Vegetation responses to managed river flow events and regimes

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Abstract

Vegetation communities are an important part of riverine ecosystems and can be severely impacted by changed flow conditions in regulated waterways, making them a priority for waterway management. Environmental flows are a commonly used tool to mitigate some of the impacts from regulated flow regimes and provide benefits to vegetation communities. Ongoing and effective use of environmental flows requires evidence of vegetation responses to managed flow events and regimes, yet few studies have demonstrated these responses in managed waterways.

We conducted vegetation surveys at 44 sites within seven major river systems across Victoria (Aus.) between 2016 and 2023. Vegetation cover and richness were sampled at a range of bank elevations impacted by different flows within each waterway. Surveys before and after flow events over multiple years enabled us to evaluate vegetation responses to flow events and regimes. Generalised linear mixed models were used to evaluate responses of richness and cover for four different plant functional groups (aquatic, emergent, riparian and terrestrial) within delimited flow elevation zones on the bank.

Our findings demonstrate that while individual managed and natural flow events may produce modest immediate vegetation responses, their cumulative impact over time can be substantial, increasing plant cover and richness that may support the resilience and stability of riverine systems. The effectiveness of environmental flows is highly influenced by context and a range of flow and non-flow variables. Short duration environmental flows with appropriate timing and duration benefit native aquatic, emergent and riparian species. Terrestrial species can benefit from flows but are the most sensitive to prolonged flow. Managers will also need to apply on-ground actions to enable ecological outcomes from flows in some cases.

1. Introduction

Riverine vegetation communities across the globe are experiencing severe degradation due to factors such as vegetation clearing, livestock grazing, pollution, proliferation of exotic plant species, and alteration of natural flow regimes (Dufour et al. 2019; Greet et al. 2019; Tickner et al. 2020; Vörösmarty et al. 2010). These pressures have led to significant declines in the integrity and functionality of riverine ecosystems. Effective management and restoration of riverine vegetation communities is now recognised as a critical priority for waterway managers worldwide (DEPI 2013; Dudgeon and Arthington 2019; MDBA 2020; Tickner et al. 2020; VEWH 2023). Vegetation is a priority not only because of the intrinsic ecological value of these communities and species, and their social and cultural values to humans, but also due to the essential ecosystem services they provide, including erosion control, water quality improvement, flow regulation, habitat provision for terrestrial and aquatic species, pollination support, and microclimate (e.g. light and temperature) stabilisation (Capon and Pettit 2018; Riis et al. 2020).

River regulation has profoundly impacted the population dynamics of riverine plant species, affecting processes such as longevity, recruitment and dispersal (Greet et al. 2011; Poff et al. 1997; Stromberg et al. 2007). To counteract these impacts, environmental flows have become a widely used tool in regulated waterways, involving the deliberate release of water from reservoirs to achieve specific ecological outcomes (Arthington et al. 2023; Overton et al. 2014; Wineland et al. 2022). For riverine vegetation, the benefits of individual environmental flow events can include increased native plant growth, the triggering of recruitment events and increased seed dispersal (Greet et al. 2024; Greet et al. 2013, Gomez-Sapiens et al. 2020). Large and long-term benefits are likely to be encountered when the individual events are incorporated into regimes within an adaptive management framework that provide cumulative benefits to the riparian community over time (Foster et al. 2018; Friedman et al. 2022; Arthington et al. 2023). Riverine vegetation communities that maintain higher native plant cover and species diversity are more likely to withstand periodic disturbances such as drought or floods (White and Stromberg 2011). Consequently, environmental flow delivery as part of the broader flow regime is likely to enhance long-term resilience.

Given the growing competing demands on water resources, particularly in regions experiencing a warming and drying climate, it is becoming increasingly important to evaluate responses to environmental water to continually improve and adapt environmental flow management to maximise its effectiveness (King et al. 2015; Arthington et al. 2023). However, evaluating the effects of environmental flows on riverine vegetation is inherently complex, and it can be particularly difficult to attribute ecological changes to environmental flow management (King et al. 2015; Arthington et al. 2023). Evaluation requires the assessment of isolated impacts of specific flow events (short-term responses) as well as the impacts of successive flows (environmental or otherwise) within the broader flow regime (medium- to long-term responses). Data collection needs to be repeated at relatively short intervals to capture the effects of specific flow events, but continued over consecutive years to capture variability in vegetation responses and cumulative impacts to sequences of flow events (King et al 2015). Evaluation should also consider the relative importance of environmental flows in comparison to other key factors that can affect vegetation, such as rainfall, livestock grazing, soil properties, the presence of exotic plant species and historical disturbances (Lester et al. 2020; Nicol et al. 2021; Campbell et al. 2023; Good and Jones 2024).

Environmental flows are used within many waterways of southeastern Australia to improve vegetation communities that are degraded via regulation. Objectives for vegetation outcomes vary in detail among waterways and regions but generally aim to improve riverine vegetation communities by increasing propagule dispersal (Greet et al. 2024), stimulating plant germination and recruitment opportunities (Tonkin et al. 2020; Pereira et al. 2021), increasing water resources for plant growth (Tonkin et al. 2020; Deng et al. 2024), and reducing competition from terrestrial plants that are less-tolerant of inundation (Greet et al. 2013; Miller et al. 2013; Vivian et al. 2020). Confirmation of these individual mechanisms in small case studies, ex-situ experiments, and expert-elicited data (e.g. Greet et al. 2023; Main et al. 2023, Nystrand et al. 2024) provides some support for existing management strategies. However, these studies need to be complemented with field data on flow responses and the influence of non-flow factors in both the short- and long-term (King et al. 2015; Arthington et al. 2023).

In this study, we aim to evaluate vegetation responses to environmental water management and to use this information to inform water management practices for vegetation outcomes. The study aims to address the lack of empirical data on vegetation responses to environmental flows, which are currently used to achieve high-level management objectives. The data come from eight years of monitoring vegetation responses to environmental flows across waterways in south-eastern Australia. Standard vegetation attributes of cover and richness were used to characterise vegetation communities. Our specific objectives were to: 1) describe detailed vegetation trends associated with environmental flows across different seasons, plant position on banks (elevation), and plant functional groups; 2) quantify vegetation responses to broader flow regimes and individual flow events while accounting for factors such as plant origin (native/exotic) and livestock grazing presence; 3) provide evidence-based recommendations for water management in regulated rivers to optimise ecological outcomes; and 4) understand the data and analytical constraints and opportunities provided by the dataset to inform future monitoring and evaluation. We hypothesized that native vegetation cover and species richness would increase in response to environmental water management, with increases being largest for plant groups with greater preference or tolerance of inundation in the bank zones inundated by environmental flows (Wijepala et al. 2026).

2. Methods

2.1. Study area

Our study area encompassed seven major river systems in the state of Victoria, Australia (Figure 1). The climate of the study area is varied, ranging from temperate in the south to semi-arid in the north and west. Waterways in the north and west are part of the Murray-Darling Basin (MDB) while the southern systems that flow to the south are part of coastal catchments that drain into Bass Strait. Average annual rainfall ranges from 200-300 mm in the north-west to over 1,000 mm in the east (Bureau of Meteorology 2023). Most environmental water is delivered in waterways located in the drier northern catchments of the study area within the MDB. The seven river systems include most major, lowland regulated systems in Victoria below storage reservoirs from which environmental water is released.

Forty-four sites were surveyed across 20 river reaches. Criteria for site inclusion included high priority areas for waterway managers, site accessibility, and a spread of sites across different climatic regions (Tonkin et al., 2020). All sites occur within landscapes largely cleared for agriculture or residential areas but have a narrow strip of remnant native vegetation along the water frontage (e.g. generally 10-50 m). At most sites, the natural vegetation type is floodplain riparian forest, dominated by *Eucalyptus* *camaldulensis* subsp. *camaldulensis* (River Red Gum), one of the subspecies of Australia's most widespread riparian tree.

Prior to river regulation, flow regimes across all seven surveyed river systems would have consisted of high flows in winter and low flows in summer. However, contemporary summer flows are artificially elevated due to regulated flow releases from reservoirs for irrigation, while winter flows are reduced due to flow capture and storage. While many of the systems are naturally intermittent, the regulated flow regimes are predominantly perennial except for several reaches in the Wimmera system that have intermittent or ephemeral regulated flow regimes.

Surveys were conducted between 2016 and 2023. In late 2022, the wettest spring on record for Victoria resulted in widespread flooding across all the surveyed river systems, with record flood peaks experienced in several of the surveyed rivers (Bureau of Meteorology 2023).

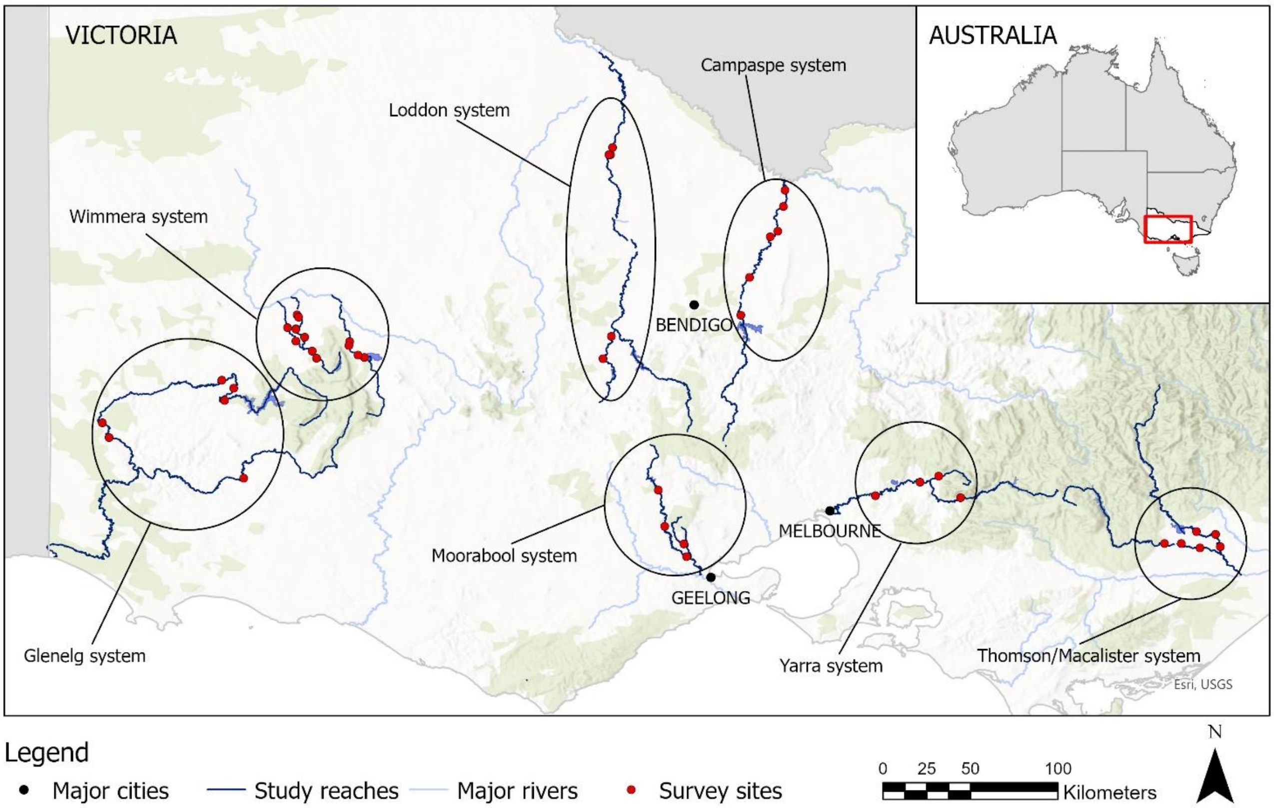

Figure 1. Study sites and associated river systems within the state of Victoria, Australia.

2.2. Survey methods

2.2.1. Vegetation surveys

At each of the 44 sites, five to ten permanent transects were established perpendicular to the flow of the river running from the low-flow water margin (bank toe) to a bank elevation position known or believed to be above the highest point that managed flows reach. Due to different channel forms (e.g. bank steepness) and stream orders, the lengths of transects varied within and between sites (range: 2–21 m). On each transect, a series of 4 m long sub-transects were positioned every metre, perpendicular to the transect (i.e. parallel to the waterway). Longer transects contained more sub-transects and so the number of sub-transects varied within and between sites (Appendix A, Table A1).

For very long transects (>10 m), the sub-transects were spaced at 2 m intervals after the first 5 m. Along each sub-transect, point-intercept samples were taken at 10 cm intervals (i.e. 40 per sub-transect) to record both the substrate type (water, bare ground, log, rock, litter) and the species identity of any plant that occupied the vertical point-intercept space, up to 5 m from the ground.

Livestock grazing was recorded as present (n=9) or absent (n=35) at each site. The identity of the livestock (sheep or cattle) was recorded but no data on stocking densities or durations were available. Grazing presence did not change substantially over time at any site.

2.2.2. Survey timing

Surveys were timed to occur before and after specific environmental flow deliveries (e.g. high flows or freshening flow pulses [‘freshes’]) or natural flow events (e.g. floods) within each system. Specific timing varied but was generally within 3 weeks before an event and approximately 8–12 weeks after an event to allow time for recruitment and growth responses (DELWP 2017; Webb and Morris 2019). In any single year, a site was typically surveyed three times: in early spring before a spring fresh or high flow, in summer between a spring and summer fresh, and in autumn after one or more summer freshes. Between 2016 and 2023, each site was surveyed between three and 16 times, totalling 263 site surveys (Appendix A, Table A1). Some sites had surveys undertaken in one year only (i.e. three surveys timed around one spring and one summer fresh) while others had surveys undertaken across multiple years. These different survey frequencies were due to funding variability between years. Additionally, freshes or high flows were not always delivered in all years in all sites; for example, the spring 2022 floods negated the needs for environmental flows in many waterways.

2.2.3. Bank elevation

The elevation of each sub-transect was determined using a high accuracy Trimble Geo7X with post-processing of point aggregates. Elevation surveys were conducted during the first year of vegetation data collection for each system. Bank geomorphology was considered relatively stable throughout the majority of the study until the flooding events at the end of the survey period, which impacted some transects. Horizontal and vertical accuracy was generally <10 cm. Elevation of water levels were also recorded to validate and calibrate elevation data for vegetation and flow levels.

2.3. Hydrological data

Continuous stream flow elevation was used to develop hydrology metrics for individual flow events or regimes. Flow elevations for each site were estimated by various methods depending on the available data and available funding. Data sources used included:

1. Logger data: Data collected at half of the field sites from Troll loggers for short periods of time (up to two years between 2017 and 2020). Loggers were levelled into Australian Height Datum (AHD).
2. Water Measurement Information System (WMIS) data: Hydrographic data collected under Victoria’s Regional Water Monitoring Partnership (accessible via http://data.water.vic.gov.au/).
3. Water Data Online: Hydrographic data sourced from the Bureau of Meteorology (BOM) (accessible via http://www.bom.gov.au/waterdata/).
4. Melbourne Water: Hydrographic data collected by Melbourne Water (accessible via https://www.melbournewater.com.au/water/rainfall-and-river-levels#/).
5. Southern Rural Water (SRW): Hydrographic data.
6. AHD and Zero Gauge Height (ZGH) values from sources above or collected directly from the site.

Data quality varied among sites due to differences in sources, but the highest quality data for all sites were extracted from existing data sets and then reviewed and quality-checked by a hydrological consultant. For each site surveyed, flow data were compiled, and an output of flow level (elevation in AHD) was produced at regular intervals (interval time depending on data inputs but was at least once daily).

2.4. Aligning hydrological and bank elevation data

High-accuracy Global Positioning System (GPS) points were required for bank elevation survey locations and flow elevation in this study. The data sources differed, so calibration of datasets was required to ensure compatibility. In all cases, the GPS data sources were calibrated to the levels of the vegetation survey bank elevation locations so that flow data and vegetation data align. Not all bank elevation locations were able to be matched to flow elevation data because of a lack of critical flow information at some sites. Consequently, we were unable to evaluate flow hydrology treatments for these sites.

2.5. Data analysis and modelling

2.5.1. Species trends and patterns

While most of the results have been presented for functional groups to aid generalisation across a large study area containing hundreds of species with differing distributions, we initially present a summary of important vegetation patterns at the species level to demonstrate the data underpinning the models. We summarised patterns in species abundance in relation to bank elevation as well as trends in abundance over time in relation to flow regimes using example species that are widely distributed across the study area and are highly typical species of their respective functional groups.

2.5.2. Response variables

Native plant cover and species richness were used to characterise vegetation communities. These variables are the most commonly used for describing plant responses and they align with the broad objectives to sustain or increase plant communities. For the bulk of the analysis and modelling, plant species were classified by functional group to enable pooling data across sites and generalisation of outcomes. Our classification consisted of four groups which we hereafter refer to as functional groups: aquatic (including submerged and floating species), emergent, riparian, and terrestrial, which matches terminologies in waterway management frameworks used in southeast Australia (e.g. VEWH 2021) and other similar studies used to evaluate vegetation responses to environmental flows (e.g. Tonkin et al. 2020; Jones et al. 2025). This plant grouping based on commonly used and clearly defined attributes enables an assessment of how plant communities are responding to environmental flows as specified in objectives. A full list of species and their classifications is provided in the data and code repository, see Appendix A, Table A2 for a summary of the most common species within each group.

Several aggregations of cover were tested during a Pilot Study. Initially, we assessed individual species cover. Projected foliage cover (percentage) was estimated for each species in each sub-transect as the percentage of hits per 40 points. Subsequently, cover within groups was assessed by summing the hits by species and estimating cover as a percentage of hits per 40 points. The summed cover allows cover values within a group to exceed 100% where plants overlap each other (separated into native and exotic species groups). Species richness within functional groups was estimated as the number of unique species per functional group (separated into native and exotic species) recorded at a sub-transect.

2.5.3. Predictor variables

Analyses included a set of predictor variables intended to characterise flow regimes, flow events, and other factors influencing spatial and temporal variation in plant species cover or occurrence. Flow events and bank zones are clearly defined in our study systems because managed flows are delivered relatively consistently between years. We classified flow events based on their depth, duration, and timing, but did not distinguish natural from managed events because they were expected to have similar responses. The predictor variables used were:

- Flow regimes: characterised by the number of days per year (averaged over the preceding three water years) where discharge exceeded baseflow or spring-fresh levels (z-scaled prior to analysis to facilitate comparisons between sites), resulting in two regime metrics (days above baseflow, and days above spring fresh per year).
- Flow events: the 'sampling period' defined by the survey timing in relation to an event (before a spring fresh, between a spring and summer fresh, after a summer fresh) that enable a before-after comparison for each event type.
- Zone: bank position in which a sub-transect occurred (below baseflow level, between baseflow and spring-fresh level, above spring-fresh level).
- Functional group: categorising preferred inundation tolerances (aquatic, emergent, riparian, terrestrial)
- Origin: differentiating indigenous from introduced species (native or exotic)
- Grazing: site grazing status by livestock (grazed or ungrazed)
- System: names for connected sets of waterbodies (e.g. tributaries) and waterways.

The identity of sites and transects (nested within sites), sub-transect height (metres above baseflow), survey year, and system/waterbody (to group spatially connected sites) were included in analyses to account for otherwise unexplained spatial and temporal variation in plant cover and species richness. See Appendix B Table B1 for a complete list of model variables and their description, units, modelling variable type and grouping.

2.5.4. Adaptive preregistration and model development process

The analysis structure and workflow were developed as part of a study of adaptive pre-registration in ecology (Gould et al. 2025). Adaptive preregistration is an open-science approach to minimise questionable research practices and ensure reproducibility and robustness of research findings, while enabling flexibility given the highly variable nature of ecological data (Powers & Hampton 2018, Wood et al. 2020) and the iterative nature of the model development process (Augusiak et al. 2014, Jakeman et al. 2006). The workflow is described by a series of proposed analyses and decision points, with explicit decision criteria to guide choices at each stage. We used the ecological modelling preregistration template (Gould et al. 2024) to preregister the analysis and modelling for this study[1]. The study design is underpinned by a thorough conceptual model of ecological processes that are used to justify the study purpose, design, target response and predictor variables, derivation of variables, and constraints as a core element of the preregistration.

