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Long-Term Ecological Responses of Inland Aquatic Vegetation to Changing Precipitation Patterns

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Abstract: Changes in precipitation will affect the area and composition of inland aquatic vegetation due to seasonal storage and delayed responses in the vegetation. Total annual precipitation itself might hide the impacts on the ecosystem. In this project, a monthly hydrology-vegetation model will be used to contrast the effects of the thirty-year response for reference seasonality, enhanced seasonality without changes in total annual precipitation, gradual drying, and a five-year drought followed by reference precipitation. Twelve papers from recent literature provide the ecological background, and all model parameters are assumptions. The storage equation bounds the potential cover of submerged and emergent growth forms, while asymmetric adjustment rates capture the fast decrease and slow increase. Two measures are analyzed: mean annual cover of vegetation and Bray- Curtis dissimilarity based on relative growth-form cover. Reference vegetation cover is 51.02%. However, increased seasonality causes reduced final cover to 42.27%, although it retains annual rainfall of 960 mm, while the final dissimilarity is still low at 0.026. Drought causes 45.20% final cover and greater compositional dissimilarity at 0.347. Drought condition achieves a minimal vegetation cover of 28.93% and maximal dissimilarity of 0.825 at year 17, followed by substantial recovery upon restoration of rainfall. These changes represent the established response rules rather than regional impacts. This illustrates how vegetation extent and composition can be differentially affected by rainfall pattern, volume, and continuity. Long-term analysis should consider both metrics and assess intervening hydrological processes first.

Keywords: Aquatic Macrophytes; Rainfall Seasonality; Hydroperiod; Vegetation Cover; Community Composition; Ecological Recovery.

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I. Introduction

Inland aquatic vegetation thrives in environments from shallow lakes to floodplains and wetlands and margin zones subject to flooding. It is sustained by the presence of water during appropriate times of the year, not merely the amount of rainfall. Long-term investigations of Potamogeton crispus in a subtropical lake have demonstrated a relationship between spatial vegetation dynamics and hydrometeorology, emphasizing the importance of examining seasonal exposure and the environmental chain that links rainfall with vegetation distributions (Yang et al., 2024). In the current research, we examine this temporal component. We apply a clear dynamic model to separate shifts in the amount of vegetated area from shifts in the proportions of submerged and emergent vegetation types.

1.1 Rainfall Signals and Ecological Interpretation

The influence of precipitation on vegetation is indirect through catchment inflow, water retention, connectivity, and inundation period. An equal amount of precipitation may occur within a long period or short wet seasons divided by droughts. Responses to it can persist even when precipitation resumes because live biomass is not restored with the same speed as it is removed. A long-term analysis should account for the seasonal pattern, a sequence of years, and recovery. Recently performed studies at Poyang Lake have identified a long-term decline in submerged vegetation and hydrological alteration and decreased transparency as its reasons. Thus, the changes in vegetation can occur under the influence of both climatic and anthropogenic factors. Rainfall cannot be viewed as a factor that solely explains the changes when there are alterations in hydraulics, bottom sediments, and water clarity (He et al., 2026). There are examples where changes in water-level management and underwater light availability affect the loss and restoration of submerged vegetation in Caohai Lake, and this proves the importance of hydrological conditions, but

does not allow us to assume a similar pattern everywhere else (Chao et al., 2024). The proposed model makes an assumption about depths only.

1.2 Study Objectives and Contribution

This evaluation investigates the following three questions: whether increased rainfall seasonality could reduce cover without altering the amount of precipitation during a year; whether gradual drying would have a different response than changed seasonality; and how cover and composition respond after a certain number of drought years. These questions are investigated using a series of thirty years per month, rather than equilibrium stressor combinations. This study's contribution is a way of separating vegetation quantity and composition of growth forms. Four precipitation patterns were fed into identical models of storage and vegetation. Ecological metric pairs are used to establish whether there is a different change in structures despite similar cover evolution.

