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Ecological Consequences of Altered Water-Level Regulation on Wetland Plant Succession

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Abstract: Wetlands represent highly variable ecosystems, where water level size, persistence, frequency, rate of changes and seasonality control plant colonization and community development. River regulation, reservoirs operation, water extraction, drainage and aquifer depletion may influence all these hydrological factors affecting plant viability, competition, species composition and succession processes. This review provides an analysis of scientific literature published from 2014 to 2022 that deals with the impact of modified water regimes on wetland and riparian vegetation. Three interrelated effects are examined: long-term flooding, long-term drawdown, and suppression of natural seasonal dynamics. Prolonged floods may cause oxygen and light limitation of flood-intolerant plants, whereas long-term drawdown may increase substrate exposure, reduce availability of aquatic habitats, and promote drought-resistant or terrestrial species. Regulation may also exclude major floods and substitute them with more small-scale frequent fluctuations, thus filtering plant communities by their tolerance abilities and life histories. This process is variable, as the response will depend on the type of wetland, geomorphology, the characteristics of the sediments, climate, the availability of propagules, and the amount of change in the hydrology. This literature review shows the consequences of hydrological change for biodiversity, habitat structure, nutrient cycling, productivity, and restoration. This paper emphasizes that the maintenance of a static water level is insufficient to achieve ecological goals. On the contrary, conservation should maintain an appropriate variability in the seasonality of the river-floodplain system, maintain connectivity, and study vegetation changes over many years.

Keywords: Wetland Hydrology; Water-Level Regulation; Plant Succession; Vegetation Dynamics; Environmental Flows; Biodiversity; Ecological Restoration.

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I. Introduction

Wetlands represent transitional areas between aquatic and terrestrial systems which sustain unique biotic communities. The ecological roles fulfilled by wetlands include water retention, flood control, sediment retention, nutrient cycling, carbon storage, and provision of habitat for plants and animals. The fulfillment of ecological roles involves interaction of factors such as hydrology, geomorphology, soils and biological processes. Of all these factors, hydrology plays a dominant role because it controls the duration and extent of flooding, the seasonality of flooding and recession, soil oxygen levels and the availability of sites for colonization (Luo et al., 2016).

The wetland flora is dynamic, and it responds to various processes such as plant recruitment and mortality, clonal spread, competition and disturbances. Submerged, floating-leaved, emergent and terrestrial plants occur at different points along gradients of water-depth and soil moisture. The natural flooding and recession cycles can ensure the presence of a diversity of habitats and allow different functional types to benefit from them. Alternatively, alteration in the regime of water-level changes will benefit some species but will be detrimental to other species.

Human activity has affected the hydrology of wetlands in various ways. Flow timing and flow magnitude may be affected through dams and reservoir construction, while abstraction may lower the water table and baseflow; drainage and channelization may reduce the hydroperiod, and regulation of water release may produce abnormal water-level changes in terms of magnitude and speed. The ecological impacts of such alterations cannot be characterized by the annual mean water level alone; frequency, duration, height, rates of rise and fall, and the time of year when the flood takes place can also play a role in determining plant response.

Linking flow regimes with riparian plant guilds may not be straightforward since plants have different hydrological requirements for different developmental stages. Linking flow attributes with riparian plant guilds provides insight into how altered flood timing and drought may influence riparian community composition and connectivity (Lytle et al., 2017). This is pertinent to wetlands, where succession is dependent not only on whether the adult plants survive at a certain water level but also on the possibility of recruitment and regeneration.

This review attempts to address the consequences of altered water-level regulation on wetland plant succession and the associated ecological processes. Four main research questions are posed: (i) What hydrologic characteristics affect vegetation dynamics the most? (ii) How do inundation and drawdown affect plant functional groups? (iii) How does regulation alter successional trajectories and ecosystem functioning? And (iv) what management strategies allow maintaining ecological resilience? The paper is a literature review, not an account of field experiments.

II. Review Method and Scope

The review is concerned with peer-reviewed literature. Pertinent references have been gathered based on various permutations of the terms wetland, riparian vegetation, water-level fluctuation, flow regulation, hydrological regime, plant succession, drawdown, inundation, environmental flow, and vegetation dynamics. Google Scholar and publisher or DOI-linked references have been used as sources for discovery and confirmation. Studies that examined the relationship between hydrological factors and plant species composition, density, traits, recruitment, and wetland condition received priority.