Adaptive Preregistration of model development and analysis occurred across three distinct stages (Table B2, Figure B1), with two interim preregistrations (Version 1 and Version 2) preceding the final preregistration (Version 3). Each preregistration version corresponded to distinct phases in the model development process. Two candidate models were initially preregistered (Version 1, Table B2, Figure B1), one for each vegetation response variable, however there was uncertainty around whether the data could support the desired models due to low sample sizes relative to the complexity and spatio-

[1] The final version of the preregistration is available through GitHub (sign in required) and located at https://github.com/egouldo/VEFMAP_VEG_Stage6/blob/master/analysis/preregistration_template.md

temporal patchiness of the data. Based on preregistered exploratory analysis (Version 1), we therefore preregistered and conducted a pilot study (described below, but see also Table B2, Figure B1) to resolve critical uncertainties in model specification and determine the feasibility of different model structures. From the pilot study, we derived and preregistered a set of preferred candidate models for fitting to the full dataset, as well as a candidate set of simplified models and decision-trees for triggering their fitting and acceptance should the preferred model specifications fail to converge or provide appropriate parameter estimates. Results from the pilot analysis informed subsequent preregistration of the Main Analysis on the full dataset (Version 3).

The process shifted a lot of the thinking and trouble shooting from later parts of the analysis to prior to the analysis, ensuring that all initial designs and processes were tied directly to the project objectives and followed a logical and transparent workflow. Preregistration of the Pilot Study and then the final analysis allowed flexibility within the design process that maintained transparency while enabling clear decision points based on unknown outcomes of the pilot analysis – given the large dataset and complex model structure.

2.5.5. Pilot study

The final data set comprised 42,356 non-zero observations for cover and 31,084 non-zero observations for species richness, across approx. 12,000 replicate sub-transect surveys. In addition, exploratory data analysis (preregistration version 1, Table B2) revealed considerable zero-inflation and potential over-dispersion of the response variables, particularly vegetation cover. To address this, we defined a maximal model structure and tested this structure with a pilot data set (all observations from the Campaspe River from 2017–2020) to identify feasible model structures and likely decision points. We developed separate analyses for vegetation cover and species richness, with the same maximal model structure for both. The maximal model structure was (in high-level, R mixed-model notation):

```
response (cover or species richness [multiple aggregations tested]) ~ cover in previous survey +
        functional group × origin × flow metrics +
        functional group × origin × zone × sampling period +
        grazing +
        (1 | site / transect) + (1 | sub-transect height) + (1 | survey year) + (1 | system) +
        offset(number of points).
```

Most variables are described above but see Appendix B for full descriptions. Vegetation cover in the previous survey was included only for analyses of cover and meant that models of vegetation cover examined how flow influenced the change in cover through time, rather than absolute vegetation cover (akin to models of population growth rate used for the long-term modelling of fish populations in Victorian rivers (Tonkin et al. 2024)). Flow regime was included with both linear and quadratic associations. System was excluded from the pilot study given the use of date from a single waterway (the Campaspe River). Results of the pilot study informed subsequent analyses.

2.5.6. Main Analysis

Based on the pilot study results, we preregistered the following modelling strategy (Version 3, Table B2, Figure B2):

1. Refit the maximal models for each response variable as described above in 2.5.5.
2. Following pre-specified decision-trees, should maximal models fail to converge or provide appropriate parameter estimates, fit model from a candidate set of simplified models (preregistration pp.20-21).

3. Simplified models separately capture different flow components for each response variable. For vegetation cover, two versions of the flow events model were specified (Flow event models A & B, Figure B1).
4. A second flexible strategy for determining model functional form (Figure B2) and to account for potential over-dispersion was preregistered based on the pilot study finding that the data distributions in the full dataset did not match expectations informed by the pilot analysis.

Maximal models failed to converge on the full dataset, consequently we fitted the preregistered candidate simplified models. Candidate simplified models of vegetation cover and species richness focused on functional groups as opposed to individual species because these supported model structures closest to the maximal structure. We systematically re-assessed interactions in the maximal models within the candidate simplified models based on the expectations that additional data would either support more-complex model structures, or else introduce additional heterogeneity (and, therefore, support less-complex model structures) than in the pilot study. This unregistered analysis did not include re-assessment of the functional group classifications. The complexity of the fitted model and data precluded interactions between species origin or grazing and functional groups or zone.

Posterior predictive checks indicated that a zero-inflated Poisson distribution reliably captured the distribution of observed vegetation cover within functional groups and a Poisson distribution (without zero-inflation) reliably captured observed distributions of species richness (results not shown, see Appendix C for checking of full models). Models of cover had excess over-dispersion, but a zero-inflated negative binomial distribution did not substantially reduce unmodelled over-dispersion and resulted in worse characterisation of zero-inflation and the observed distribution of cover data (results not shown). Therefore, subsequent models of vegetation cover and species richness assumed that data were derived from a Poisson distribution, with additional parameters for zero-inflation specific to each functional group in the case of vegetation cover.

2.5.7. Analysis of vegetation cover

The full data set supported a slightly more complex model than identified in the pilot study, with this model including the three-way interaction between zone, sampling period, and functional group. However, separate models were still required for flow metrics and categorical flow terms (zone and sampling period). We defined the model with flow metrics as the flow-regime model, which examines how realised flow conditions over the preceding three years influence vegetation cover within each functional group and had the following structure:

```
functional group cover ~ cover in previous survey +
      functional group × (days above baseflow + days above spring fresh) +
      functional group × (days above baseflow^2 + days above spring fresh^2) +
      origin +
      (1 | site / transect) + (1 | sub-transect height) + (1 | survey year) + (1 | system) +
      offset(number of points)
```

Similarly, we defined the model with categorical flow terms as the flow-event model, which examines how vegetation cover in each zone changes before and after key flow events (spring and summer freshes) and had the following structure:

```
Functional group cover ~ cover in previous survey +
      functional group × zone × sampling period +
      origin + grazing +
      (1 | site / transect) + (1 | sub-transect height) + (1 | survey year) + (1 | system) +
```

```
        offset(number of points)
```

2.5.8. *Analysis of vegetation species richness*

As for cover, the full data set supported a more complex model than the pilot study, with all predictors included in a single model and a three-way interaction between zone, sampling period, and functional group. Quadratic associations with flow metrics were unable to be fitted at the functional-group level and were instead included as a single term for all functional groups. The final model structure was:

```
Functional group species richness ~ functional group × (days above baseflow + days above spring fresh)+
        days above baseflow^2 + days above spring fresh^2 +
        functional group × zone × sampling period +
        origin + grazing +
        (1 | site / transect) + (1 | sub-transect height) + (1 | survey year) + (1 | waterbody) +
        offset(number of points)
```

2.5.9. *Computational details and model performance*

All models were fitted using the glmmTMB R package version 1.1.8 (Brooks et al. 2017) in R 4.3.1 (R Core Team 2023). Comparisons were made between model outputs from the Pilot study (data from the one system with most data) and the full model across all systems. Model performance was evaluated using goodness of fit tests, indicated by Pearson's r^2 and posterior predictive checks. Thresholds for interpreting the model fit statistics were defined a priori in the preregistration of the study and are summarised as: < 0.25 is poor, 0.25 - 0.5 is moderate, 0.5 - 0.75 is good, 0.75 - 1.0 is excellent, but probably indicates overfitting. These thresholds are broadly consistent with many ecological studies, e.g., Thomas et al. (2019) and Hale et al. (2023), that indicate values over ~0.5 provide adequate to strong support. Posterior predictive checks were implemented with the performance R package version 0.10.8 (Lüdecke et al. 2021) and modelled associations were extracted with the effects R package version 4.2-2 (Fox 2003). The full set of packages used in the analysis for this study is described in Appendix D Model code, including version history and associated pre-registration documents is recorded on a private GitHub repository and will made available alongside manuscript submission.

3. Results

3.1. Model evaluation

Models for vegetation cover and species richness had moderate goodness-of-fit, with r^2 values (based on Pearson's r) of 0.54 for the flow-regime model of vegetation cover, 0.55 for the flow-event model of vegetation cover, and 0.32 for the model of vegetation species richness. Posterior predictive checks indicated that models were sufficiently capturing the distribution of observed data, including the high proportion of zero values in cover data, although with some evidence of mismatch for low and intermediate (but not zero) values of cover (Figures C1–C3 in Appendix C). Alternative model distributions did not improve model fit (results not shown), indicating high levels of heterogeneity in vegetation cover data.

3.2. General vegetation patterns

Species cover and richness varied among waterways and sites. Waterways with more sites generally had greater species richness totals (Appendix E, Table E1) due to species-area relationships. Overall, aquatic, emergent and riparian vegetation groups were dominated by native species, while the terrestrial group was dominated by exotic species (Appendix E, Tables E1 and E2). Waterways in higher rainfall regions (e.g. Macalister, Thomson, Yarra Rivers) had a higher prevalence of exotic species compared to natives, and lower abundance of aquatic and emergent species than waterways in lower rainfall regions (e.g. Loddon, Wimmera, Campaspe Rivers). The correlation with high rainfall could be a result of the increased water resources or factors at the system level, including plant traits, levels of disturbance, and neighbouring land use.

At the individual site and species level, there were clear patterns of distribution from low to high bank elevation that correspond with flow levels and events (Figure 2). The individual species patterns are informative for investigating trends and patterns that are reflected by the broader functional groups in the models. For example, at a site on the Campaspe River, the emergent *Phragmites australis* (Common Reed) was common from the baseflow to spring fresh level, the riparian *Juncus amabilis* (Hollow Rush) was common above the baseflow margin, the damp-tolerant terrestrial grass *Poa labillardierei* (Common Tussock-grass) was distributed around the spring fresh peak level, and the flood-intolerant exotic terrestrial herb *Oxalis pes-caprae* (Soursob) was largely restricted to elevations above the spring fresh. The dominant species varied among waterways (Appendix A, Table A2).

Trends over time for the three most abundant functional groups (emergent, riparian and terrestrial) show broadly increasing vegetation cover over the survey period for all three groups, within spring fresh zone targeted by elevated environmental flows (Figure 3). The increasing trends in this zone are indictive of a cumulative response to repeated management over consecutive years. In contrast, there was no apparent trend for any group above the spring fresh level or for riparian and terrestrial groups below the baseflow level. Emergent plants that more commonly occur on the river bed showed an increase in cover over the survey period. Terrestrial and riparian species were generally heavily impacted by the natural floods in late 2022, resulting in dramatic declines in 2023 (survey 16, Figure 3). However, the emergent species were only marginally impacted by the floods. The terrestrial group contained a large proportion of annual species and geophytes, and therefore showed strong seasonal abundance fluctuations (Figure 3).

Additionally, there were clear negative relationships between native and exotic species, where one was often able to outcompete the other (Appendix E, Figure E1). Most sites in the study area had terrestrial vegetation communities dominated by exotic species (e.g. invasive herbs and agricultural grasses), and the prevalence of exotic riparian species differed among sites and rainfall regions. This means that responses by native riparian species may be constrained by the increases in exotic species that exclude them.

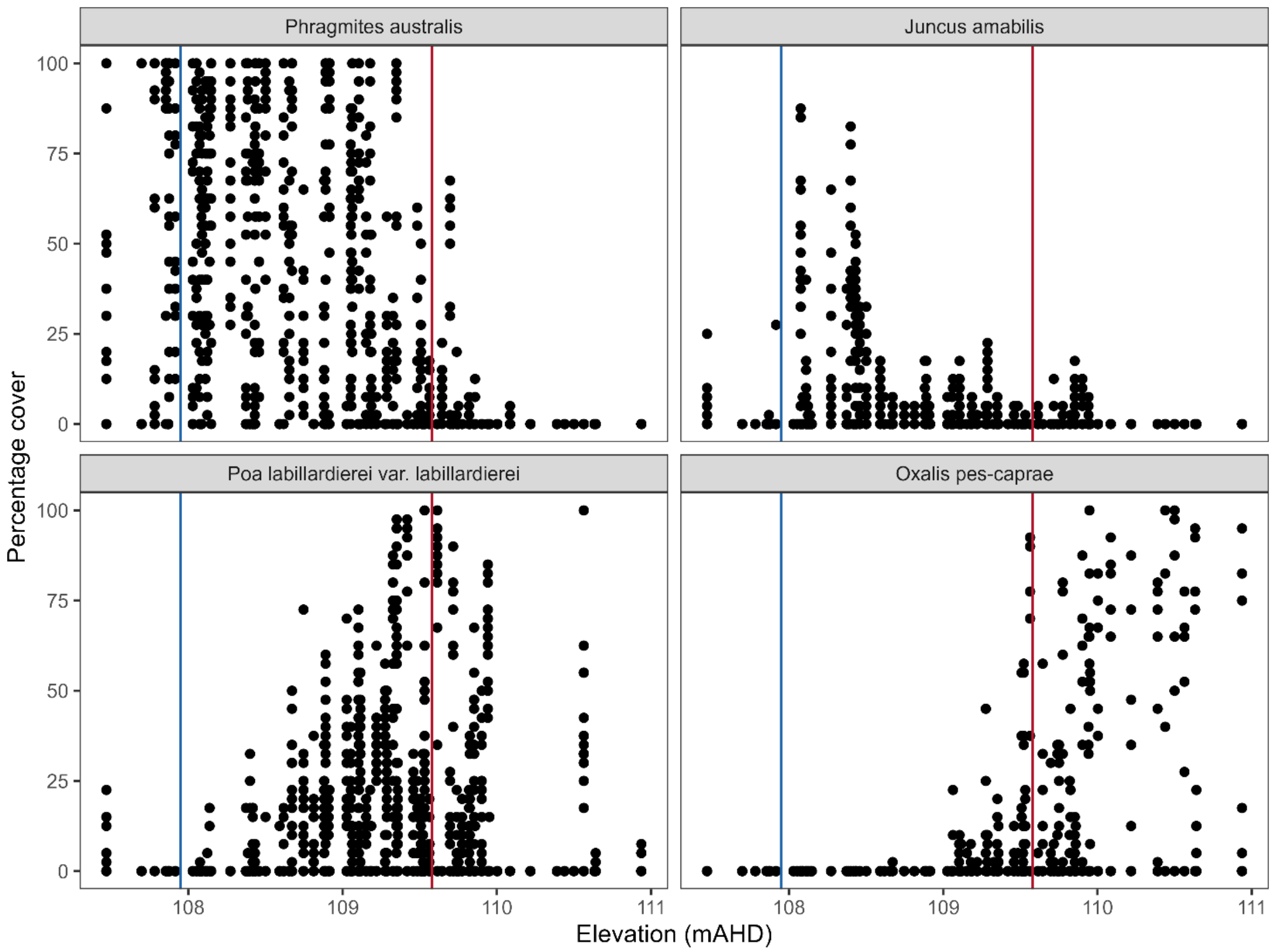

Figure 2. Four common plant species distributions in relation to elevation and flow events at a single site (Spencer) on the Campaspe River. Blue lines indicate the baseflow peak level, and red lines indicate spring fresh peak levels.

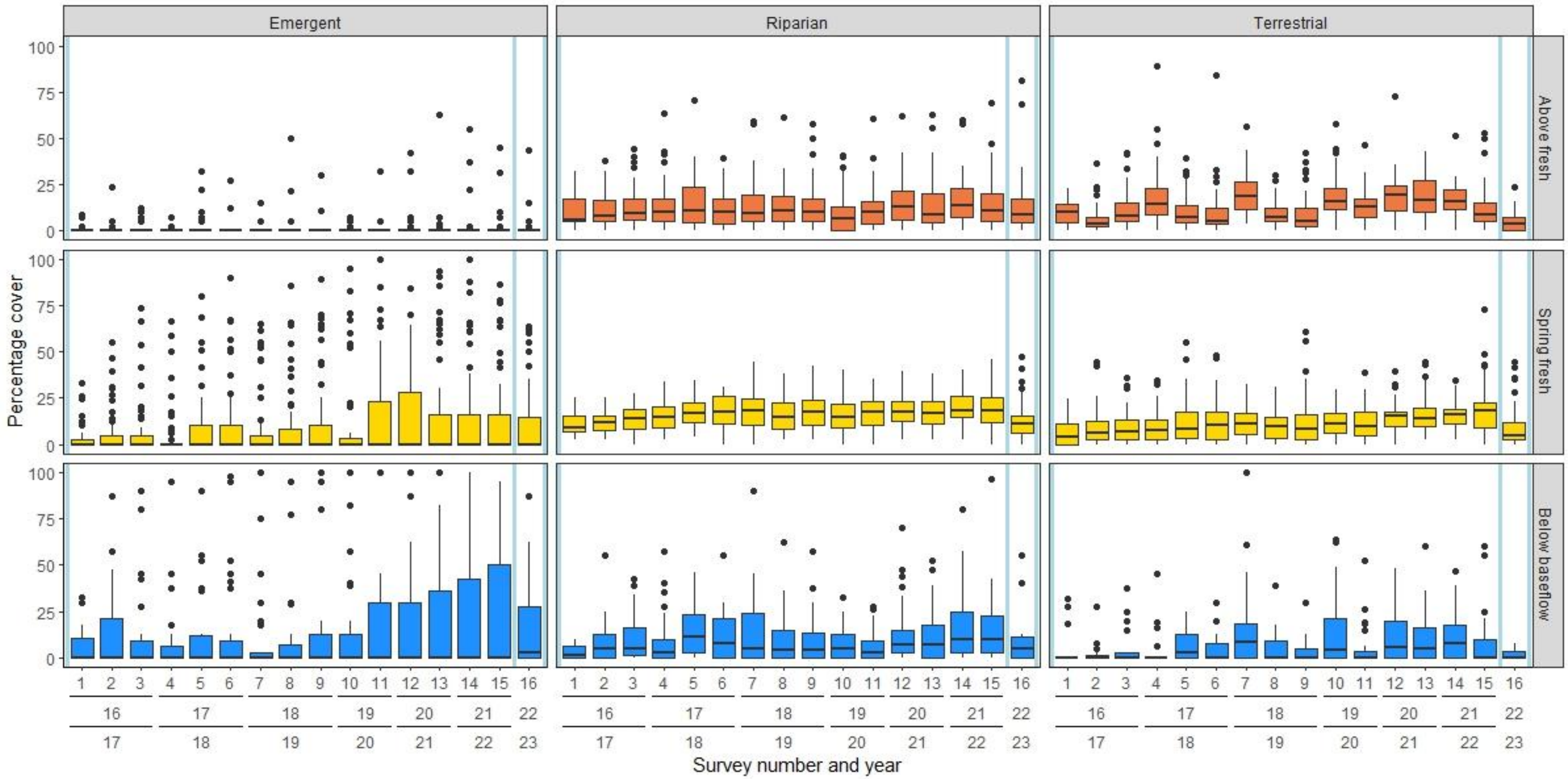

Figure 3. The abundance (as percentage cover) of all plants in three functional groups (emergent, riparian and terrestrial) within the three bank zones recorded during 16 surveys over the study period at all sites on the Campaspe River. Vertical lines indicate major floods. Boxplots show the median and the range between the first and third quartiles of the data, the whiskers extend up to 1.5 x the inter-quartile range.

3.3. Flow regime influences on plant cover and richness

Associations of plant cover with flow regimes (days above baseflow or spring-fresh levels over the prior three years) generally reflected negative effects of sustained baseflows, positive effects of short freshes (15–25 days), and negative effects of sustained, elevated flows (> 25 days per year above spring-fresh level) (Figure 4). These results implicitly consider the cumulative influence of flows and rainfall in prior years as opposed to event-based responses. Aquatic species differed most from the other functional groups, with evidence of positive associations with sustained baseflows (Figure 4a) and weaker associations with sustained, elevated flows (Figure 4b). The elevated cover of aquatic plants with few days above baseflow was a common outcome in sites where persistent shallow water provided ideal conditions for aquatic plants. Few sites in this study have long cease to flow periods, so the low flow systems typically had high cover of aquatic plants.

Species richness of functional groups showed peaked associations between species richness and the number of days above spring-fresh level, particularly for riparian and terrestrial species, indicating positive effects of elevated flows (above spring-fresh levels) for 10–30 days per year but negative effects when elevated flows were sustained for >30 days per year (Figure 5). Terrestrial species richness peaked at the lowest number of elevated flow days (~25), followed by riparian plants (~34) and then emergent (~38). Richness flow regime models identified negative associations between the number of riparian and terrestrial species and the number of days with discharge above baseflow level, with no clear evidence of associations between days above baseflow and the number of aquatic or emergent species (Figure 5).

Conditional on associations with flow regimes, variation in vegetation cover occurred primarily among sites, with less variation among systems, transects, sub-transect heights, and years (Appendix F, Figure F1). Residual variation among systems (i.e., variation at system level, but not explained by flow regimes) indicated generally higher-than-expected vegetation cover in the Moorabool and West Gippsland systems and average or slightly-below-average cover elsewhere (Appendix F, Figure F2). These two systems are both southern systems, but the Moorabool has relatively low local rainfall and flow compared to high rainfall and flow in West Gippsland. Cover of vegetation functional groups did not differ considerably between native or exotic species (Appendix F, Figure F3).