II. Hydrological and Vegetation Evidence

Data derived from field surveys, imagery series, and modeling of optics in lakes show that the availability of light underwater limits the survival of Vallisneria spinulosa in the Poyang floodplain sub-lakes. This study reveals varying distributions of the habitat without continuous shrinking over the scope considered. The result obtained is inconsistent with the general estimates of submerged vegetation loss, stressing the importance of identifying species, habitats, periods, and methods used (Hu et al., 2025). Field and experimental studies conducted in the Dongting Lake revealed that drought magnitude, timing of drawdown, and reproductive system play a role in affecting submerged macrophytes. Seed bank resilience may contribute to regeneration in case of a decline in clonal species. This leads to the need for separation of loss and regrowth rates despite the absence of this in the current two-group model (He et al., 2026).

Multi-lake analysis involving both the depth and turbidity of water is conducted to assess the thresholds for collapse and recovery of the submerged macrophytes. The findings of the analysis reveal that a combination of depth and light may be more useful than the isolated factors. The current analysis of habitat functions based on storage ignores this process; they are not threshold functions and cannot model the regime transitions from clear-water to turbid-water conditions (Yu et al., 2025). A study involving the integration of water level magnitude and timing in Poyang Lake assesses the sequence of floods and droughts. It gives a good reason for employing a sequence-based monthly model. Sequence analysis helps differentiate a climatic change from disturbances with recovery (Peng et al., 2025).

The study involving the process-based approach and satellite imagery shows how the changes in submerged vegetation can be reconstructed in a Poyang sub-lake and how a major drought event leads to biomass reduction. This study shows the importance of using a combination of ecological processes and observations, while at the same time making a distinction between biomass and mapped areal coverage. The model used in this study estimates the percentage cover and not biomass and remote sensing reflectance (Qi et al., 2025). Inter-annual research in Lake Erhai involves the study of different plant communities in relation to different elevations during contrasting hydrological years (Zhu et al., 2024).

Studies on vegetation and carbon sink reactions in a seasonal lake wetland consider productivity in conjunction with vegetation patterns. Such an extended approach explains why an increase in cover does not necessarily imply an increase in carbon storage. Neither carbon flux nor productivity can be quantified using the two measures used in this paper (Huang et al., 2024). A comprehensive wetland analysis in Madhubani, India, considers rainfall, evapotranspiration, moisture indicators, vegetation productivity, and land-cover change over several decades. The study framework highlights the need to distinguish between aquatic vegetation and agricultural or terrestrial greening in remote sensing signals. Vegetation indices of the catchment are not comparable to those of aquatic macrophytes (Sharma & Das, 2026). In Brazil's Pantanal, surveys conducted a decade apart relate macrophyte diversity and structure to hydrological stages and shifting rainfall regimes. Emergent rooted macrophytes are better adapted to drought in this

environment. Such geographic variation in evidence supports studies on composition as well as cover, without assuming similar responses across floodplain ecosystems (de Morais et al., 2022).

III. Analytical Methods

3.1 Evidence Selection and Simulation Domain

Twelve primary research studies between the years 2022 and 2026 were chosen based on purposeful searches that included the following terms: aquatic vegetation, precipitation, water levels, droughts, long-term trends, and recovery. The search was conducted on 10 November 2026, using publisher websites, bibliographies, and research databases. Selected studies are biased towards Asian lake ecosystems and augmented by data from the Pantanal and do not constitute a geographically representative systematic review. No numerical coefficient was calculated or aggregated from these studies. The simulation depicts a fictitious landscape of a freshwater littoral system of a certain area. Precipitation dictates the effective storage depth and hence the amount of submerged and emergent cover potential. Other factors such as nutrient load, temperature, turbidity, management, and species availability are constant. Study years one through thirty are simulated.

3.2 Precipitation Scenarios

Reference rain history consists of values (in mm): 40, 35, 45, 65, 90, 130, 160, 150, 100, 65, 45, and 35. Summed for an annual amount of 960 mm, which is repeated for thirty years. No months were assigned a specific order for belonging to some regional monsoon; months were simply numbered sequentially. Reference seasonality history uses the unchanged sequence above. Enhanced seasonality applies transformation of every month to $80 + 1.6(P_m - 80)$, which leads to increase in differences from the monthly mean while sum still equals 960 mm annually. Drought gradually decreases every year rainfall history sequence by multiplier $1 - 0.25(y - 1)/29$, with final annual total equal to 720 mm.

