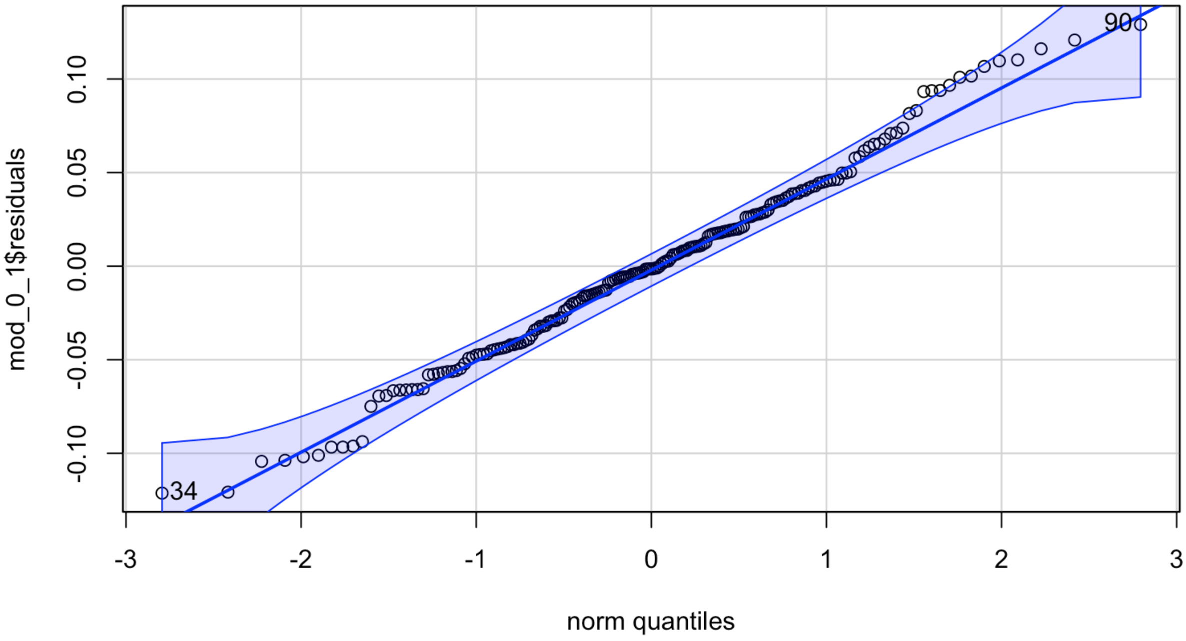
Appendix Figure 3: QQ-plot of residuals in RARC scores across 2017, 2019, and 2021. Residuals adequately met the assumption of normality.



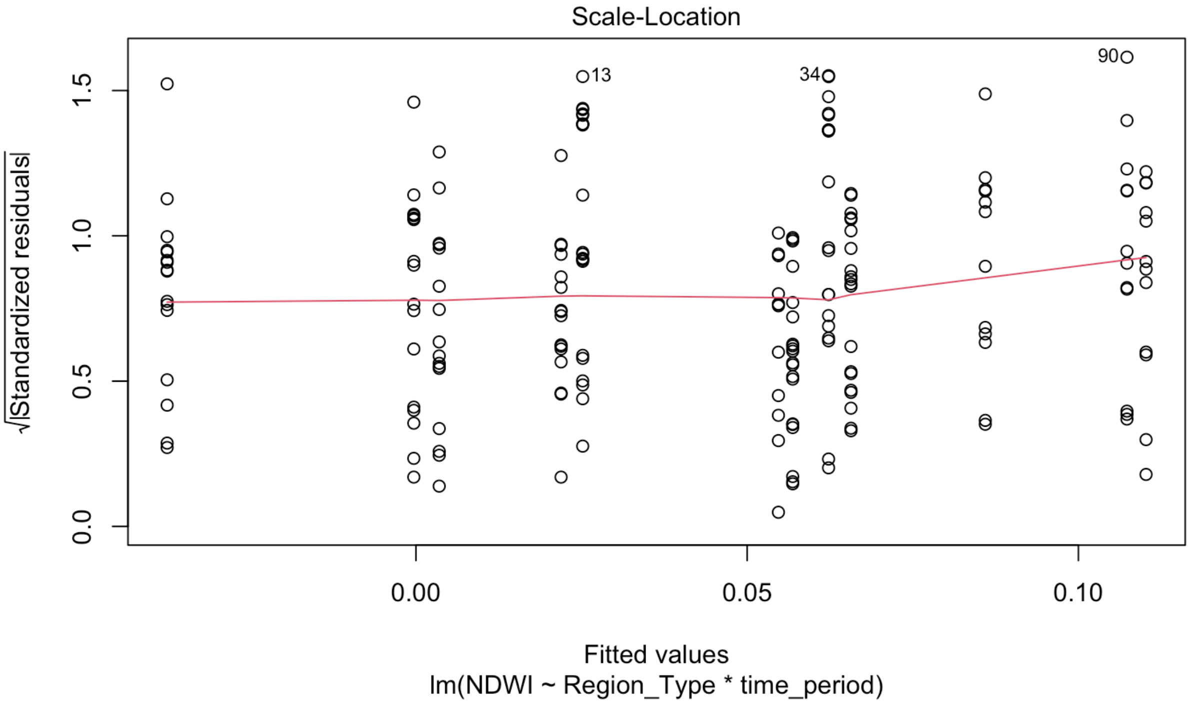
Appendix Figure 4: QQ-plot of residuals in NDVI scores from 2012 to 2024. Residuals adequately met the assumption of normality.



Appendix Figure 5: Scale-Location plot for NDVI values. The fitted line is roughly horizontal, and there are no clear patterns in residual distribution. Our data met the assumption of homogeneous variances.



Appendix Figure 6: QQ-plot of residuals in NDWI scores from 2012 to 2024. Residuals adequately met the assumption of normality.



Appendix Figure 7: Scale-Location plot for NDWI values. The fitted line is roughly horizontal, and there are no clear patterns in residual distribution. Our data met the assumption of homogeneous variances.

Conflicts of Interest:

Alex Sun conducted various surveys of the Mulloon Catchment in 2024. During this time, he was listed as a volunteer under the supervision of the Mulloon Institute.

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