Variation in vegetation species richness for regime and event models was similar among systems, sites, transects, and sub-transect heights, with less variation among years (Appendix F, Figure F8). Residual variation among systems (i.e., variation at system level, but not explained by flow regimes) indicated generally higher-than-expected species richness in the Moorabool and (to a lesser extent) Yarra systems, average species richness in the Campaspe, Glenelg, and Wimmera systems, and lower-than-expected species richness in the Loddon and West Gippsland systems (Appendix F, Figure F9). Again, these system patterns do not follow a clear pattern of rainfall or climate, and the patterns of low or high richness can be driven by multiple factors such as high productivity leading to high diversity or competitive exclusion; with low productivity leading to lack of resources or reduced competition.

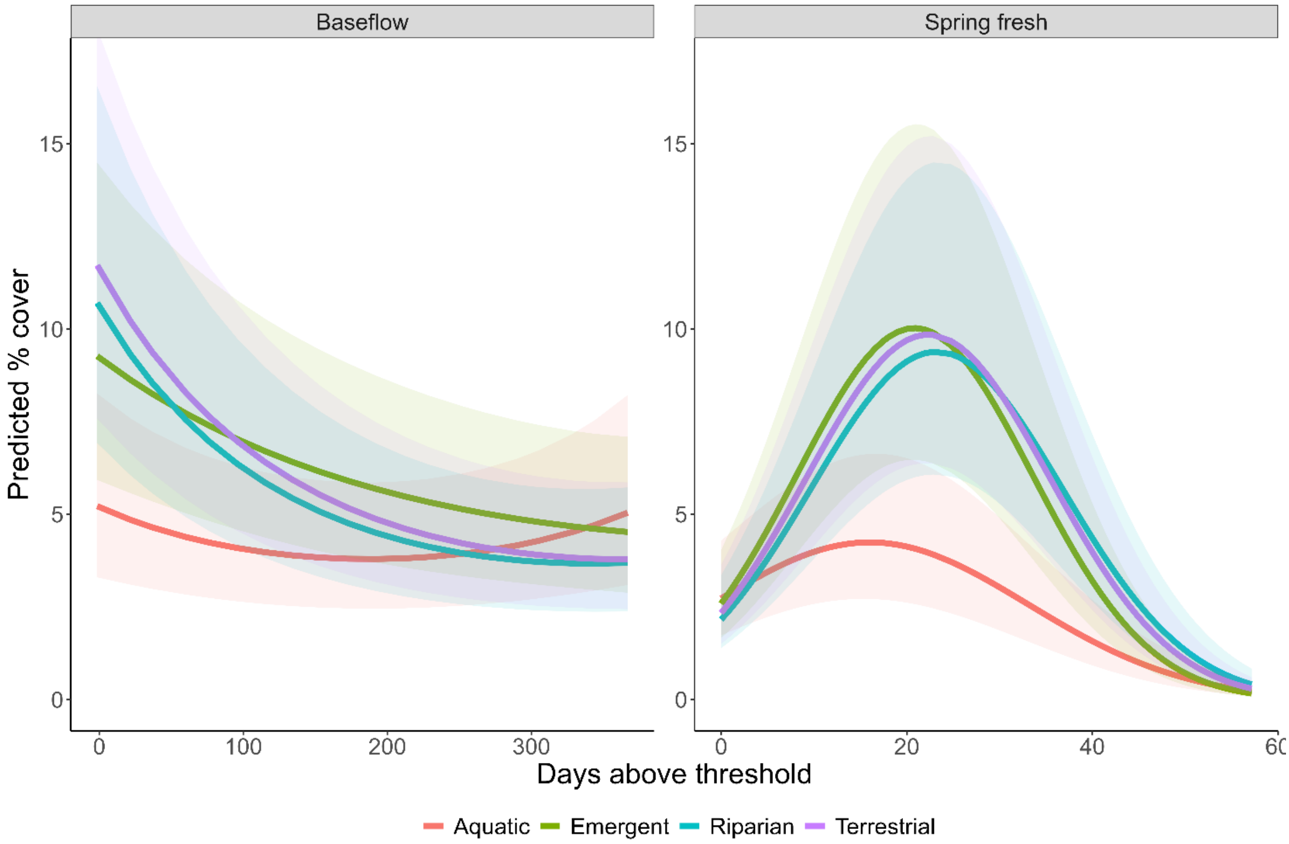

Figure 4. Predicted associations between vegetation cover and the number of days with discharge above (a) baseflow levels and (b) spring fresh levels, and in the three years preceding a survey. Solid lines are mean estimates of cover for each functional group and shaded regions bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 15%, which reflects the relatively low values of average cover given zero-inflation in the dataset.

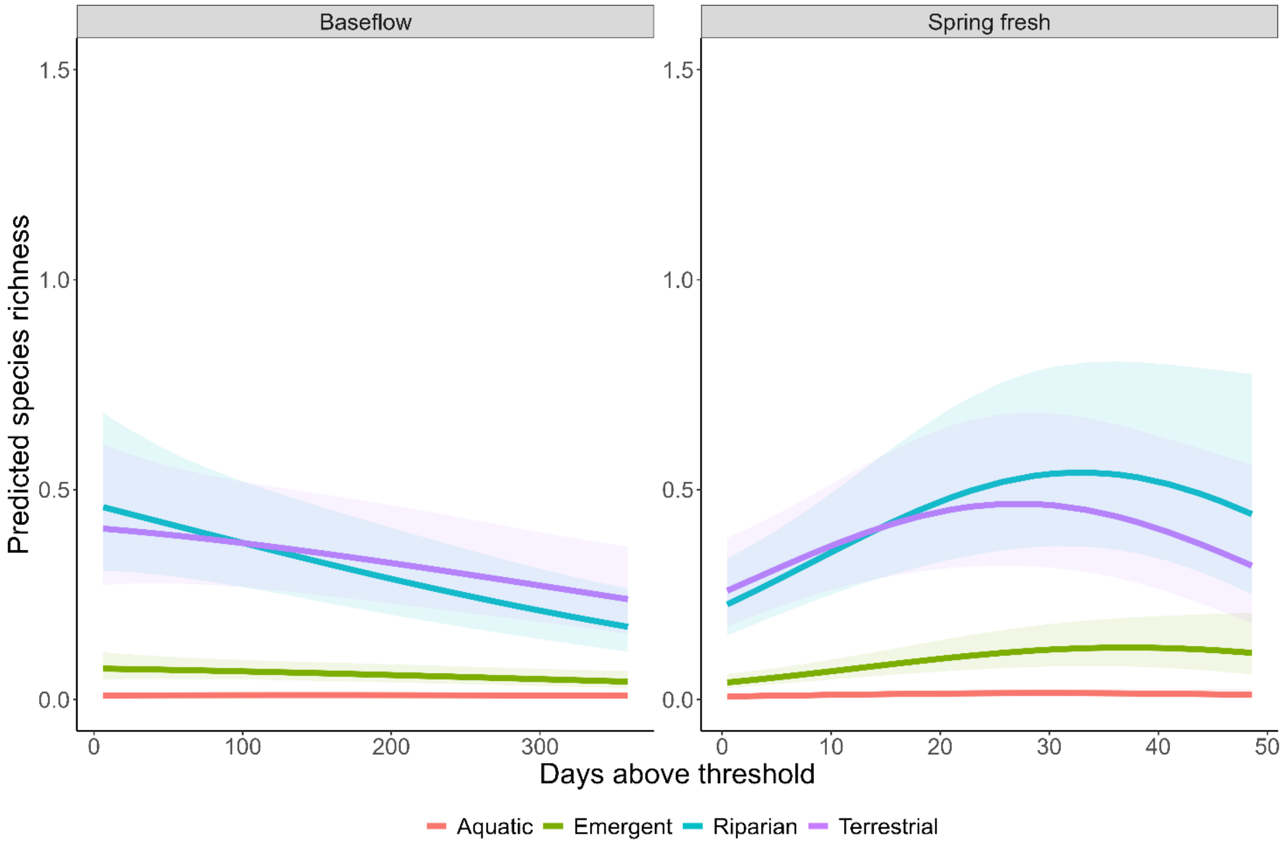

Figure 5. Predicted associations between vegetation species richness and the number of days with discharge above spring-fresh and baseflow levels in the three years preceding a survey.
Solid lines are mean estimates of species richness for each functional group and shaded regions bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 1.00 species, which reflects the relatively low values of average species richness at the sub-transect level on average over all bank elevations.

3.4. Flow event influences on plant cover and richness

Associations of plant cover with flow events (zone and sampling period) suggested that vegetation responses to flow events (spring and summer freshes) differed among zones (bank location relative to baseflow and spring-fresh levels) and functional groups (Figure 6). The summed cover of aquatic species above the spring-fresh level or below the baseflow level did not change markedly following spring or summer freshes because of the very low abundance at that high bank elevation (Figure 6). By contrast, there was a clear, near-linear increase in cover of aquatic species between the baseflow and spring-fresh levels following both spring and summer fresh events which suggests a positive response for these plants in the zone targeted by the freshes (Figure 6). The summed cover of emergent species increased following spring freshes, with increases apparent in all zones but clearest above the spring-fresh level where cover was lowest at the start of the growth season (Figure 6). Cover of emergent species decreased slightly following summer freshes in all zones due to seasonal senescence but remained elevated above their pre-spring fresh level (Figure 6). Riparian species had relatively weak associations with flow events in all zones. Terrestrial species had clear, but opposite associations above the spring-fresh level and below the baseflow level (Figure 6). Over the spring fresh period, there was a decline in cover above the fresh level and an increase below the baseflow level, but this was largely driven by the different pre-fresh cover levels. Before the spring fresh, terrestrial plants have high abundance at high bank elevations following autumn recruitment from rainfall, but they have low cover below baseflow level when the winter baseflows are higher and prevent terrestrial recruitment. Summer freshes were associated with minor declines in terrestrial cover in inundated zones.

Models of flow events (spring and summer freshes) highlighted relatively low intra-annual variation in vegetation species richness, with slight increases in the number of riparian species following spring freshes in all zones and slight decreases in the number of terrestrial species above baseflow and spring-fresh levels following spring and summer freshes (Figure 7). Riparian and terrestrial plants showed clearly divergent preferences for wetter and drier bank positions respectively. Aquatic vegetation richness was low and largely restricted to below the baseflow levels, while emergent species followed a similar but more slightly more abundant pattern.

Conditional on associations with flow events, variation in vegetation cover occurred primarily among sites, transects, and sub-transect heights, with slightly less variation among systems and much less variation among years (Appendix F, Figure F4). High levels of variation among transects and sub-transect heights were not observed in the flow-regime model, which indicates that flow regimes may partially explain variation in vegetation cover among transects and sub-transect heights (compare Appendix F, Figures F1 and F4). Residual variation among systems (i.e., variation at system level but not explained by flow events) indicated generally higher-than-expected vegetation cover in the Moorabool, West Gippsland, and Yarra systems, average cover in the Loddon and Wimmera systems, and lower-than-expected cover in the Campaspe and Glenelg systems (Appendix F, Figure F5). These patterns do not follow a clear rainfall pattern, neither was there a consistent trend of livestock grazing influence. Cover of vegetation functional groups differed little between native and exotic species (Appendix F, Figure F6) and was negatively associated with the occurrence of grazing (Appendix F, Figure F7).

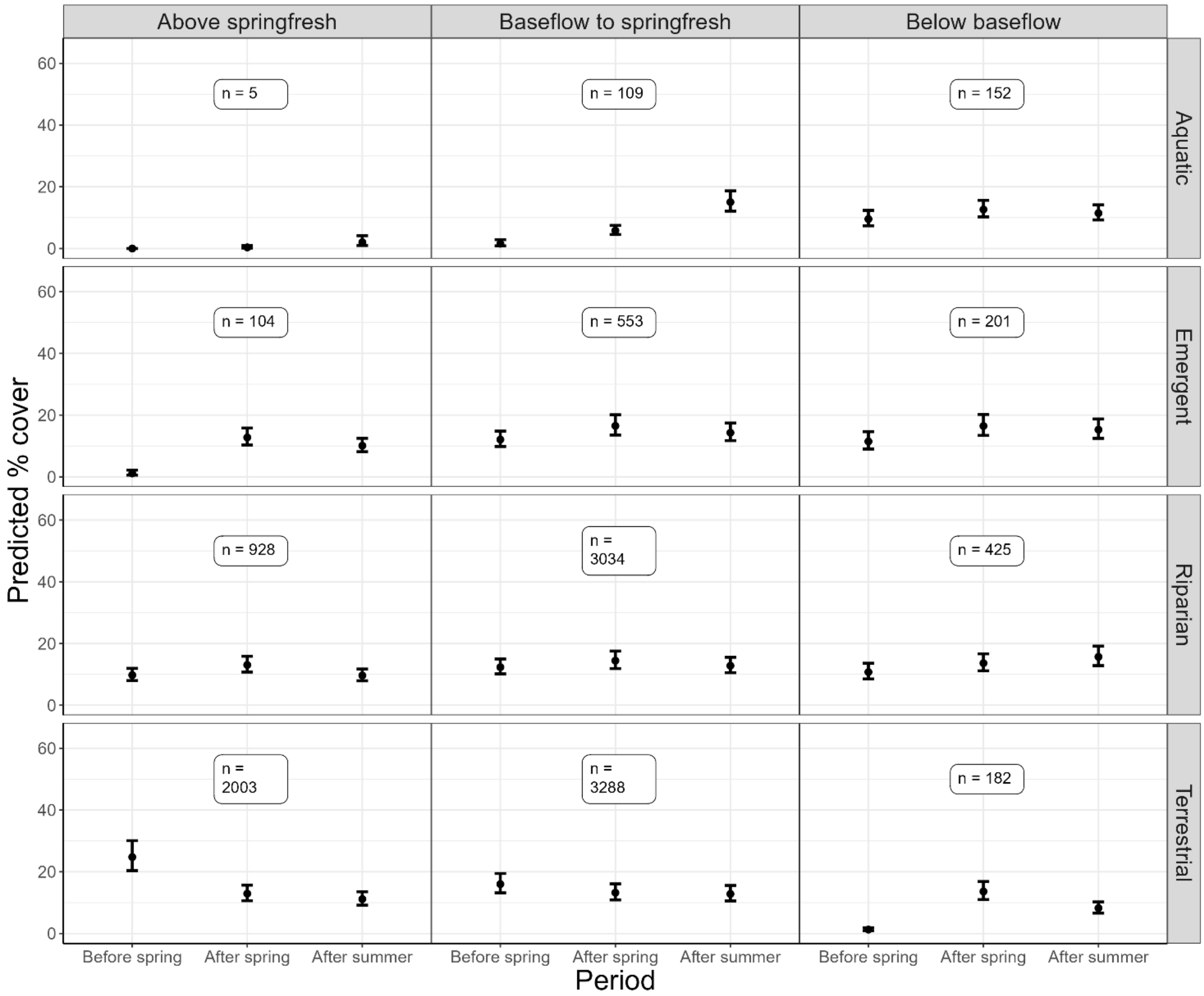

Figure 6. Predicted associations between vegetation cover and flow events (spring and summer freshes) in each zone and sampling period.

Solid points are mean estimates of cover for each functional group and error bars bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 60%, which reflects the relatively low values of average cover given many zeros in the data set.

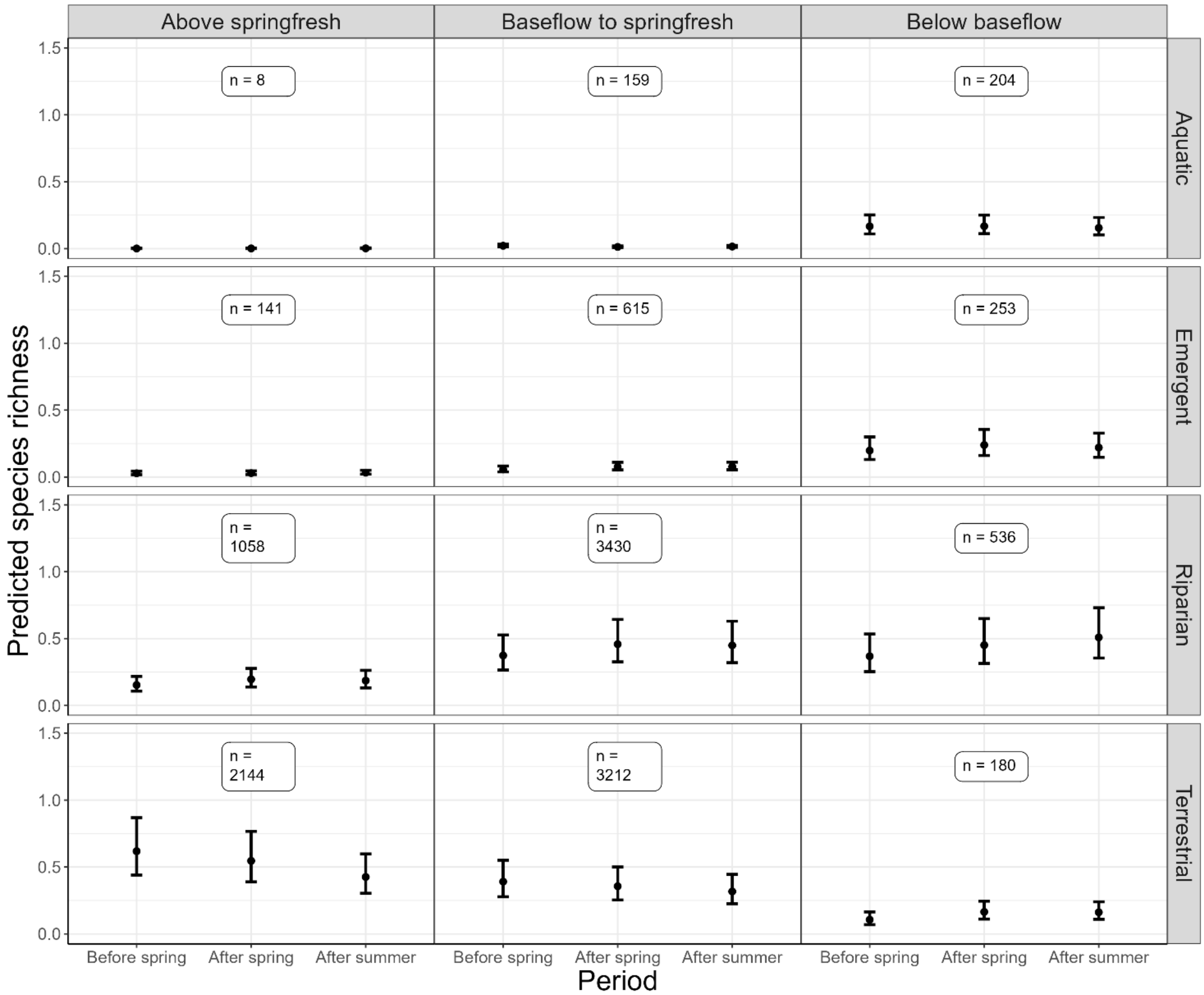

Figure 7. Predicted associations between vegetation species richness and flow events (spring and summer freshes) in each zone and sampling period.

Solid points are mean estimates of species richness for each functional group and error bars bound 95% confidence intervals. Note that the y-axis varies between functional groups is truncated to a maximum value of 0.8, which reflects the relatively low values of average species richness at the sub-transect level.

4. Discussion

This study highlights the complex and multifaceted nature of riverine vegetation dynamics in regulated river systems, emphasising the critical role of environmental flows in maintaining and restoring these modified ecosystems. Our findings demonstrate that while individual flow events may produce modest immediate vegetation responses, their cumulative impact over time is substantial, which is expected to increase the resilience of riverine systems to disturbances. However, the effectiveness of environmental flows is not uniform across all vegetation groups or sites; it is highly context-dependent, influenced by local environmental conditions, species-specific traits, and the interplay of non-flow factors such as grazing, soil properties, and the presence of exotic species.

The variability in vegetation responses reveals the necessity for tailored, adaptive management approaches that consider the unique characteristics of each river system and the site-specific ecological objectives. Short-duration freshes are beneficial for emergent and riparian species, while prolonged elevated flows can be detrimental to riparian and terrestrial species in particular if not carefully managed. Moreover, the influence of non-flow factors, specifically the dominance of exotic species and the impacts of livestock grazing, suggests that environmental flows alone will be insufficient to achieve desired ecological outcomes without additional livestock or weed management. Integrated management strategies that address both hydrological and non-hydrological pressures are essential for the long-term health and functionality of riverine ecosystems.