The enhanced seasonality history allows one to analyze temporal effects of rainfall only at constant yearly input. Drought and gradual drying change both total amount of yearly input, and thus are not isolated to the temporal variation only. Average yearly precipitation of thirty-year rainfall period equals 960, 960, 840, and 872 mm for reference, seasonality, gradual drying, and drought scenarios.

3.3 Monthly Storage Equation

The effective water depth h_t, measured in metres, is recalculated by using equation 1, where precipitation P_t is measured in mm per month. Storage retention coefficient equals 0.90, rainfall transformation coefficient equals 0.0015 m per mm, and constant withdrawal rate equals 0.045 m. The upper limit of capacity is 1.80 m, while the lower limit is zero.

$$h_t = min\{1.80, max[0, 0.90h_{t-1} + 0.0015P_t - 0.045]\} \quad (1)$$

Conversion factor refers to the effectiveness of catchment contribution compared to the wetland size, not the rainfall depth. Withdrawal represents fixed loss. This storage relationship model does not incorporate a calibrated catchment water balance and does not consider any groundwater, flow routing, or water abstractions directly.

3.4 Growth-Form Cover and Ecological Memory

The potential submerged cover Ks and emergent cover Ke are smooth functions of the effective depth according to equation 2. The maxima of 55% and 35%, respectively, relate to different land allocations within the constant landscape model. The depth centres and widths are suitability values instead of optima of the species.

$$K_s(h) = 55\, exp\{-[(h - 0.75)/0.40]^2\};$$

$$K_e(h) = 35\, exp\left\{-\left[\frac{h-0.25}{0.35}\right]^2\right\} \quad (2)$$

Cover realization X_i of growth form i is calculated using equation 3. The adjustment factor α_i is 0.06 per month if potential cover is greater than realized cover, but 0.25 if potential cover is less than realized cover. This mechanism results in slower regrowth compared to decay but maintains bounded positive states.

$$X_{i,t} = X_{i,t-1} + \alpha_i[K_i(h_t) - X_{i,t-1}]. \quad (3)$$

The reference spin-up process takes 100 years to create a consistent seasonal cycle based on h= 0.75 m, submerged vegetation covers 30% and emergent vegetation cover 15%. Each simulation is initialized from the end-of-season cycle.

3.5 Two Ecological Metrics

A_φ = Mean annual vegetated cover of both submerged and emergent vegetation as a percentage of the fixed landscape in twelve months. The measure indicates the coverage. Relative contribution of growth-forms is calculated using the ratio of annual mean growth-form covers to the total in equation 4.

$$A_\gamma = (1/12)\Sigma_m[X_{s,\gamma m} + X_{e,\gamma m}]. \quad (4)$$

The growth-form compositional dissimilarity, B_γ, is the Bray-Curtis dissimilarity between the scenario and reference relative cover proportions in the same simulation year. When using normalized proportions, the denominator will always be two, resulting in equation 5. The values will range from 0 to 1, depending on whether the composition is the same or not.

$$B_\gamma = \tfrac{1}{2}\Sigma_i|p_{i,\gamma} - p_{i,\gamma}(reference)|. \quad (5)$$

B has two growth forms, where B is the absolute difference between any group's proportional contribution. It fails to measure replacement of species within a group and cannot be considered taxonomic beta diversity. Normalization eliminates differences in total cover intentionally so that composition and extent can be distinguished.

3.6 Sensitivity and Computational Checks

Comparison of the monthly regrowth fractions 0.03 and 0.12 was done for 0.06 with different reference spin-up cases and matched trajectories. The timing of recovery is quantified by when the first year after the drought reaches 95% of the reference match cover. Input, bounds, rainfall totals, and metric identifications were verified. deterministic output does not mean confidence interval or significance.