4.1. Vegetation patterns and drivers

The distribution of species along bank elevations at the site scale provides a clear demonstration of the impact of flow events and regimes at different bank zones, with species such as *Phragmites australis* occupying lower elevations close to baseflow, while flood-intolerant species like *Oxalis pes-caprae* were restricted to higher elevations above the spring-fresh level. This zonation illustrates the importance of hydrological gradients in structuring riverine vegetation communities. However, the variation in dominant species among different waterways and the lack of uniform patterns across sites complicate efforts to generalise vegetation responses to flow events and regimes. These varying species assemblages and traits among waterways and regions mean that no single management approach will apply to all waterways, however there are generalisable categories that can help inform management actions given the conditions and constraints of a system (e.g. Good and Jones 2026).

Long term data trends that were available at a small number of sites (6/44) highlight the rates of change in vegetation under relatively consistent flow regimes. These clearly show increasing trends in plant cover for emergent, riparian and terrestrial species in the spring fresh zone, with no trends above the fresh zone (too dry) or for riparian and terrestrial plants below the baseflow level (too wet). The trends suggest a cumulative benefit of regular (annual) delivery of environmental flows for emergent species in the baseflow zone and most species in the fresh zone. The slow rate of change in relatively low rainfall regions provides important context to management expectations, objectives, and the need for long-term data to detect important vegetation change. However, the rates of change are likely to be muted by the competitive influence of exotic riparian species that will reduce the magnitude of change in native riparian plants at many sites (Catford et al. 2011), particularly for sites in more productive regions that have higher exotic plant abundance. These rates will also be important for vegetation communities to recover following flood or drought disturbance and to build resilience prior to future disturbances, which are predicted to increase in frequency and intensity in the future within the study region (Zhang et al. 2020).

4.2. Vegetation responses to flows

Clear short term benefits to aquatic and emergent species following freshes (or natural flows with equivalent flow attributes) are expected due to the high preference and tolerance to inundation (Vivian et al. 2025). Emergent species benefits above the spring-fresh level likely result from belowground water resources via lateral bank recharge (Deng et al. 2024), that diminish in autumn with seasonal plant senescence. The high variability in plant responses to specific flow events is likely to be largely influenced by the relatively small short term changes as a result of brief managed flows compared to the variability among years, seasons and sites. In contrast, the long-term effects of flow regimes showed clear positive associations with managed flows that closely corresponded with vegetation response patterns derived from recent experimental studies. Maintaining beneficial flow regimes in the long term is likely to be important for riparian plant communities to recover following disturbances and build resilience to threats.

Sustained baseflows were generally detrimental to riparian and terrestrial species that are intolerant of extended inundation (Vivian et al. 2020; Main et al. 2023). However, aquatic species benefited from these conditions, as sustained baseflows provided consistent water availability, supporting their growth and persistence. Regimes of short-duration freshes (15–25 days) were associated with the highest cover in all vegetation groups within the fresh zone, indicating that regimes of freshes approximately 10-30 days long in late-winter/spring flow events can stimulate vegetation growth without causing the adverse effects associated with prolonged inundation found in controlled nursery studies (Vivian et al. 2020; Kitanovic et al. 2023; Main et al. 2023; Wijepala et al. 2026). Inundation duration beyond ~30 days resulted in declines in all species, matching the tolerance thresholds observed in controlled conditions. Negative impacts on species richness occurred following longer inundation durations (~26, 35, and 38 days for terrestrial, riparian and emergent plants respectively) because richness only declines when the plants die, while declines in health and biomass occur earlier (Vivian et al. 2020; Kitanovic et al. 2023; Main et al. 2023; Wijepala et al. 2026). Aquatic plants showed no significant indication of mortality from extended flows, as expected.

The variation in functional group cover and species richness among different systems, sites, and transects further highlights the importance of local context in shaping vegetation responses to flow regimes. For example, the Moorabool and West Gippsland systems exhibited higher-than-expected overall cover, suggesting that other flow or site-specific factors, such as soil properties, water quality, land use, or historical disturbances, may be playing a significant role in these areas. Plant responses to inundation can vary substantially between species even within plant functional groups, making generalisation difficult (Van Eck et al. 2006; Main et al. 2022). Additional factors could be added to future versions of this assessment, but the statistical models are already very complex and there are limits to what can be done without also increasing the vegetation survey data volume at all sites to support model complexity. The lack of significant differences in cover between native and exotic species across functional groups suggests that they have similar responses and flow regimes alone may not be sufficient to control the spread of exotic species, highlighting the need for integrated management approaches to achieve native vegetation objectives that vary among waterways or regions (Good and Jones 2026).

While the regimes recorded within this study were influenced by environmental flows and unregulated natural flows in different years, the regimes were indicative of the environmental flow regulated system for each waterway. The spatial influences were also restricted to areas most heavily influenced by consistently applied environmental flows. It is impossible to create a monitoring design in the field where the effects of environmental flows and unregulated natural flows can be fully disentangled from one another. The insights from this analysis relate directly to real-world management scenarios that are shaped by environmental flows.

4.3. The influence of non-flow factors

The role of non-flow factors in shaping vegetation patterns and responses cannot be overstated (Campbell et al. 2023; Good and Jones 2024; Nystrand et al. 2025). In many of the study sites, the presence of exotic species, particularly in agricultural landscapes, was a dominant factor influencing vegetation dynamics. Exotic species, such as invasive herbs and agricultural grasses, have similar responses to flows as native species and compete with native vegetation, leading to reduced native species richness and cover where they are abundant (Appendix E1). The dominant functional group of exotic plants varied among waterways and therefore had a different relative influence depending on the starting species composition. In drier landscapes, exotic plants were primarily terrestrial and so had limited impact on the native riparian plants on the lower bank of waterways when flows were present. While in wetter regions, the exotic plants were commonly flood-tolerant and were more often found to fully exclude native riparian plants. Exotic plant influences will continue to be a major threat to native plant populations in regulated rivers in the study region and will need to be actively managed, particularly where they are primarily flood-tolerant species (Catford et al. 2011; Greet et al. 2013; Tonkin et al 2020).

Grazing pressure was another critical factor, with sites subjected to livestock grazing showing significant reductions in vegetation cover and species richness, particularly among native species. This finding aligns with previous studies that have demonstrated the negative impacts of grazing on riverine vegetation, particularly in terms of trampling, soil compaction, and the preferential consumption of palatable native species (Jones and Vesk 2016; Jones et al. 2022; Nystrand et al. 2025). However, the impact of grazing was often inconsistent within a site and therefore the use of a whole site variable for grazing presence is likely to have been less informative than assessing grazing influence at the transect (sub-site) scale. Other non-flow factors that can have an important influence on vegetation, including soil properties (Hale et al. 2014, Fagundes et al. 2019) and historical disturbances (Capon et al. 2016), were not assessed in this study. These interacting influences reinforce the need for a holistic approach to vegetation management—one that considers the full range of environmental influences on riverine ecosystems (Campbell et al. 2023; Good and Jones 2026; Nystrand et al. 2025).

4.4. Implications for management and monitoring

Environmental flows have clear benefits to native aquatic, emergent and riparian plants in regulated waterways that are cumulative over several years. These benefits were larger for cover than richness, but a small cumulative increase in richness may be adequate for ecosystem health and function. This positive outcome is also significant considering the high occurrence of exotic species that are present within some sites and respond positively to flows and outcompete native species (Catford et al. 2011; Tonkin et al. 2020). Importantly, given that native and exotic species respond in similar ways to flows, riparian or flood tolerant exotic species cannot be controlled with flows and would need a co-ordinated management strategy of flow and non-flow actions to reduce their populations (Good and Jones 2024).

While it is important for managers to consider their local context when applying management actions, this study supports the development of clear management ranges that will best support native vegetation in riparian zones. Freshes of around 15-20 days (range 10-25) are optimal for most riparian and emergent plant cover, but flows should be restricted to <25 days in spring and <10 days in summer (Vivian et al. 2020; Main et al. 2023; Wijepala et al. 2025) to avoid negative impacts. Species richness may be optimised by longer flow durations (~35 days), but this may come at a risk of maintaining plant abundance, health and function. Larger and longer duration freshes (within the bounds above) that occur annually are likely to provide the most benefit to desirable plant functional groups while disadvantaging terrestrial plants, but low flow periods of up to 12-14 weeks after floods (Gower et al. 2024) and >4 weeks between freshes should be used to enable growth and recovery.

Given the influence of non-flow factors observed in this study and others, integrated management approaches that address grazing pressures, the spread of exotic species, and other land-use impacts are essential for achieving long-term ecological health (Good and Jones 2024; Nystrand et al. 2025). Moreover, the variability in vegetation responses among different systems and sites highlights the importance of local context in informing management decisions. This includes variability at the site level caused by historical and future climate, soils, historical disturbances, and threats. By integrating site-specific knowledge with broader ecological principles, waterway managers can develop more effective strategies for maintaining and restoring the health of riverine vegetation (Good and Jones

2024). Future studies could build on the results presented here to address data shortfalls, limited data coverage (spatially and temporally), and the influences of integrated flow and non-flow management.

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Appendix A

Table A1. Site and survey information.

Catchment	Waterway	Number of sites	Number of transects	Number of sub-transects	Number of site surveys	Number of visits to waterbody	Survey years
Campaspe	Campaspe	6	61	565	96	16	2016–2023
Glenelg	Glenelg	6	54	267	27	7	2018-19, 2022-23
Glenelg	Wannon	1	5	24	3	3	2018-2019
Loddon	Loddon	2	10	55	6	3	2017-2018
Loddon	Tullaroop	2	20	109	6	3	2017-2018
Loddon	Twelve Mile	2	10	56	6	3	2017-2018
Moorabool	Moorabool	5	46	227	20	6	2017-18, 2022-23
Moorabool	Sutherland	1	10	41	3	3	2017-2018
Thomson	Macalister	4	21	102	10	3	2018-2019
Thomson	Thomson	3	21	106	9	3	2018-2019
Wimmera	Burnt	4	20	89	22	6	2017-2019
Wimmera	McKenzie	4	19	88	24	6	2017-2019
Wimmera	Mt William	4	22	93	18	6	2017-2019
Yarra	Watts	1	5	24	3	3	2018-2019
Yarra	Yarra	3	34	188	10	4	2018-2019

Table A2. The most common species within each vegetation group in each waterway.

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
Campaspe	NA	*Cycnogeton procerum*, *Characeae* spp., *Myriophyllum* spp., *Vallisneria australis*, *Potamogeton crispus*	NA	*Phragmites australis*, *Bolboschoenus medianus*, *Typha* spp., *Typha domingensis*, *Bolboschoenus* spp.	*Paspalum distichum*, *Cyperus eragrostis*, *Juncus acutus* subsp. *acutus*, *Juncus articulatus* subsp. *articulatus*, *Agrostis stolonifera*	*Lachnagrostis filiformis* s.l., *Juncus usitatus*, *Carex bichenoviana*, *Persicaria prostrata*, *Juncus amabilis*	*Cynodon dactylon* var. *dactylon*, *Panicum coloratum*, *Paspalum dilatatum*, *Lolium* spp., *Bromus diandrus*	*Poa labillardierei* var. *labillardierei*, *Paspalidium jubiflorum*, *Hemarthria uncinata* var. *uncinata*, *Themeda triandra*, *Rytidosperma* spp.
Glenelg	*Elodea canadensis*	*Cycnogeton procerum*, *Ranunculus amphitrichus*, *Cycnogeton alcockiae*, *Characeae* spp., *Potamogeton ochreatus*	*Typha latifolia*	*Phragmites australis*, *Baumea juncea*, *Typha* spp., *Baumea* spp., *Baumea arthrophylla*	*Paspalum distichum*, *Agrostis stolonifera*, *Juncus articulatus* subsp. *articulatus*, *Polypogon monspeliensis*, *Cotula coronopifolia*	*Juncus amabilis*, *Eragrostis infecunda*, *Alternanthera denticulata*, *Selliera radicans*, *Lachnagrostis filiformis* s.l.	*Lolium* spp., *Holcus lanatus*, *Phalaris aquatica*, *Vulpia* spp., *Romulea rosea*	*Poa labillardierei* var. *labillardierei*, *Distichlis distichophylla*, *Rytidosperma* spp., *Crassula* spp., *Hemarthria uncinata* var. *uncinata*
Wannon	*Elodea canadensis*	*Cycnogeton procerum*, *Ornduffia reniformis*, *Characeae* spp., *Cycnogeton alcockiae*, *Nitella* sp.	*Typha latifolia*	*Phragmites australis*, *Eleocharis acuta*, *Baumea juncea*, *Baumea arthrophylla*, *Baumea* spp.	*Agrostis stolonifera*, *Cotula coronopifolia*, *Cynosurus echinatus*, *Cyperus eragrostis*, *Isolepis hystrix*	*Lachnagrostis filiformis* s.l., *Carex appressa*, *Selliera radicans*, *Isolepis inundata*, *Glyceria australis*	*Anthoxanthum odoratum*, *Leontodon saxatilis*, *Hypochaeris radicata*, *Holcus lanatus*, *Phalaris aquatica*	*Poa labillardierei* var. *labillardierei*, *Lobelia anceps*, *Senecio biserratus*, *Lomandra longifolia*, *Senecio minimus*
Loddon	NA	*Cycnogeton procerum*, *Myriophyllum* spp., *Ranunculus inundatus*	NA	*Bolboschoenus medianus*, *Eleocharis acuta*, *Phragmites australis*,	*Cyperus eragrostis*, *Agrostis stolonifera*, *Mentha pulegium*,	*Cyperus exaltatus*, *Carex tereticaulis*, *Alternanthera denticulata*,	*Lolium rigidum*, *Lolium perenne*, *Helminthotheca echioides*, *Symphyotrichum*	*Poa fordeana*, *Asperula gemella*, *Paspalidium jubiflorum*, *Walwhalleya*

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
				Schoenoplectus tabernaemontani	*Paspalum distichum, Polypogon monspeliensis*	*Juncus aridicola, Juncus amabilis*	*subulatum, Cirsium vulgare*	*proluta, Asperula conferta*
Tullaroop	NA	*Cycnogeton procerum, Myriophyllum* spp., *Ranunculus inundatus*	NA	*Phragmites australis, Bolboschoenus medianus, Schoenoplectus tabernaemontani, Eleocharis acuta*	*Cyperus eragrostis, Paspalum distichum, Agrostis stolonifera, Polypogon monspeliensis, Mentha pulegium*	*Juncus usitatus, Lachnagrostis filiformis* s.l., *Carex bichenoviana, Juncus amabilis, Carex tereticaulis*	*Cynodon dactylon* var. *dactylon, Cirsium vulgare, Phalaris aquatica, Oxalis pes-caprae, Bromus catharticus*	*Hemarthria uncinata* var. *uncinata, Lythrum hyssopifolia, Oxalis perennans, Rumex brownii, Euchiton involucratus* s.l.
Twelve Mile	NA	*Cycnogeton procerum, Ranunculus inundatus, Myriophyllum* spp.	NA	*Schoenoplectus tabernaemontani, Bolboschoenus medianus, Eleocharis acuta, Phragmites australis*	*Cyperus eragrostis, Mentha pulegium, Paspalum distichum, Ranunculus sceleratus* subsp. *sceleratus, Agrostis stolonifera*	*Eragrostis infecunda, Juncus aridicola, Alternanthera denticulata, Cyperus exaltatus, Juncus amabilis*	*Lolium rigidum, Helminthotheca echioides, Symphyotrichum subulatum, Polygonum aviculare, Cirsium vulgare*	*Calotis scapigera, Oxalis perennans, Rumex tenax, Lythrum hyssopifolia, Rytidosperma* spp.
Moorabool	*Elodea canadensis*	*Cycnogeton procerum, Potamogeton crispus, Ceratophyllum demersum, Myriophyllum* spp., *Lemna disperma*	NA	*Phragmites australis, Schoenoplectus tabernaemontani, Eleocharis acuta, Bolboschoenus medianus, Typha domingensis*	*Agrostis stolonifera, Juncus acutus* subsp. *acutus, Paspalum distichum, Juncus articulatus* subsp. *articulatus, Cyperus eragrostis*	*Ficinia nodosa, Lachnagrostis filiformis* s.l., *Carex appressa, Persicaria decipiens, Isolepis inundata*	*Phalaris aquatica, Ehrharta erecta* var. *erecta, Anthoxanthum odoratum, Bromus diandrus, Dactylis glomerata*	*Poa labillardierei* var. *labillardierei, Microlaena stipoides* var. *stipoides, Pteridium esculentum, Lomandra longifolia, Senecio quadridentatus*
Sutherland	*Elodea canadensis*	*Cycnogeton procerum,*	NA	*Phragmites australis,*	*Juncus acutus* subsp. *acutus,*	*Ficinia nodosa, Lachnagrostis*	*Phalaris aquatica,*	*Oxalis perennans,*

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
		Ceratophyllum demersum, *Characeae* spp., *Lemna disperma*, *Myriophyllum* spp.		*Bolboschoenus medianus*, *Typha domingensis*, *Eleocharis acuta*, *Schoenoplectus tabernaemontani*	*Polypogon monspeliensis*, *Paspalum distichum*, *Agrostis stolonifera*, *Cyperus eragrostis*	*filiformis* s.l., *Montia australasica*, *Isolepis cernua*, *Alternanthera denticulata*	*Ehrharta erecta* var. *erecta*, *Cynodon dactylon* var. *dactylon*, *Bromus diandrus*, *Galenia pubescens*	*Lobelia anceps*, *Rumex brownii*, *Rytidosperma* spp., *Acaena echinata*
Macalister	NA	*Cycnogeton procerum*, *Potamogeton crispus*, *Potamogeton* spp.	NA	*Phragmites australis*, *Schoenoplectus tabernaemontani*, *Baumea* spp., *Bolboschoenus medianus*, *Bolboschoenus* spp.	*Phalaris arundinacea*, *Cyperus eragrostis*, *Paspalum distichum*, *Glyceria maxima*, *Agrostis stolonifera*	*Isachne globosa*, *Persicaria praetermissa*, *Persicaria subsessilis*, *Carex appressa*, *Persicaria decipiens*	*Cynodon dactylon* var. *dactylon*, *Cenchrus clandestinus*, *Tradescantia fluminensis*, *Dactylis glomerata*, *Hypochaeris radicata*	*Microlaena stipoides* var. *stipoides*, *Hemarthria uncinata* var. *uncinata*, *Rumex brownii*, *Lobelia anceps*, *Lythrum hyssopifolia*
Thomson	NA	*Potamogeton* spp., *Potamogeton crispus*, *Cycnogeton procerum*	NA	*Schoenoplectus tabernaemontani*, *Baumea* spp., *Schoenoplectus* spp., *Bolboschoenus medianus*, *Bolboschoenus* spp.	*Ranunculus repens*, *Phalaris arundinacea*, *Agrostis stolonifera*, *Cyperus eragrostis*, *Paspalum distichum*	*Persicaria hydropiper*, *Persicaria praetermissa*, *Persicaria subsessilis*, *Juncus amabilis*, *Isolepis inundata*	*Tradescantia fluminensis*, *Vinca major*, *Dactylis glomerata*, *Cynodon dactylon* var. *dactylon*, Monocot grass	*Microlaena stipoides* var. *stipoides*, *Cardamine* spp., *Dichondra repens*, *Lythrum hyssopifolia*, *Centella cordifolia*
Burnt	*Callitriche brutia* var. *brutia*, *Callitriche stagnalis*	*Cycnogeton procerum*, *Myriophyllum simulans*, *Ottelia ovalifolia* subsp. *ovalifolia*, *Gratiola peruviana*, *Potamogeton cheesemanii*	NA	*Eleocharis acuta*, *Baumea arthrophylla*, *Baumea articulata*, *Eleocharis sphacelata*, *Phragmites australis*	*Paspalum distichum*, *Juncus articulatus* subsp. *articulatus*, *Polypogon monspeliensis*, *Cyperus eragrostis*, *Agrostis stolonifera*	*Carex tereticaulis*, *Juncus amabilis*, *Carex gaudichaudiana*, *Ficinia nodosa*, *Baloskion tetraphyllum* subsp. *tetraphyllum*	*Ehrharta calycina*, *Paspalum dilatatum*, *Lolium rigidum*, *Romulea rosea*, *Holcus lanatus*	*Rytidosperma* spp., *Lythrum hyssopifolia*, *Eragrostis brownii*, *Microlaena stipoides* var. *stipoides*, *Goodenia humilis*

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
McKenzie	*Callitriche brutia* var. *brutia*, *Callitriche stagnalis*	*Cycnogeton procerum*, *Characeae* spp., *Gratiola pumilo*, *Ceratophyllum demersum*, *Gratiola peruviana*	NA	*Schoenoplectus tabernaemontani*, *Baumea arthrophylla*, *Baumea articulata*, *Eleocharis acuta*, *Eleocharis sphacelata*	*Juncus articulatus* subsp. *articulatus*, *Agrostis stolonifera*, *Cynosurus echinatus*, *Cyperus eragrostis*, *Cotula coronopifolia*	*Juncus amabilis*, *Carex gaudichaudiana*, *Lachnagrostis filiformis* s.l., *Juncus procerus*, *Chorizandra enodis*	*Ehrharta calycina*, *Holcus lanatus*, *Romulea rosea*, *Briza maxima*, *Phalaris aquatica*	*Hemarthria uncinata* var. *uncinata*, *Microlaena stipoides* var. *stipoides*, *Rytidosperma* spp., *Poa labillardierei* var. *labillardierei*, *Caesia* spp.
Mt William	*Callitriche stagnalis*, *Callitriche brutia* var. *brutia*	*Cycnogeton procerum*, *Ceratophyllum demersum*, *Characeae* spp., *Myriophyllum simulans*, *Gratiola peruviana*	*NA*	*Phragmites australis*, *Eleocharis sphacelata*, *Baumea articulata*, *Eleocharis acuta*, *Baumea arthrophylla*	*Paspalum distichum*, *Cynosurus echinatus*, *Juncus articulatus* subsp. *articulatus*, *Cotula coronopifolia*, *Ranunculus sceleratus* subsp. *sceleratus*	*Juncus amabilis*, *Juncus pallidus*, *Carex appressa*, *Lachnagrostis filiformis* s.l., *Triglochin striata*	*Holcus lanatus*, *Bromus diandrus*, *Lolium rigidum*, *Anthoxanthum odoratum*, *Monocot grass*	*Microlaena stipoides var. stipoides*, *Lobelia anceps*, *Rytidosperma* spp., *Euchiton involucratus* s.l., *Acaena echinata*
Watts	*Callitriche stagnalis*, *Elodea canadensis*	*Gratiola peruviana*, *Azolla* spp.	*NA*	*Phragmites australis*	*Glyceria maxima*, *Ranunculus repens*, *Cyperus eragrostis*, *Paspalum distichum*, *Juncus articulatus* subsp. *articulatus*	*Persicaria praetermissa*, *Carex appressa*, *Persicaria decipiens*, *Isolepis inundata*, *Carex fascicularis*	*Vinca major*, *Lonicera japonica*, *Ehrharta erecta* var. *erecta*, *Cenchrus clandestinus*, *Oxalis incarnata*	*Tetrarrhena juncea*, *Blechnum nudum*, *Oxalis exilis*, *Lythrum hyssopifolia*, *Centella cordifolia*
Yarra	*Elodea canadensis*, *Callitriche stagnalis*	*Gratiola peruviana*, *Azolla* spp.	NA	*Phragmites australis*	*Phalaris arundinacea*, *Paspalum distichum*, *Cyperus*	*Persicaria hydropiper*, *Alternanthera denticulata*, *Persicaria*	*Cenchrus clandestinus*, *Tradescantia fluminensis*, *Allium*	*Microlaena stipoides* var. *stipoides*, *Poa labillardierei* var. *labillardierei*,

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
					eragrostis, Ranunculus repens, Glyceria maxima	*praetermissa, Juncus amabilis, Carex appressa*	*triquetrum, Cynodon dactylon* var. *dactylon, Dactylis glomerata*	*Pteridium esculentum, Poa ensiformis, Lomandra longifolia*

Appendix B

Table B1. Data analysis and modelling dataset

Variable Name	Unit	Definition	Variable Type	Variable Group
Species vegetation cover	Continuous: Cover	Cover per *species*, per *sub-transect*	Response	Vegetation Cover
Plant functional group cover		Cover per *plant functional group*, per *sub-transect*		
Sub-transect vegetation cover		Total cover (sum all species), per sub-transect		
Species richness	Integer: Counts	Number unique Species Functional Group, per *sub-transect*		Species Richness
Days above baseflow / spring-fresh levels	Integer, Counts: Z-scale	Number of days per year (averaged over preceding 3 water-years) discharge > baseflow or spring-fresh levels, Z-scaled	Predictor	Flow Regime
Sub-transect zone	Factor	Zone in which a sub-transect occurred: • Below baseflow level • Between baseflow and spring-fresh levels • Above spring-fresh level		
Flow event	Factor	Timing of sampling: • Before spring fresh • Between spring and summer fresh • After summer fresh		Flow Event
Site grazing status	Factor	Grazing status of site: • Grazed • Ungrazed		Other factors influencing spatio-temporal variation in

Variable Name	Unit	Definition	Variable Type	Variable Group
Species functional group	Factor	For each *Origin* group (native or exotic): • Aquatic • Emergent • Riparian • Terrestrial		cover / abundance
Species origin	Factor	Origin of the recorded species: • Native • Exotic	Predictor	
Site identity	Factor	Name / Identity of the site	Random effect	
Transect identity	Factor	Identity of nested within sites		
Sub-transect height	Continuous: Metres above baseflow	Height of the sub-transect along bank		
Survey year	Date: YYYY	Year in which the sample was recorded		
Waterbody	Factor	Waterbody in which the site is located		

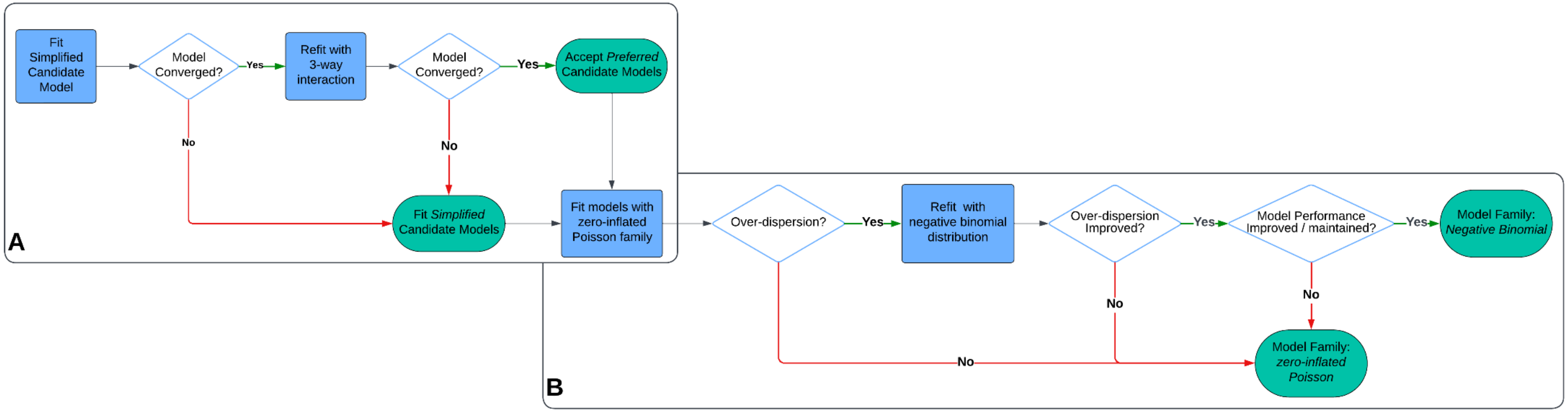

Figure B2. Preregistered decision-tree for selecting model structure (A) and selecting an alternative model functional form over the default zero-inflated *Poisson* (B). The decision-tree was preregistered in version 2 and version 3 of the preregistration (Figure B1, Table B2). Reproduced with permission from Gould et al. (2025).

Initial model fitting assumed a zero-inflated Poisson distribution for both vegetation cover and species richness, with zero-inflated negative binomial distributions designated in cases where over-dispersion was severe (Figure B2). This approach does not introduce an upper bound on estimates of cover (e.g., specifying a maximum cover level of 100%). We used this approach for three reasons. First, overlapping species may generate cover estimates that exceed 100%. Second, parameters of bounded distributions are challenging to estimate when many values occur near the bounds. Third, bounded distributions require link functions (e.g., the logit function) that complicate the specification and interpretation of autoregressive models. We note that the Poisson distribution approximates the bounded binomial distribution in the limit of many trials. The extent of zero-inflation and over-dispersion (and a model's capacity to capture these patterns) was assessed using posterior predictive checks, which use values simulated from the fitted model to determine whether the model structure captures the observed distribution of the response variable (Gelman and Hill, 2007; Gelman et al. 2014). Pilot study models of vegetation cover at the species level did not converge in any instance. Models of vegetation cover aggregated to plant functional groups converged but required separate models of two-way interactions instead of the three- and four-way interactions included in the maximal model structure. Models of vegetation cover aggregated to functional groups (aquatic, emergent, riparian, terrestrial) converged but required removal of interactions with species origin and separate analyses of flow metrics and for each of the categorical flow terms (zone and sampling period). Models of vegetation species richness within functional groups converged but required separate models of two-way interactions instead of the three- and four-way interactions included in the maximal model structure. Models of vegetation species richness within functional groups converged but required removal of interactions with species origin and separate models for the two categorical flow variables (zone and sampling period).

Table B2. Key stages of the modelling and Adaptive Preregistration process (reproduced with permission from Gould et al. 2025). Version numbers in parentheses are GitHub tags, marking snapshots of the repository for each Preregistration Version.

Preregistration Version	Preregistration Process	Modelling and Analysis Process
Version 1: (v0.10 – v0.8.1)	Establish problem context, study background and aims, describe data collection and data cleaning process, articulate modelling objectives, and specify candidate models.	Data cleaning and preparation undertaken concurrently by lead and supporting researchers due to limited resourcing and short timelines for project deliverables. Candidate models addressing different components of the research question were preregistered. Data structural properties and potential consequences for model fitting were identified
Version 2: (v0.9.0 – v.0.12.5)	Describe Pilot Analysis on data subset and specify registered flexibility in the form of decision heuristics.	Critical uncertainties in modelling decisions were articulated (e.g. how do we classify best flow regime based on inundation data?). In addition, data partitioning, exploratory data analysis, refined candidate models and model checking procedure preregistered
Version 3: (v0.13.0 – v.0.20.1)	Describe Main Analysis, including specification of decision tree for model selection process based on results of pilot analysis.	Conducted modelling and analysis as outlined in preregistration. Reported deviations and rationale as necessary.

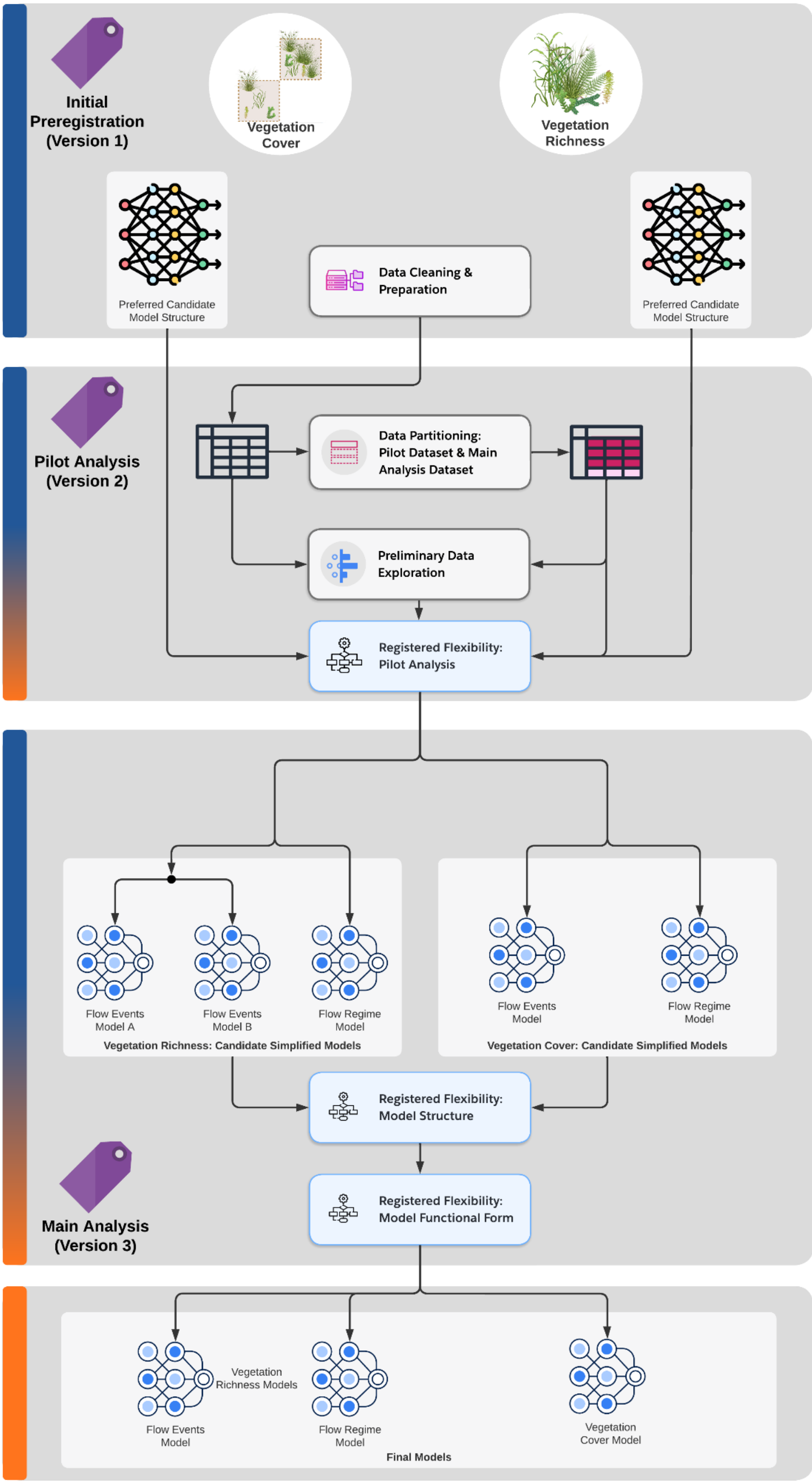

Figure B1. Model development and adaptive preregistration process (reproduced with permission from Gould et al. 2025). Three versions of the model analysis plan were preregistered. Each preregistration version and stage of the modelling process is briefly described in Table B2. The two registered flexibility steps in the Main Analysis (v3) (boxes shown in blue) are shown.

Appendix C

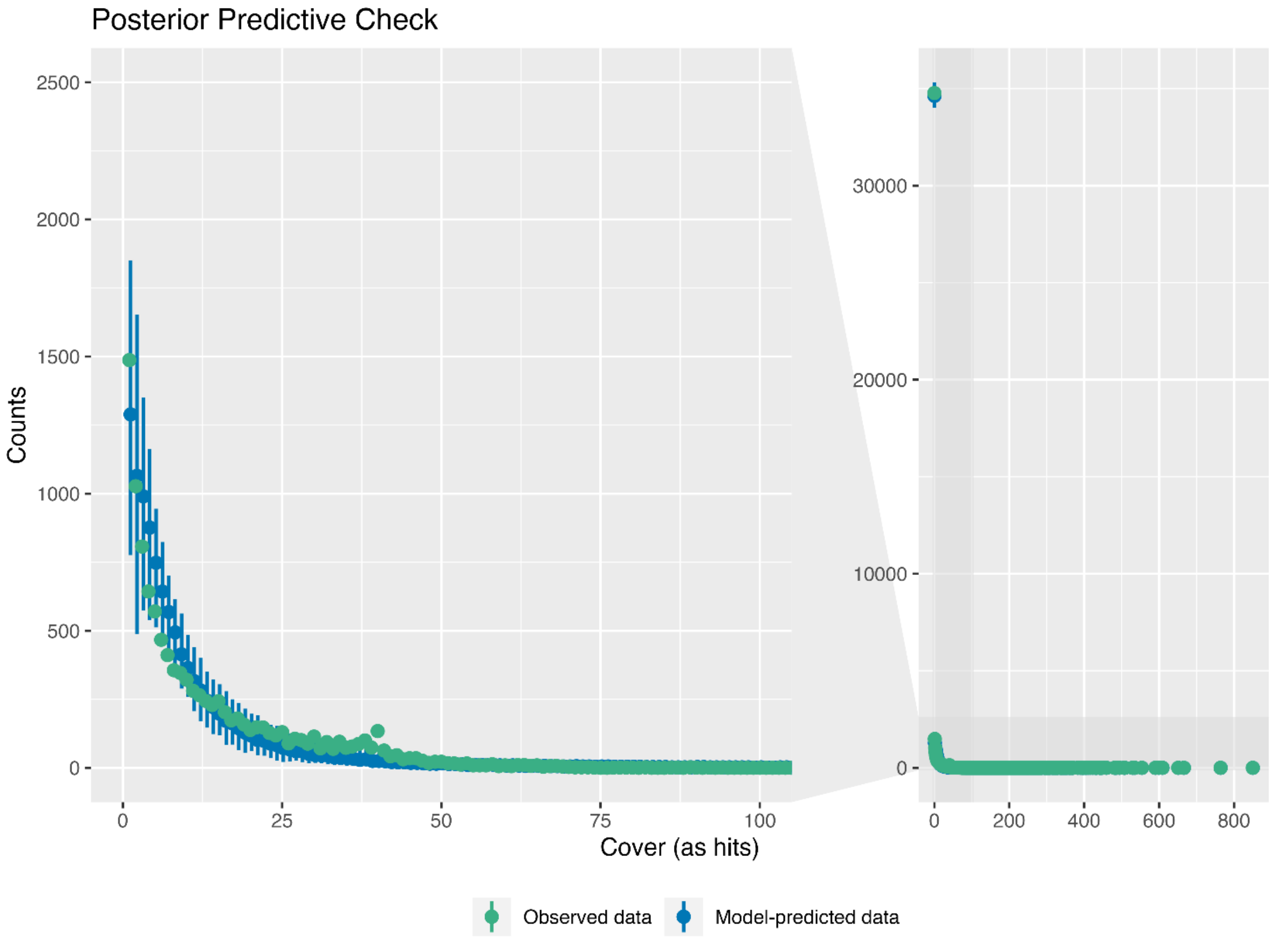

Figure C1. Posterior predictive check for the flow-regime model of vegetation cover. Blue points display the median predicted density of cover and green points display the observed density of vegetation cover. Error bars (not visible) bound 95% confidence intervals.

A model that reliably captures variation in a given response variable is indicated by close agreement between the blue and green points. This figure illustrates close agreement for zero observations (i.e., the model characterises zero-inflation well) but under-prediction at very low levels of cover and over-prediction at intermediate levels of cover. Assessments of alternative model structures (e.g., negative binomial distributions) did not improve alignment between modelled and observed values.