IV. Results

4.1 Long-Term Changes in Vegetated Extent

As shown in figure 1, the annual average cover for all of the four simulated precipitation sequences is 51.02% under reference conditions for seasonality. More pronounced seasonality results in lower coverage levels in the initial period, coming closer to 42.27%, an 8.75 percentage point drop of 17.15%. This happens without altering the precipitation levels on a yearly basis.

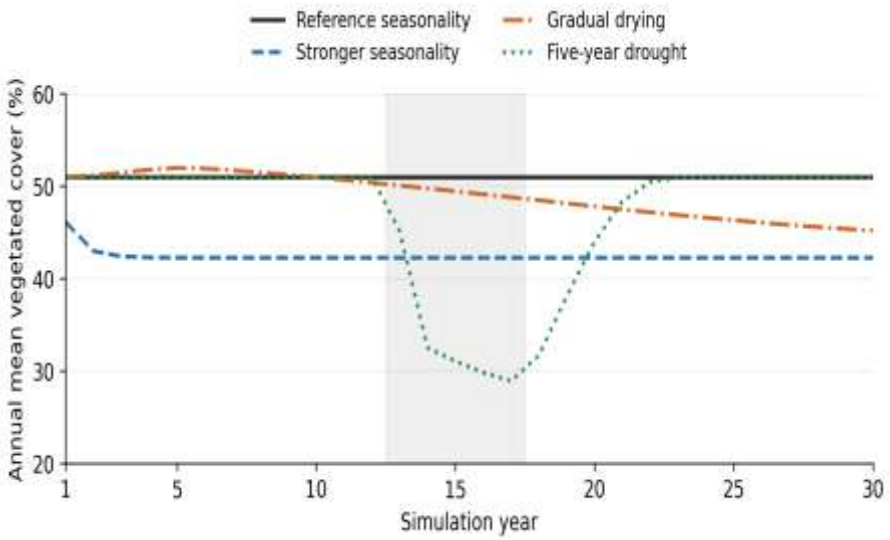


Figure 1: Annual Mean Vegetated Cover Under Four Modelled Precipitation Histories

A more gradual drying causes less decline in cover, to 45.20%, equivalent to 11.42% of the reference case. This result is not to be taken as indication that a 25% decrease in rainfall is less ecologically significant than increasing seasonality. It results from the storage memory chosen, depth preference parameters used, and the counteraction of cover expansion. The composition index is required to evaluate the compensation for this last effect. In the drought case, the initial state is equal to the reference, and the lowest annual cover value of 28.93% occurs in year seventeen. The cover decline is 43.30% relative to the reference level. When rainfall returns to reference conditions, the cover increases to 31.70% in year eighteen, 44.00% in year twenty, and 50.47% in year twenty-two. Finally, in the last year, it reaches approximately 51.02%, about the reference value. Therefore, recovery takes longer, even though reference precipitation is restored as early as in year eighteen.

4.2 Growth-Form Composition and Recovery Pathways

Figure 2 illustrates compositional dissimilarity irrespective of the cover. Seasonality that is stronger leads to an overall dissimilarity of 0.026, considering the large drop in extent. The average submerged and emergent cover per year at the end of this situation are 38.30% and 3.97%, respectively. This is close to that of the reference, which stands at 47.56% and 3.46%, respectively.

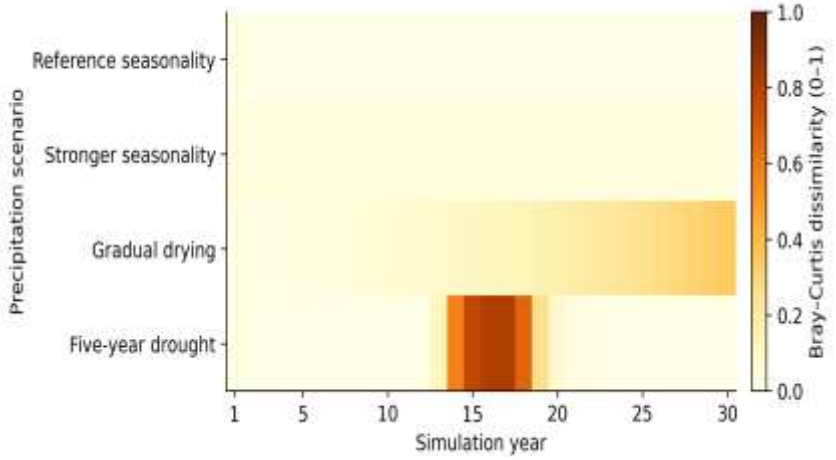


Figure 2: Temporal Variation in Bray–Curtis Dissimilarity Across Different Precipitation Scenarios