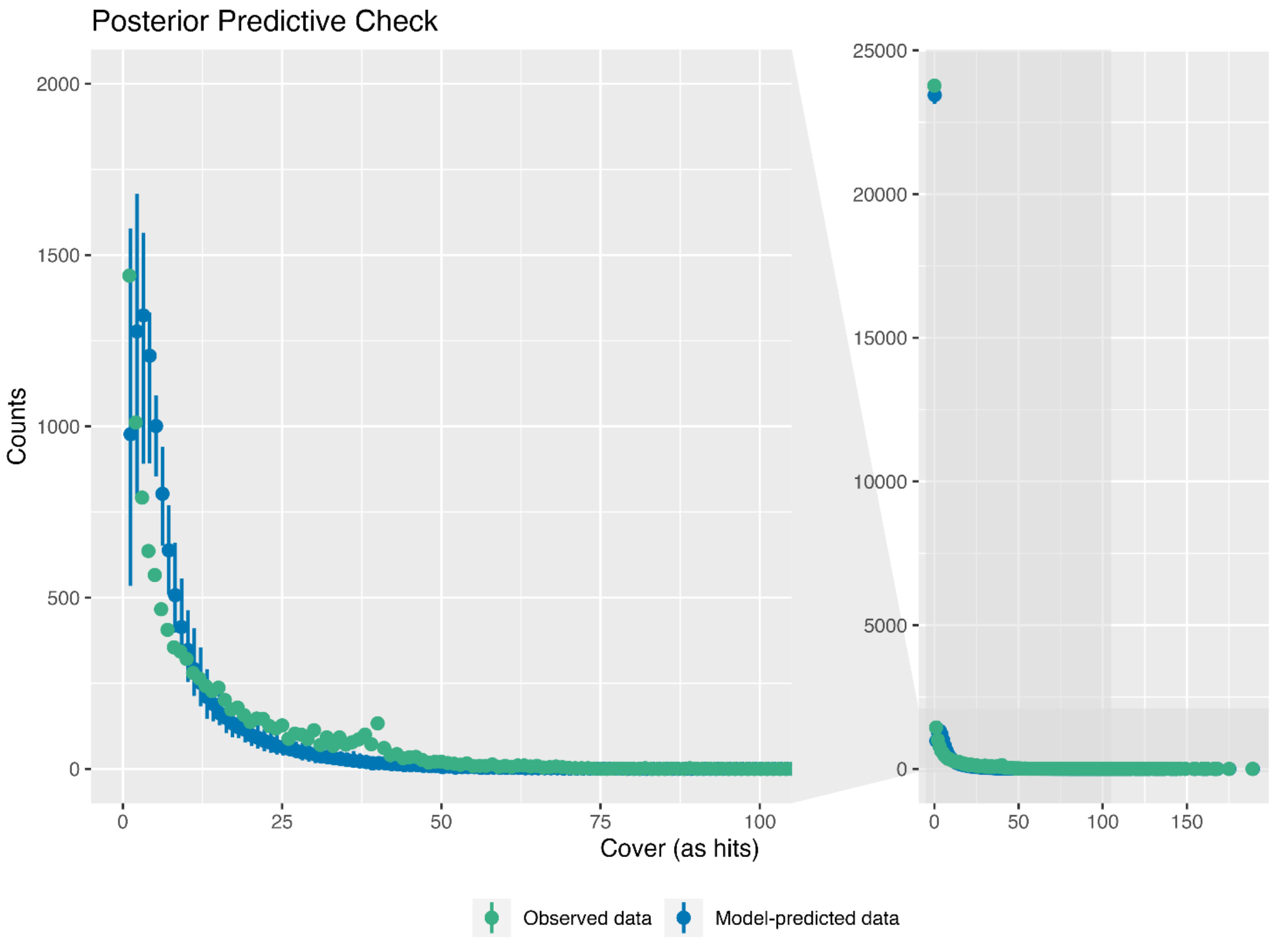

Figure C2. Posterior predictive check for the flow-event model of vegetation cover. Blue points display the median predicted density of cover and green points display the observed density of vegetation cover. Error bars (not visible) bound 95% confidence intervals.

A model that reliably captures variation in a given response variable is indicated by close agreement between the blue and green points. This figure illustrates close agreement for zero observations (i.e., the model characterises zero-inflation well) but under-prediction at very low levels of cover and over-prediction at intermediate levels of cover. Assessments of alternative model structures (e.g., negative binomial distributions) did not improve alignment between modelled and observed values.

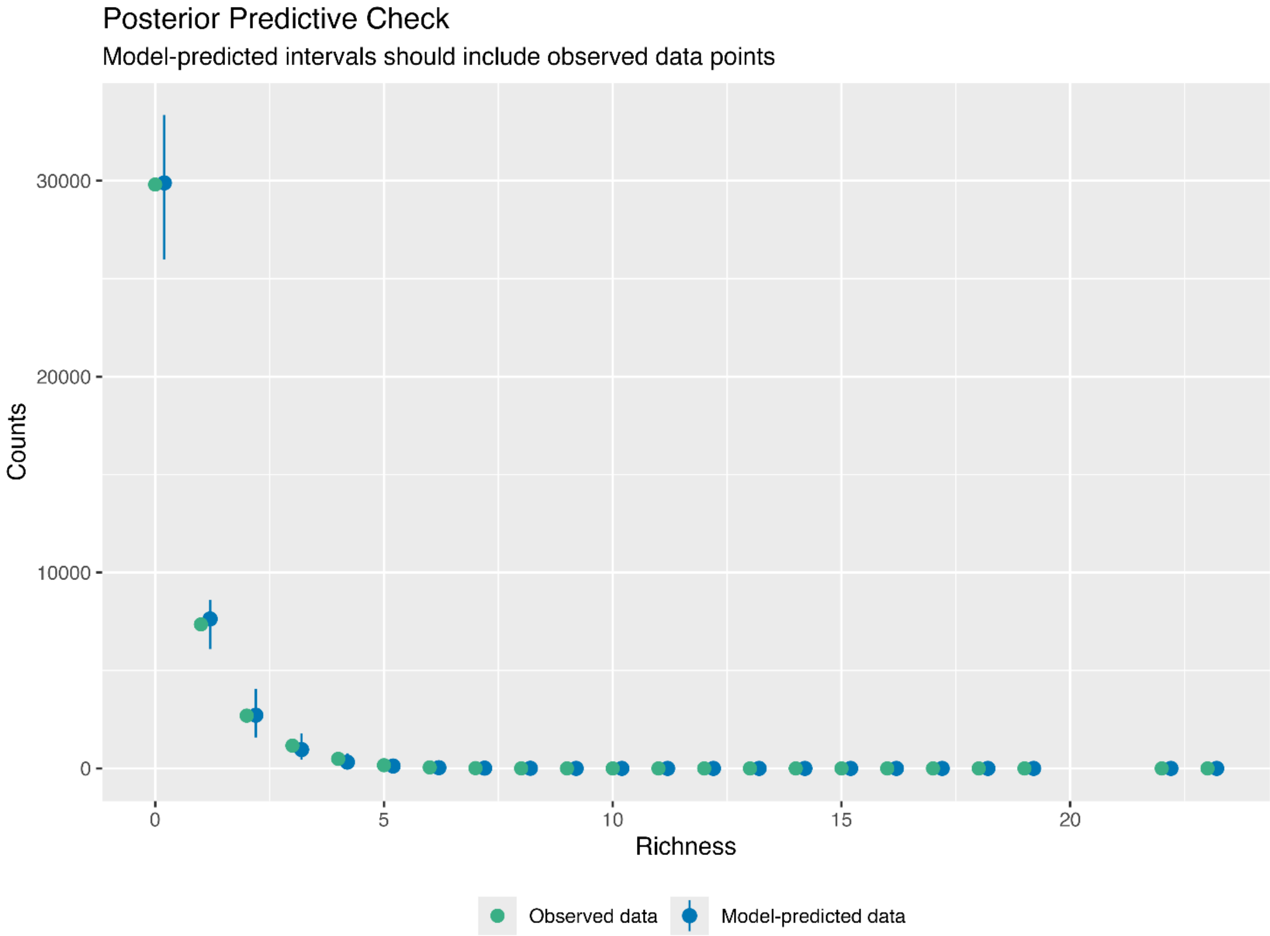

Figure C3. Posterior predictive check for the model of vegetation species richness. Blue points display the median predicted density of species richness and green points display the observed density of vegetation species richness. Error bars (visible for modelled but not observed values) bound 95% confidence intervals.

A model that reliably captures variation in a given response variable is indicated by close agreement between the blue and green points. This figure illustrates close agreement between modelled and observed species richness over the observed range of values.

Table C1. Assessment of overdispersion for all models.

Overdispersion was assessed using the *check_overdispersion()* function from the *performance* package (Ludecke, et al. 2021). For richness models (which do not include a zero-inflation parameter), overdispersion tests were based on the sum of squared Pearson residuals. The ratio of this sum to the residual degrees of freedom (assuming one model degree of freedom for each variance or covariance parameter) should approximately follow a $\chi 2$ distribution (from which a p-value can be calculated)[2]. For cover models, this test is based on simulated residuals rather than Pearson residuals, and this approach does not return an exact $\chi 2$ estimate or residual degrees of freedom[3]. Overdispersion is likely when the dispersion ratio is greater than 1 and when the *p* value for the dispersion ratio estimate is <0.05. If the p value is greater than 0.05 but the dispersion ratio is 1, then overdispersion is unlikely. If the dispersion ratio is < 1 then underdispersion is likely.

Model	χ^2	Dispersion Ratio	Residual *df*	*p*-value	Overdispersion
Richness	46,360.75	1.11	41,682	<2e-16	Overdispersion detected
Cover: flow regime	NA	0.45	NA	0.496	No overdispersion detected
Cover: flow event	NA	1.72	NA	0.064	No overdispersion detected

Table C2. Assessment of zero-inflation for all models.

Zero-inflation was assessed using the *check_zeroinflation()* function from the *performance* R package (Ludecke, et al. 2021). For the richness model, which did not contain a zero-inflation parameter, zero-inflation was assessed by simulating from the fitted model and comparing the number of predicted zeros with the number present in the observed data. Zero-inflation occurs when the number of observed zeros exceeds the number of predicted zeros[4]. For the cover models, the test of zero-dispersion is based on simulated residuals[5]. When the ratio of observed versus predicted zeros is less than a tolerance threshold (default of 1 +/-0.05 for the richness model and 1 +/-0.1 for the cover models), the model is said to be underfitting zeros, while if the ratio is greater than the upper tolerance threshold, then the model is said to be overfitting zeros. When the ratio falls within the upper and lower limits of tolerance, no zero-inflation or under-fitting of zeros is detected.

Model	Number predicted zeros	Observed zeros	Dispersion ratio	Tolerance	*P* value	Zero-inflation
Richness	29,033	29,804	0.9741310	0.05	NA	No zero-inflation detected
Cover: flow regime	35,011	35,154	0.9959188	0.10	0.640	No zero-inflation detected
Cover: flow event	23,436	23,773	0.9858253	0.10	0.096	No zero-inflation detected

[2] See https://easystats.github.io/performance/reference/check_overdispersion.html for details.

[3] See https://easystats.github.io/performance/reference/simulate_residuals.html

[4] See https://easystats.github.io/performance/reference/check_zeroinflation.html?q=zeroinflation#null for details.

[5] See https://easystats.github.io/performance/reference/simulate_residuals.html

Appendix D

Table D1: R packages, versions and citations used directly in this analysis

Package	Version	Reference
aae.hydro	0.0.1.9003	Yen (2020)
assertthat	0.2.1	Wickham (2019)
base	4.4.0	R Core Team (2024)
brms	2.21.0	Bürkner (2017), Bürkner (2018), Bürkner (2021)
cowplot	1.1.3	Wilke (2024)
effects	4.2.2	Fox and Weisberg (2019), Fox and Weisberg (2018), Fox (2003), Fox and Hong (2009)
ggforce	0.4.2	Pedersen (2024a)
ggtext	0.1.2	Wilke and Wiernik (2022)
glmmTMB	1.1.9	Brooks et al. (2017)
glue	1.7.0	Hester and Bryan (2024)
here	1.0.1	Müller (2020)
interactions	1.1.5	Long (2019)
jtools	2.2.2	Long (2022)
lme4	1.1.35.3	Bates et al. (2015)
mgcv	1.9.1	S. N. Wood (2011), S. N. Wood et al. (2016), S. N. Wood (2004), S. N. Wood (2017), S. N. Wood (2003)
mixedup	0.4.0	Clark (2024)
parameters	0.21.7	Lüdecke et al. (2020)
patchwork	1.2.0	Pedersen (2024b)
performance	0.11.0	Lüdecke, Ben-Shachar, et al. (2021)
pointblank	0.12.1	Iannone, Vargas, and Choe (2024)
qs	0.26.3	Ching (2024)
R.utils	2.12.3	Bengtsson (2023)
remotes	2.5.0	Csárdi et al. (2024)
renv	0.17.3	Ushey (2023)
rmarkdown	2.27	Allaire et al. (2024), Xie, Allaire, and Grolemund (2018), Xie, Dervieux, and Riederer (2020)
rstanarm	2.32.1	Goodrich et al. (2024), Brilleman et al. (2018)
see	0.8.4	Lüdecke, Patil, et al. (2021)
sessioninfo	1.2.2	Wickham et al. (2021)
tidyverse	2.0.0	Wickham et al. (2019)
withr	3.0.0	Hester et al. (2024)

Table D2: R Session Information

```
─ Session info ───────────────────────────────────────────
setting  value
```

```
version  R version 4.4.0 (2024-04-24)
os       macOS Ventura 13.6.6
system   aarch64, darwin20
ui       RStudio
language (EN)
collate  en_US.UTF-8
ctype    en_US.UTF-8
tz       Australia/Melbourne
date     2024-06-05
rstudio  2024.04.1+748 Chocolate Cosmos (desktop)
pandoc   3.1.12.2 @ /opt/homebrew/bin/pandoc

─ Packages ──────────────────────────────────────────────
! package       * version    date (UTC) lib source
   aae.hydro     * 0.0.1.9003 2024-06-04 [1] Github (aae-stats/aae.hydro@ab38b12)
P bit             4.0.5      2022-11-15 [?] RSPM (R 4.4.0)
P bit64           4.0.5      2020-08-30 [?] RSPM (R 4.4.0)
P cachem          1.1.0      2024-05-16 [?] RSPM (R 4.4.0)
P cellranger      1.1.0      2016-07-27 [?] RSPM (R 4.4.0)
P cli             3.6.2      2023-12-11 [?] RSPM (R 4.4.0)
P colorspace      2.1-0      2023-01-23 [?] RSPM (R 4.4.0)
P commonmark      1.9.1      2024-01-30 [?] RSPM (R 4.4.0)
P crayon          1.5.2      2022-09-29 [?] RSPM (R 4.4.0)
P curl            5.2.1      2024-03-01 [?] RSPM (R 4.4.0)
P datapasta       3.1.0      2020-01-17 [?] RSPM (R 4.4.0)
P devtools        2.4.5      2022-10-11 [?] RSPM (R 4.4.0)
P digest          0.6.35     2024-03-11 [?] RSPM (R 4.4.0)
P dplyr         * 1.1.4      2023-11-17 [?] RSPM (R 4.4.0)
P ellipsis        0.3.2      2021-04-29 [?] RSPM (R 4.4.0)
P evaluate        0.23       2023-11-01 [?] RSPM (R 4.4.0)
P fansi           1.0.6      2023-12-08 [?] RSPM (R 4.4.0)
P farver          2.1.2      2024-05-13 [?] RSPM (R 4.4.0)
P fastmap         1.2.0      2024-05-15 [?] RSPM (R 4.4.0)
P forcats       * 1.0.0      2023-01-29 [?] RSPM (R 4.4.0)
P fs              1.6.4      2024-04-25 [?] RSPM (R 4.4.0)
P generics        0.1.3      2022-07-05 [?] RSPM (R 4.4.0)
P ggplot2       * 3.5.1      2024-04-23 [?] RSPM (R 4.4.0)
P ggtext          0.1.2      2022-09-16 [?] CRAN (R 4.4.0)
P glue            1.7.0      2024-01-09 [?] RSPM (R 4.4.0)
P gluedown        1.0.9      2024-03-11 [?] CRAN (R 4.4.0)
P grateful        0.2.4      2023-10-22 [?] RSPM (R 4.4.0)
P gridtext        0.1.5      2022-09-16 [?] CRAN (R 4.4.0)
P gt            * 0.10.1     2024-01-17 [?] RSPM (R 4.4.0)
P gtable          0.3.5      2024-04-22 [?] RSPM (R 4.4.0)
P here          * 1.0.1      2020-12-13 [?] RSPM (R 4.4.0)
P highr           0.11       2024-05-26 [?] CRAN (R 4.4.0)
P hms             1.1.3      2023-03-21 [?] RSPM (R 4.4.0)
P htmltools       0.5.8.1    2024-04-04 [?] RSPM (R 4.4.0)
P htmlwidgets     1.6.4      2023-12-06 [?] RSPM (R 4.4.0)
P httpuv          1.6.15     2024-03-26 [?] RSPM (R 4.4.0)
P httr            1.4.7      2023-08-15 [?] RSPM (R 4.4.0)
   httr2           1.0.1      2024-04-01 [1] CRAN (R 4.4.0)
P jsonlite        1.8.8      2023-12-04 [?] RSPM (R 4.4.0)
P knitr           1.47       2024-05-29 [?] CRAN (R 4.4.0)
P labeling        0.4.3      2023-08-29 [?] RSPM (R 4.4.0)
P later           1.3.2      2023-12-06 [?] RSPM (R 4.4.0)
P lattice         0.22-6     2024-03-20 [?] CRAN (R 4.4.0)
P lifecycle       1.0.4      2023-11-07 [?] RSPM (R 4.4.0)
P lubridate     * 1.9.3      2023-09-27 [?] RSPM (R 4.4.0)
P magrittr        2.0.3      2022-03-30 [?] RSPM (R 4.4.0)
P markdown        1.12       2023-12-06 [?] RSPM (R 4.4.0)
P Matrix          1.7-0      2024-03-22 [?] CRAN (R 4.4.0)
P memoise         2.0.1      2021-11-26 [?] RSPM (R 4.4.0)
P mgcv            1.9-1      2023-12-21 [?] CRAN (R 4.4.0)
P mime            0.12       2021-09-28 [?] RSPM (R 4.4.0)
P miniUI          0.1.1.1    2018-05-18 [?] RSPM (R 4.4.0)
P munsell         0.5.1      2024-04-01 [?] RSPM (R 4.4.0)
P nlme            3.1-164    2023-11-27 [?] CRAN (R 4.4.0)
P pillar          1.9.0      2023-03-22 [?] RSPM (R 4.4.0)
```

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P pkgbuild        1.4.4      2024-03-17 [?] RSPM (R 4.4.0)
P pkgconfig       2.0.3      2019-09-22 [?] RSPM (R 4.4.0)
P pkgload         1.3.4      2024-01-16 [?] RSPM (R 4.4.0)
P profvis         0.3.8      2023-05-02 [?] RSPM (R 4.4.0)
P promises        1.3.0      2024-04-05 [?] RSPM (R 4.4.0)
P purrr           1.0.2      2023-08-10 [?] RSPM (R 4.4.0)
P qs            * 0.26.3     2024-05-16 [?] CRAN (R 4.4.0)
P R6              2.5.1      2021-08-19 [?] RSPM (R 4.4.0)
P ragg            1.3.2      2024-05-15 [?] RSPM (R 4.4.0)
P RApiSerialize   0.1.3      2024-05-14 [?] CRAN (R 4.4.0)
P rappdirs        0.3.3      2021-01-31 [?] RSPM (R 4.4.0)
P Rcpp            1.0.12     2024-01-09 [?] RSPM (R 4.4.0)
P RcppParallel    5.1.7      2023-02-27 [?] CRAN (R 4.4.0)
P readr         * 2.1.5      2024-01-10 [?] RSPM (R 4.4.0)
P readxl        * 1.4.3      2023-07-06 [?] RSPM (R 4.4.0)
P remotes         2.5.0      2024-03-17 [?] RSPM (R 4.4.0)
P renv            0.17.3     2023-04-06 [?] CRAN (R 4.4.0)
P rlang           1.1.3      2024-01-10 [?] RSPM (R 4.4.0)
P rprojroot       2.0.4      2023-11-05 [?] RSPM (R 4.4.0)
P rstudioapi      0.16.0     2024-03-24 [?] RSPM (R 4.4.0)
P scales          1.3.0      2023-11-28 [?] RSPM (R 4.4.0)
P sessioninfo     1.2.2      2021-12-06 [?] RSPM (R 4.4.0)
P shiny           1.8.1.1    2024-04-02 [?] RSPM (R 4.4.0)
P stringfish      0.16.0     2023-11-28 [?] CRAN (R 4.4.0)
P stringi         1.8.4      2024-05-06 [?] RSPM (R 4.4.0)
P stringr       * 1.5.1      2023-11-14 [?] RSPM (R 4.4.0)
P systemfonts     1.1.0      2024-05-15 [?] RSPM (R 4.4.0)
P textshaping     0.4.0      2024-05-24 [?] CRAN (R 4.4.0)
P tibble          3.2.1      2023-03-20 [?] RSPM (R 4.4.0)
P tidyr         * 1.3.1      2024-01-24 [?] RSPM (R 4.4.0)
P tidyselect      1.2.1      2024-03-11 [?] RSPM (R 4.4.0)
P timechange      0.3.0      2024-01-18 [?] RSPM (R 4.4.0)
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P utf8            1.2.4      2023-10-22 [?] RSPM (R 4.4.0)
P vctrs           0.6.5      2023-12-01 [?] RSPM (R 4.4.0)
P vroom           1.6.5      2023-12-05 [?] RSPM (R 4.4.0)
P withr           3.0.0      2024-01-16 [?] RSPM (R 4.4.0)
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P xtable          1.8-4      2019-04-21 [?] RSPM (R 4.4.0)
P yaml            2.3.8      2023-12-11 [?] RSPM (R 4.4.0)

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P ── Loaded and on-disk path mismatch.
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Appendix E

Table E1. Number of species recorded in each waterway by vegetation group.

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)	Total (native)	Total (exotic)
Campaspe	0	9	0	7	8	26	89	53	95	97
Glenelg	1	9	1	9	13	33	66	39	90	81
Wannon	0	2	0	3	0	14	11	10	29	11
Loddon	0	0	0	0	1	10	15	13	23	16
Tullaroop	0	2	0	4	4	7	40	7	20	44
Twelve Mile	0	2	0	1	4	14	19	10	27	23
Moorabool	1	10	0	6	5	28	63	36	80	69
Sutherland	0	1	0	3	3	4	23	4	12	26
Macalister	0	1	0	5	6	13	40	10	29	46
Thomson	0	2	0	3	8	14	42	4	23	50
Burnt	0	5	0	2	4	25	48	41	73	52
McKenzie	0	3	0	1	4	20	40	37	61	44
Mt William	2	4	0	4	7	18	51	20	46	60
Watts	0	1	0	0	5	10	27	9	20	32
Yarra	2	2	0	1	11	23	72	30	56	85

Table E2. Mean percentage cover for a sub-transect in each waterway by vegetation group.

Waterway	Aquatic (exotic)	Aquatic (native)	Emergent (exotic)	Emergent (native)	Riparian (exotic)	Riparian (native)	Terrestrial (exotic)	Terrestrial (native)
Campaspe	0	0.4	0	5.3	5.3	16.3	24.1	10.9
Glenelg	0	8.5	0.4	6.2	3.5	17.4	24.5	15.7
Wannon	0	4	0	19.8	0	49.1	6.6	37.2
Loddon	0	0	0	0	0	30	3.6	15.6
Tullaroop	0	0.6	0	23.7	3.9	2.9	31.7	0.5
Twelve Mile	0	2.5	0	0	21.2	38.4	8.7	3.6
Moorabool	0	6.1	0	12.9	2.9	10.5	28.4	26.4
Sutherland	0	0.6	0	10.8	3.2	2.3	62.4	0.7
Macalister	0	0.2	0	3.6	18.1	28.3	30.7	3.5
Thomson	0	0.3	0	1.3	32.4	16.2	47.3	4.6
Burnt	0	3.3	0	2.6	2.3	35.3	29	5.9
McKenzie	0	2.6	0	0	1.2	23.6	22.5	19.3
Mt William	0.1	6.7	0	8.8	5.4	27.6	48.8	2.7
Watts	0	0.9	0	0	17.8	17.4	27.4	19.5
Yarra	0	0.5	0	0.3	17	21	46.3	13.2

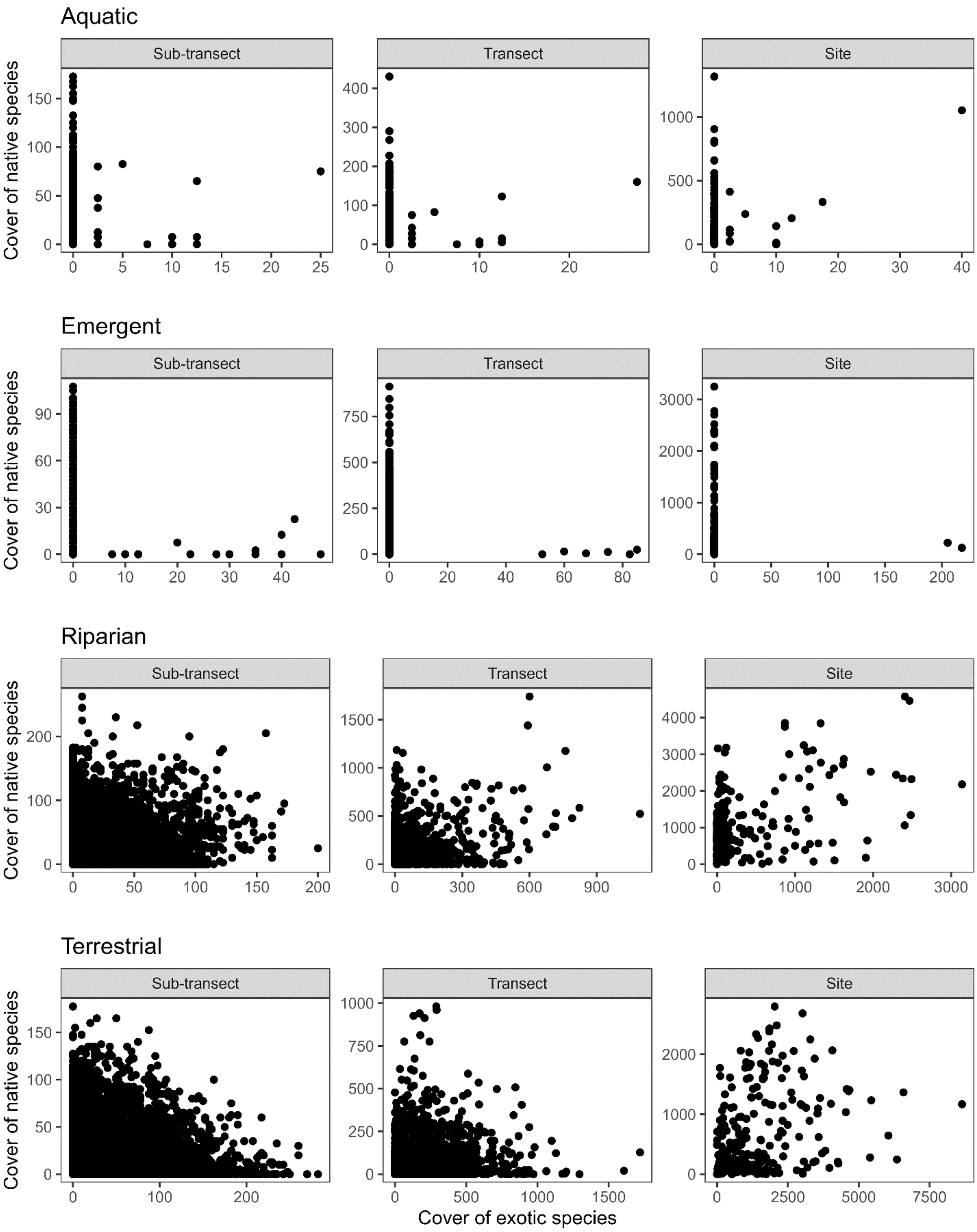

Figure E1. The summed percentage cover of native versus exotic species in the four functional groups within each sub-transect, transect, and site using all survey data.

Appendix F

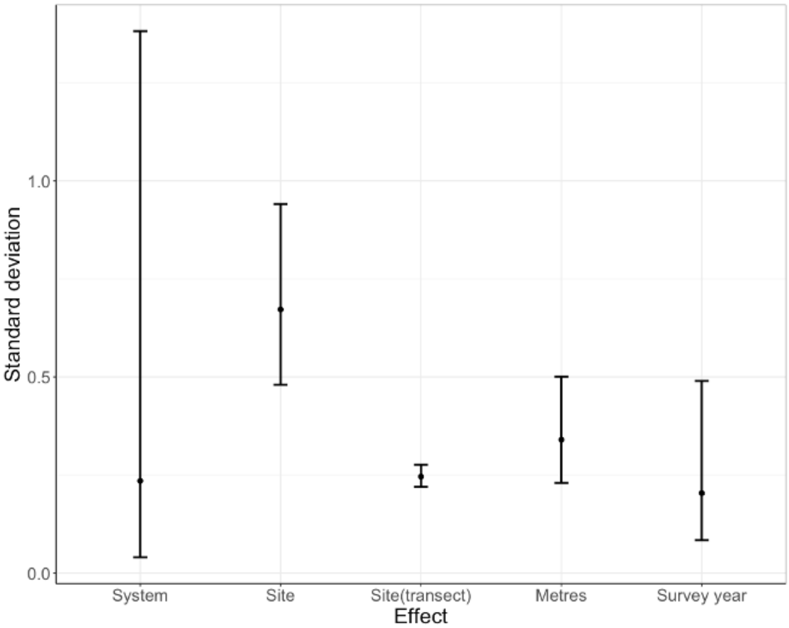

Figure F1. Estimated standard deviations of random intercepts for different factors included in the analysis of vegetation cover as a function of flow regimes (days above baseflow and spring-fresh levels).

Points are mean estimated standard deviations and bars bound 95% confidence intervals. Standard deviations of random effects reflect the amount of variation among levels of each random factor, with high values highlighting the level/s at which variation is most pronounced.

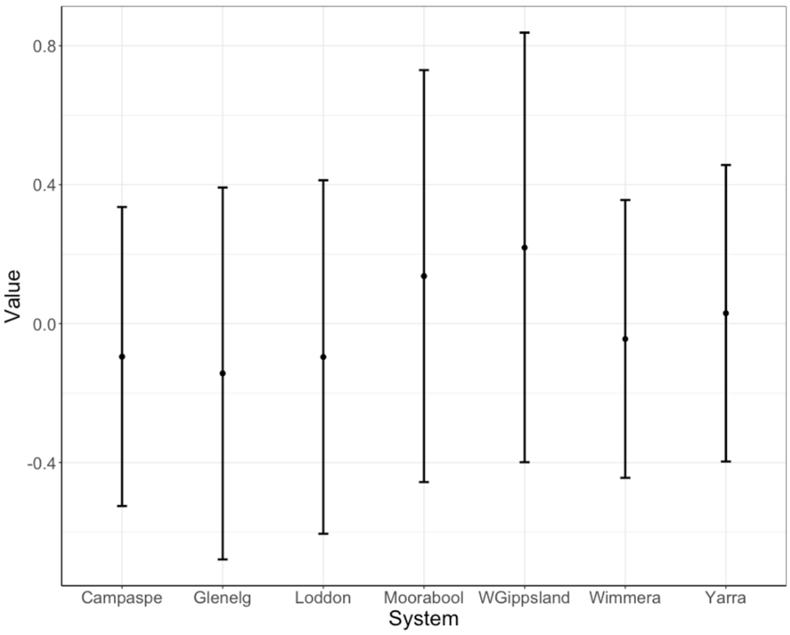

Figure F2. Estimated random intercepts for different systems included in the analysis of vegetation cover as a function of flow regimes (days above baseflow and spring-fresh levels).

Points are mean estimated intercepts on the link scale and bars bound 95% confidence intervals. Random intercepts reflect the deviation of each level (here, different systems) from the average value over all levels. Higher values indicate generally higher-than-average cover and low values the opposite. Systems may include multiple waterways (see main text for sampling details).

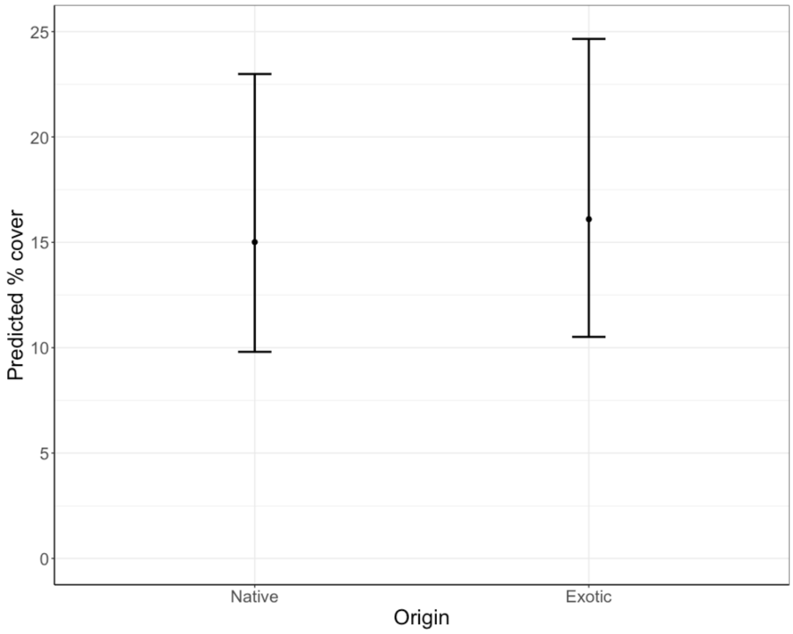

Figure F3. Predicted associations between vegetation cover and species origin from the analysis of vegetation cover as a function of flow regimes.

Solid points are mean estimates of cover for each functional group and error bars bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 20%, which reflects the relatively low values of average cover given many zeros in the data set.

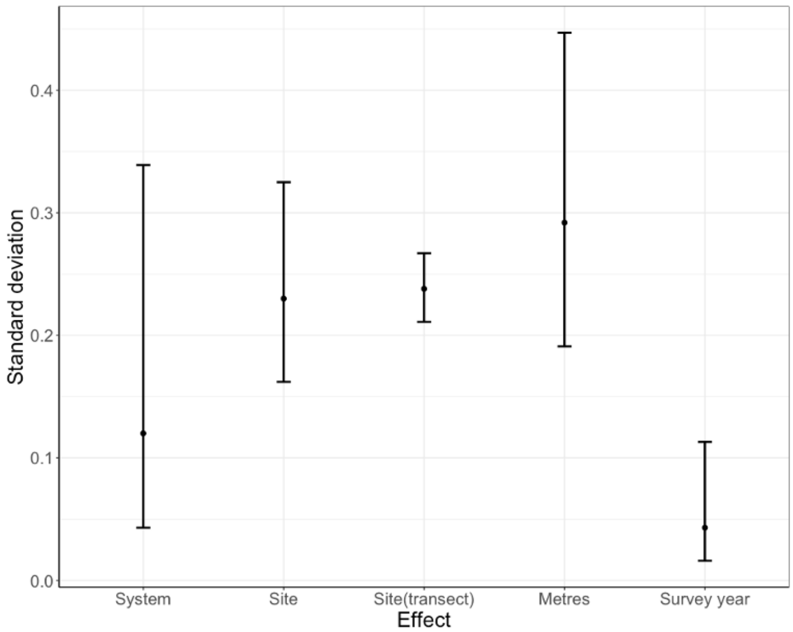

Figure F4. Estimated standard deviations of random intercepts for different factors included in the analysis of vegetation cover as a function of flow events (spring and summer freshes). Points are mean estimated standard deviations and bars bound 95% confidence intervals.

Standard deviations of random effects reflect the amount of variation among levels of each random factor, with high values highlighting the level/s at which variation is most pronounced.

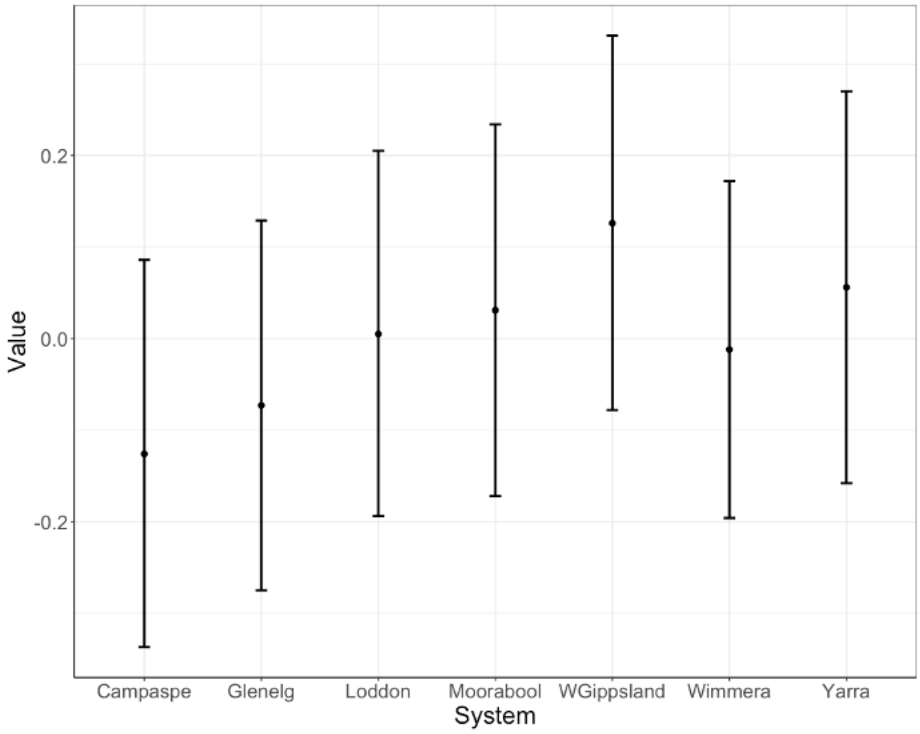

Figure F5. Estimated random intercepts for different systems included in the analysis of vegetation cover as a function of flow events (spring and summer freshes).

Points are mean estimated intercepts on the link scale and bars bound 95% confidence intervals. Random intercepts reflect the deviation of each level (here, different systems) from the average value over all levels. Higher values indicate generally higher-than-average cover and low values the opposite. Systems may include multiple waterways (see main text for sampling details).

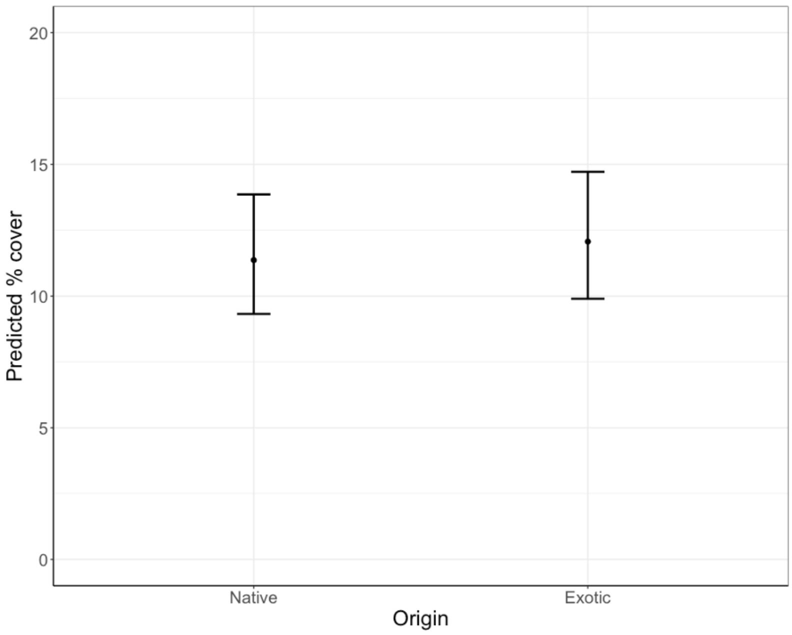

Figure F6. Predicted associations between vegetation cover and species origin from the analysis of vegetation cover as a function of flow events.

Solid points are mean estimates of cover for each functional group and error bars bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 20%, which reflects the relatively low values of average cover given many zeros in the data set.

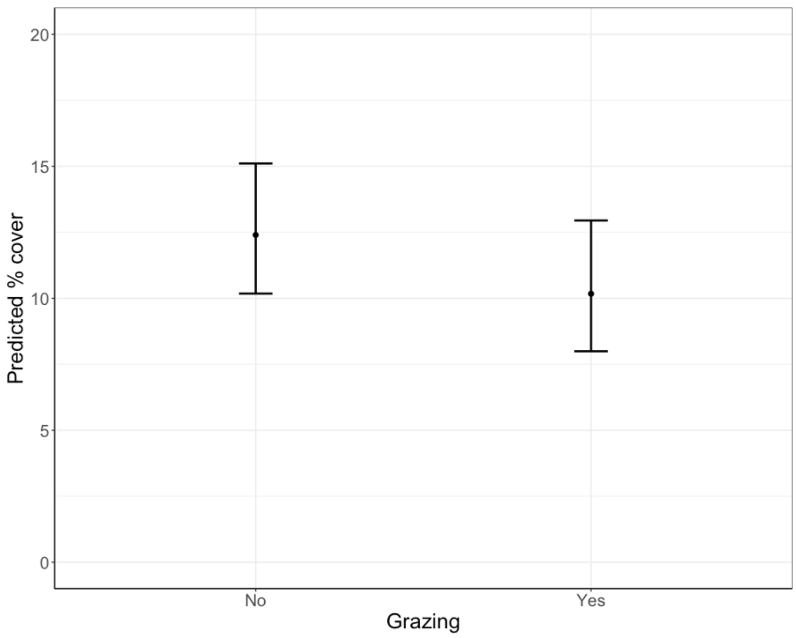

Figure F7. Predicted associations between vegetation cover and the occurrence of livestock grazing from the analysis of vegetation cover as a function of flow events (Yes: grazing occurs; No: no grazing occurs).

Solid points are mean estimates of cover for each functional group and error bars bound 95% confidence intervals. Note that the y-axis is truncated to a maximum value of 20%, which reflects the relatively low values of average cover given many zeros in the data set.