Drying gradually leads to final submerged and emergent cover percentages of 26.45% and 18.75%, respectively. The difference in their relative distribution boosts B to 0.347, which is much greater than for more pronounced seasonality despite having higher total cover. Therefore, these two measures classify the scenarios differently as the former is characterized by a greater extent loss, whereas the latter – by greater persistent composition deviation from the reference one. During the drought lasting five years, the maximum dissimilarity coefficient equals 0.825 in the seventeenth year and corresponds to the minimum cover percentage. In the eighteenth year, it equals 0.662, and in the twentieth one – 0.066. In the twenty-second year, it equals 0.004.

4.3 Dependence of Recovery on Regrowth Assumptions

Modification of the coefficient of growth per month will influence the time when 95% of matched reference cover will be reached for the first time. This criterion is achieved after twenty-four years if $\alpha = 0.03$; after twenty-two years if $\alpha = 0.06$; and after twenty years if $\alpha = 0.12$. This proves that recovery time depends on ecological adaptation conditions. This is a sensitivity comparison, not probabilities, and 95% is not full recovery.

V. Discussion

Extent decline and growth form changes are different. More seasonality results in less cover with minimal shifts in composition, while expansion of emergent vegetation under gradual drying makes up for the lost submerged vegetation. A single vegetation-area index may thus overlook an important change in aquatic habitat quality. Field observations suggest that these two aspects need to be analyzed separately rather than assuming a single universal reaction. Water depth, underwater light, and regeneration processes affect submerged vegetation in diverse case studies. This is why the importance of these variables shows what processes are not captured by the simple models of suitability, namely the sediment-related light reduction and seedling survival (Hu et al., 2025; He et al., 2026; Yu et al., 2025). The drought recovery in the model is dependent upon the continuation of the regrowth capability. This does not imply the occurrence of irreversible seed bank destruction, persistent turbidity, invasion, and change in connectivity. A rainfall event might not result in the restoration of the habitat if these additional limiting factors exist. The distinctions made in the long-term vegetation studies should also be considered in terms of species, water level, and method of observation (He et al., 2026; Qi et al., 2025).

Operational monitoring requires a combination of stable aquatic-vegetation maps and data on water levels and precipitation, differentiation between submerged and emergent vegetation, and consistent seasons of observations. Habitat stratification and classification verification are vital when water depths conceal submerged vegetation. Management and land-cover changes must be considered in attribution due to the concurrent catchment greening and wetland shrinkage (Zhu et al., 2024; Sharma & Das, 2026). A number of issues limit applicability. The precipitation data are artificial, the storage function is uncalibrated, and the model accounts for only two vegetation types without competition or species-specific dynamics. Monthly time steps do not take into account short floods and droughts, and annual averaging ignores phenology. Sensitivity analysis addresses only regrowth, but not the whole uncertainty or other models. There is no regional precipitation projection, restoration threshold, or causal inference of an observed wetland.

VI. Conclusion

The 30-year analysis of scenarios of precipitation change reveals possible impacts of different trajectories of variation on the inland aquatic vegetation through its changes in cover and growth form composition. Increased seasonality decreases the final cover to 42.27% from the initial 51.02% at unchanged annual amount of precipitation, whereas steady drying causes higher compositional dissimilarity – 0.347. Finite drought decreases cover to 28.93% and compositional dissimilarity increases to 0.825 under recovering precipitation conditions. Those results reflect outputs of the theoretical model that do not show

long-term real-life changes. Practical implications of such model consist in possibility of joint evaluation of extent and composition of inland aquatic vegetation.

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