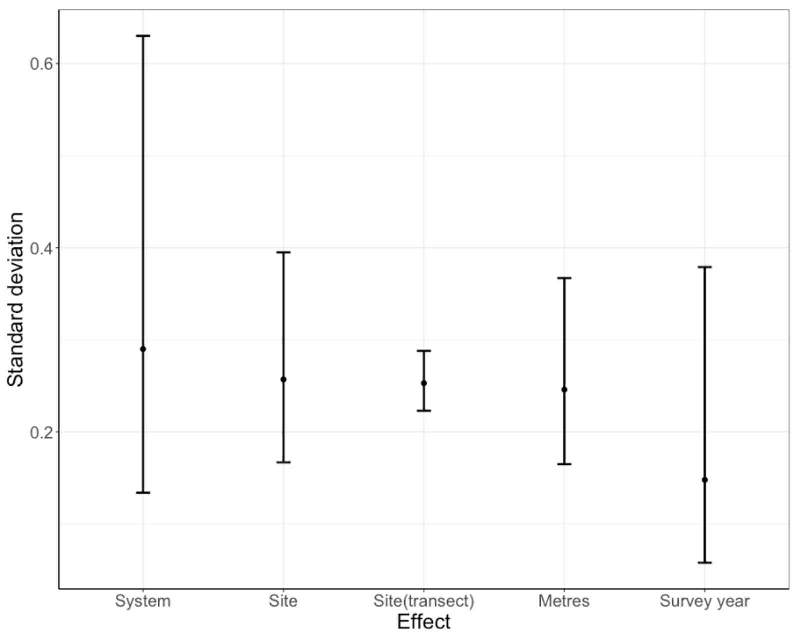

Figure F8. Estimated standard deviations of random intercepts for different factors included in the analysis of vegetation species richness.

Points are mean estimated standard deviations and bars bound 95% confidence intervals. Standard deviations of random effects reflect the amount of variation among levels of each random factor, with high values highlighting the level/s at which variation is most pronounced.

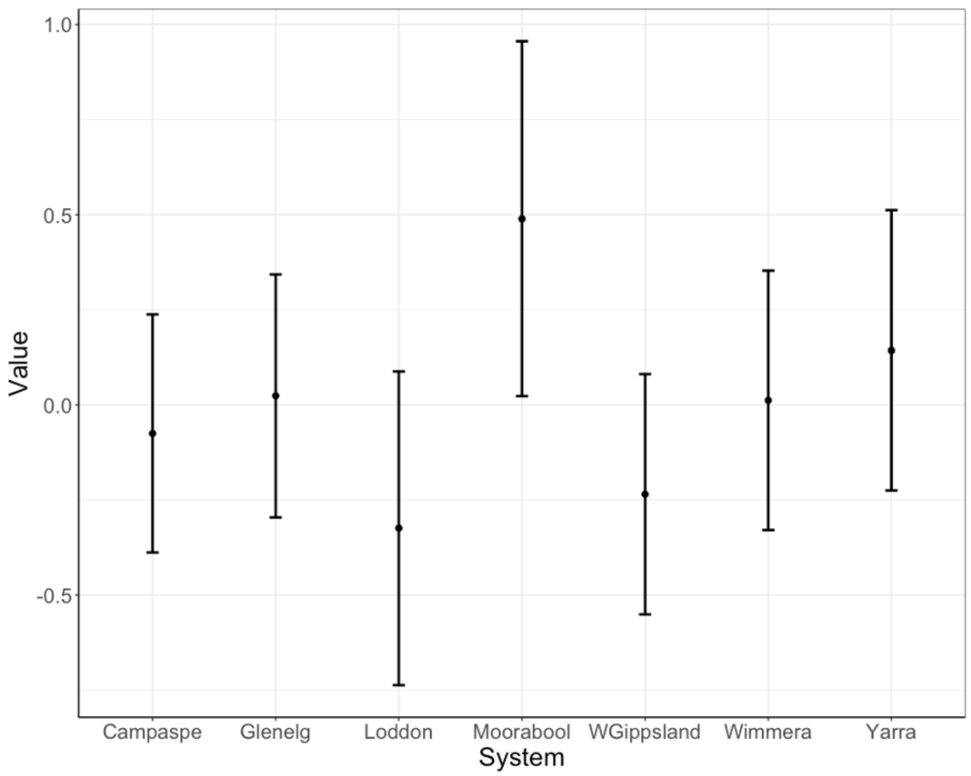

Figure F9. Estimated random intercepts for different systems included in the analysis of vegetation species richness.

Points are mean estimated intercepts on the link scale and bars bound 95% confidence intervals. Random intercepts reflect the deviation of each level (here, different systems) from the average value over all levels. Higher values indicate generally higher-than-average species richness and low values the opposite. Systems may include multiple waterways (see main text for sampling details).

Table F1. Parameter estimates for vegetation richness model. SE: standard error, SD: standard deviation, std: standardised, wpfg: water plant functional group.

Parameter	Coefficient	SE	95% CI	z	p
Fixed Effects					
(Intercept)	-3.88	0.26	(-4.39, -3.37)	-14.87	< .001
days above baseflow std	0.02	0.08	(-0.13, 0.17)	0.24	0.810
wpfg (Emergent)	1.20	0.23	(0.74, 1.65)	5.15	< .001
wpfg (Riparian)	2.94	0.20	(2.54, 3.33)	14.57	< .001
wpfg (Terrestrial)	3.87	0.20	(3.48, 4.26)	19.41	< .001
days above springfresh std	0.37	0.11	(0.15, 0.58)	3.33	< .001
origin (native)	0.28	0.01	(0.25, 0.31)	18.94	< .001
origin (unknown)	-3.94	0.10	(-4.13, -3.75)	-40.41	< .001
days above baseflow std^2	-0.01	0.02	(-0.05, 0.03)	-0.70	0.485
days above springfresh std^2	-0.07	0.03	(-0.13, -0.02)	-2.61	0.009
zone (baseflow_to_springfresh)	0.26	0.24	(-0.22, 0.73)	1.05	0.295
zone (below_baseflow)	2.35	0.24	(1.89, 2.82)	9.86	< .001
period (after_summer)	0.06	0.27	(-0.47, 0.60)	0.24	0.813
period (before_spring)	-0.10	0.29	(-0.68, 0.47)	-0.36	0.721
grazing (Y)	-0.22	0.10	(-0.42, -0.03)	-2.24	0.025
days above baseflow std × wpfg (Emergent)	-0.11	0.07	(-0.24, 0.02)	-1.60	0.109
days above baseflow std × wpfg (Riparian)	-0.22	0.06	(-0.33, -0.10)	-3.77	< .001
days above baseflow std × wpfg (Terrestrial)	-0.13	0.06	(-0.24, -0.02)	-2.23	0.026
wpfg (Emergent) × days above springfresh std	0.09	0.06	(-0.04, 0.21)	1.38	0.167
wpfg (Riparian) × days above springfresh std	0.03	0.06	(-0.08, 0.13)	0.47	0.635
wpfg (Terrestrial) × days above springfresh std	-0.08	0.06	(-0.19, 0.02)	-1.51	0.130
wpfg (Emergent) × zone (baseflow_to_springfresh)	0.43	0.28	(-0.11, 0.98)	1.55	0.121
wpfg (Riparian) × zone (baseflow_to_springfresh)	0.49	0.25	(7.74e-03, 0.98)	1.99	0.046
wpfg (Terrestrial) × zone (baseflow_to_springfresh)	-0.72	0.25	(-1.20, -0.23)	-2.91	0.004
wpfg (Emergent) × zone (below_baseflow)	-0.62	0.29	(-1.18, -0.06)	-2.18	0.030
wpfg (Riparian) × zone (below_baseflow)	-1.67	0.25	(-2.16, -1.19)	-6.76	< .001
wpfg (Terrestrial) × zone (below_baseflow)	-3.61	0.26	(-4.12, -3.10)	-13.93	< .001
zone (baseflow_to_springfresh) × period (after_summer)	0.08	0.33	(-0.57, 0.74)	0.25	0.805
zone (below_baseflow) × period (after_summer)	-0.13	0.33	(-0.78, 0.52)	-0.38	0.703
zone (baseflow_to_springfresh) × period (before_spring)	0.55	0.35	(-0.13, 1.24)	1.59	0.113
zone (below_baseflow) × period (before_spring)	0.18	0.35	(-0.50, 0.86)	0.52	0.606
wpfg (Emergent) × period (after_summer)	-0.01	0.32	(-0.64, 0.62)	-0.04	0.972
wpfg (Riparian) × period (after_summer)	-0.09	0.28	(-0.64, 0.46)	-0.31	0.755

wpfg (Terrestrial) × period (after_summer)	-0.33	0.28	(-0.87, 0.22)	-1.18	0.240
wpfg (Emergent) × period (before_spring)	0.04	0.34	(-0.64, 0.71)	0.10	0.917
wpfg (Riparian) × period (before_spring)	-0.11	0.30	(-0.69, 0.48)	-0.35	0.725
wpfg (Terrestrial) × period (before_spring)	0.21	0.30	(-0.37, 0.79)	0.71	0.477
(wpfg (Emergent) × zone (baseflow_to_springfresh)) × period (after_summer)	-0.12	0.39	(-0.88, 0.63)	-0.32	0.747
(wpfg (Riparian) × zone (baseflow_to_springfresh)) × period (after_summer)	-0.08	0.34	(-0.74, 0.59)	-0.23	0.819
(wpfg (Terrestrial) × zone (baseflow_to_springfresh)) × period (after_summer)	0.07	0.34	(-0.59, 0.74)	0.22	0.830
(wpfg (Emergent) × zone (below_baseflow)) × period (after_summer)	-1.46e-03	0.40	(-0.79, 0.79)	-3.63e-03	0.997
(wpfg (Riparian) × zone (below_baseflow)) × period (after_summer)	0.21	0.35	(-0.47, 0.89)	0.60	0.546
(wpfg (Terrestrial) × zone (below_baseflow)) × period (after_summer)	0.47	0.36	(-0.24, 1.18)	1.29	0.196
(wpfg (Emergent) × zone (baseflow_to_springfresh)) × period (before_spring)	-0.78	0.41	(-1.58, 0.01)	-1.93	0.054
(wpfg (Riparian) × zone (baseflow_to_springfresh)) × period (before_spring)	-0.56	0.36	(-1.26, 0.13)	-1.59	0.113
(wpfg (Terrestrial) × zone (baseflow_to_springfresh)) × period (before_spring)	-0.56	0.35	(-1.25, 0.13)	-1.60	0.110
(wpfg (Emergent) × zone (below_baseflow)) × period (before_spring)	-0.34	0.43	(-1.18, 0.49)	-0.81	0.420
(wpfg (Riparian) × zone (below_baseflow)) × period (before_spring)	-0.11	0.37	(-0.83, 0.61)	-0.30	0.768
(wpfg (Terrestrial) × zone (below_baseflow)) × period (before_spring)	-0.55	0.39	(-1.31, 0.21)	-1.41	0.158
Random Effects					
SD (Intercept: transect:site)	0.25				
SD (Intercept: site)	0.26				
SD (Intercept: metres)	0.25				
SD (Intercept: survey_year)	0.15				
SD (Intercept: system)	0.29				

Table F2. Parameter estimates for vegetation cover flow-regime model. SE: standard error, SD: standard deviation, std: standardised, wpfg: water plant functional group.

Parameter	Coefficient	SE	95% CI	z	p
Fixed Effects (Count Model)					
(Intercept)	1.30	0.22	(0.86, 1.73)	5.88	< .001
log hits tm1	0.49	2.75e-03	(0.49, 0.50)	178.72	< .001
days above baseflow std	-0.06	0.03	(-0.12, 2.59e-03)	-1.88	0.060
wpfg (Emergent)	0.48	0.04	(0.40, 0.56)	12.01	< .001
wpfg (Riparian)	0.30	0.04	(0.23, 0.38)	7.90	< .001
wpfg (Terrestrial)	0.39	0.04	(0.32, 0.47)	10.10	< .001
days above springfresh std	0.24	0.07	(0.10, 0.39)	3.25	0.001
days above baseflow std^2	0.05	0.02	(0.02, 0.08)	3.35	< .001
days above springfresh std^2	-0.16	0.02	(-0.20, -0.12)	-7.61	< .001
origin (native)	-0.07	6.65e-03	(-0.08, -0.06)	-10.48	< .001
origin (unknown)	-4.49	0.07	(-4.63, -4.36)	-67.13	< .001
days above baseflow std × wpfg (Emergent)	-0.11	0.03	(-0.16, -0.06)	-3.97	< .001
days above baseflow std × wpfg (Riparian)	-0.22	0.02	(-0.26, -0.17)	-9.04	< .001
days above baseflow std × wpfg (Terrestrial)	-0.23	0.02	(-0.27, -0.18)	-9.47	< .001
wpfg (Emergent) × days above springfresh std	0.49	0.06	(0.37, 0.62)	7.80	< .001
wpfg (Riparian) × days above springfresh std	0.52	0.06	(0.40, 0.63)	9.05	< .001
wpfg (Terrestrial) × days above springfresh std	0.51	0.06	(0.40, 0.62)	9.02	< .001
wpfg (Emergent) × days above baseflow std^2	-0.03	0.02	(-0.06, 4.15e-04)	-1.93	0.053
wpfg (Riparian) × days above baseflow std^2	9.48e-04	0.01	(-0.03, 0.03)	0.07	0.945
wpfg (Terrestrial) × days above baseflow std^2	-3.20e-03	0.01	(-0.03, 0.02)	-0.23	0.817
wpfg (Emergent) × days above springfresh std^2	-0.13	0.02	(-0.16, -0.09)	-7.32	< .001
wpfg (Riparian) × days above springfresh std^2	-0.09	0.02	(-0.12, -0.06)	-5.70	< .001
wpfg (Terrestrial) × days above springfresh std^2	-0.11	0.02	(-0.14, -0.07)	-6.62	< .001
Fixed Effects (Zero-Inflation Component)					
(Intercept)	3.09	0.06	(2.96, 3.21)	48.92	< .001
wpfg (Emergent)	-1.35	0.07	(-1.50, -1.21)	-18.48	< .001

Parameter	Coefficient	SE	95% CI	z	p
wpfg (Riparian)	-2.73	0.07	(-2.86, -2.60)	-41.30	< .001
wpfg (Terrestrial)	-3.12	0.07	(-3.24, -2.99)	-47.16	< .001
Random Effects Variances					
SD (Intercept: transect:site)	0.25				
SD (Intercept: site)	0.67				
SD (Intercept: metres)	0.34				
SD (Intercept: survey_year)	0.20				
SD (Intercept: system)	0.23				

Table F3. Parameter estimates for vegetation cover flow-event model. SE: standard error, SD: standard deviation, std: standardised, wpfg: water plant functional group.

Parameter	Coefficient	SE	95% CI	z	p
Fixed Effects (Count Model)					
(Intercept)	1.28	0.13	(1.03, 1.54)	9.80	< .001
log hits tm1	0.52	2.86e-03	(0.51, 0.52)	180.40	< .001
zone (baseflow_to_springfresh)	-0.60	0.11	(-0.83, -0.38)	-5.26	< .001
zone (below_baseflow)	-7.81e-03	0.10	(-0.20, 0.18)	-0.08	0.935
wpfg (Emergent)	0.13	0.09	(-0.05, 0.31)	1.37	0.172
wpfg (Riparian)	0.17	0.09	(5.80e-03, 0.34)	2.03	0.043
wpfg (Terrestrial)	0.12	0.09	(-0.05, 0.28)	1.36	0.174
period (after_summer)	-0.26	0.12	(-0.49, -0.03)	-2.24	0.025
period (before_spring)	2.50e-03	0.87	(-1.70, 1.71)	2.87e-03	0.998
origin (native)	-0.06	6.69e-03	(-0.07, -0.05)	-8.97	< .001
grazing (Y)	-0.20	0.08	(-0.36, -0.03)	-2.35	0.019
zone (baseflow_to_springfresh) × wpfg (Emergent)	0.86	0.12	(0.62, 1.09)	7.06	< .001
zone (below_baseflow) × wpfg (Emergent)	0.16	0.11	(-0.05, 0.37)	1.53	0.127
zone (baseflow_to_springfresh) × wpfg (Riparian)	0.64	0.11	(0.42, 0.87)	5.61	< .001
zone (below_baseflow) × wpfg (Riparian)	-0.04	0.10	(-0.23, 0.16)	-0.37	0.708
zone (baseflow_to_springfresh) × wpfg (Terrestrial)	0.64	0.11	(0.41, 0.86)	5.56	< .001
zone (below_baseflow) × wpfg (Terrestrial)	-0.09	0.11	(-0.29, 0.12)	-0.82	0.411
zone (baseflow_to_springfresh) × period (after_summer)	1.13	0.15	(0.84, 1.42)	7.66	< .001

Parameter	Coefficient	SE	95% CI	z	p
zone (below_baseflow) × period (after_summer)	0.25	0.13	(-0.01, 0.51)	1.87	0.062
zone (baseflow_to_springfresh) × period (before_spring)	-1.64	0.93	(-3.46, 0.18)	-1.77	0.077
zone (below_baseflow) × period (before_spring)	-0.18	0.87	(-1.90, 1.53)	-0.21	0.835
wpfg (Emergent) × period (after_summer)	0.07	0.13	(-0.19, 0.32)	0.52	0.604
wpfg (Riparian) × period (after_summer)	0.01	0.12	(-0.22, 0.25)	0.11	0.912
wpfg (Terrestrial) × period (after_summer)	0.12	0.12	(-0.12, 0.35)	0.97	0.330
wpfg (Emergent) × period (before_spring)	-2.49	0.93	(-4.31, -0.66)	-2.67	0.008
wpfg (Riparian) × period (before_spring)	-0.31	0.87	(-2.02, 1.39)	-0.36	0.719
wpfg (Terrestrial) × period (before_spring)	0.65	0.87	(-1.05, 2.35)	0.75	0.455
(zone (baseflow_to_springfresh) × wpfg (Emergent)) × period (after_summer)	-1.08	0.16	(-1.39, -0.77)	-6.82	< .001
(zone (below_baseflow) × wpfg (Emergent)) × period (after_summer)	-0.13	0.15	(-0.42, 0.16)	-0.87	0.387
(zone (baseflow_to_springfresh) × wpfg (Riparian)) × period (after_summer)	-0.99	0.15	(-1.28, -0.69)	-6.61	< .001
(zone (below_baseflow) × wpfg (Riparian)) × period (after_summer)	0.07	0.14	(-0.20, 0.34)	0.49	0.622
(zone (baseflow_to_springfresh) × wpfg (Terrestrial)) × period (after_summer)	-1.02	0.15	(-1.31, -0.73)	-6.86	< .001
(zone (below_baseflow) × wpfg (Terrestrial)) × period (after_summer)	-0.28	0.15	(-0.57, 3.19e-03)	-1.94	0.053
(zone (baseflow_to_springfresh) × wpfg (Emergent)) × period (before_spring)	3.80	0.99	(1.86, 5.73)	3.85	< .001
(zone (below_baseflow) × wpfg (Emergent)) × period (before_spring)	2.32	0.94	(0.48, 4.15)	2.47	0.014
(zone (baseflow_to_springfresh) × wpfg (Riparian)) × period (before_spring)	1.79	0.93	(-0.02, 3.61)	1.93	0.053
(zone (below_baseflow) × wpfg (Riparian)) × period (before_spring)	0.45	0.88	(-1.27, 2.16)	0.51	0.610
(zone (baseflow_to_springfresh) × wpfg (Terrestrial)) × period (before_spring)	1.17	0.93	(-0.65, 2.99)	1.26	0.208
(zone (below_baseflow) × wpfg (Terrestrial)) × period (before_spring)	-1.68	0.89	(-3.42, 0.06)	-1.89	0.058
Fixed Effects (Zero-Inflation Component)					
(Intercept)	2.97	0.07	(2.84, 3.10)	45.68	< .001
wpfg (Emergent)	-1.31	0.08	(-1.46, -1.17)	-17.47	< .001

Parameter	Coefficient	SE	95% CI	z	p
wpfg (Riparian)	-2.66	0.07	(-2.79, -2.52)	-38.99	< .001
wpfg (Terrestrial)	-3.07	0.07	(-3.20, -2.94)	-45.04	< .001
Random Effects Variances					
SD (Intercept: transect:site)	0.24				
SD (Intercept: site)	0.23				
SD (Intercept: metres)	0.29				
SD (Intercept: survey_year)	0.04				
SD (Intercept: system)	0.12				