Inclusion criteria have involved the examination of both natural and regulated wetlands and riparian zones, as well as studies providing generalizable information concerning the response of vegetation to changes in hydrological conditions. Constructed wetlands have been used only for general considerations of hydrological control without implying their naturalness. Results have been categorized according to hydrological determinants, plant responses at the individual level, community succession, and ecosystem impacts. Since studies vary geographically, methodologically, and in terms of the response variables, results are reported qualitatively.

This paper does not aim to be a systematic review or meta-analysis. This review does not provide any pooled effect size. In addition, it does not use any original observations made in the field. There is geographical variation in the literature, with a lot of studies coming from rivers that have been modified by humans as well as certain wetland systems. Therefore, the conclusions need to be considered in the context of the local environment.

III. Hydrological Regulation as a Driver of Wetland Vegetation

Components of the Water Regime

The water regime is multi-dimensional. The depth of water decides the vertical placement of plant tissues in relation to the water surface and affects the availability of light to the sediment surface. The duration of inundation decides the period of saturation or anoxia of roots and rhizomes. The frequency of floods decides the number of times the plants get disturbed, as well as the periodicity of exposure of substrate to support germination. The speed of water rise may affect the submergence of seedlings and mechanical stresses on plants, whereas the timing of floods may decide if sensitive phases of the life cycle coincide with the floods. (Pal & Sarda, 2021)

In other words, even if the average water level remains relatively stable in a year, a wetland may undergo a significant ecological transition. For instance, switching from short seasonal flooding to continuous flooding can limit the recruitment periods of those plants requiring exposure of the substrate. Similarly, a decrease in flood peaks allows woody or terrestrial plants to occupy the disturbed area.

Natural Variability and Habitat Heterogeneity

Natural fluctuations in water level produce a dynamic mosaic of wet, moist and dry conditions. Heterogeneity of this type may enable species with different habitat preferences to persist. For wetlands with seasonal inundation, the process of drawdown can trigger the emergence of seedlings from the seed bank, with flooding favoring aquatic and emergent species. It is thus the degree and timing of the water level fluctuations, rather than their maximization or minimization, which determines the ecological importance of fluctuations.

Studies at prairie potholes have demonstrated the ecological significance of subtle differences in mean water level and the magnitude of fluctuations on wetland vegetation communities (van der Valk & Mushet, 2016).

Effects of Dams and Flow Regulation

Reservoir management can change the flow regime through storing water when natural flows are high and using the stored water at other times of the year. Sometimes this results in an antiseasonal regime in terms of water level, which does not resemble the historic flood pulse. Flow regulation can also reduce the occurrence of disturbance and increase temporal variation due to hydropower production. This regime may benefit species that do well under conditions of frequent flooding or water stress but harm species requiring big floods or dry spells. (Butterfield et al., 2018).

In a study of regulated rivers in southwestern Europe, it was discovered that water storage in reservoirs affects the abundance and distribution of riparian woody-plant guilds, as hydrology and land use interact together (Aguiar et al., 2018). The conclusion is that flow regulation occurs along with catchment effects and is not independent of them.

IV. Plant-Level Responses to Altered Water Levels

Responses to Prolonged Inundation

The factors influencing the impact of floodings on vegetation are the low oxygen levels in the rhizosphere, modification of the redox state, reduction of light availability and physical disturbance. Flood-resistant plants have such adaptation features as the presence of aerenchymata, adventitious roots, flexible stems and ability for shoots' elongation. Plants without any of these adaptation properties will grow slower or even die if flooding will exceed their resistance. Response is plant-specific and depends on seedling or adult stage of the plant.

Research of temperate European riparian ecosystems demonstrated that floods and droughts were able to modify composition of plant community both taxonomically and functionally, especially in case of floods (Baattrup-Pedersen et al., 2018). It means that flooding can be regarded as one of selective filters decreasing number of effective ecological strategies in the community.

Responses to Drawdown and Drought

Drawdown can reveal the sediment bed and form suitable microsites for seed germination and recruitment. It could thus contribute to regeneration of emergent species and preserve the diversity of plant communities. Extreme drawdown, however, would dry up the sediment, limit aquatic habitats, cause temperature stress, and decrease the chances of survival of submerged plants. This depends on the degree and length of the drawdown event, as well as sediment characteristics and presence of propagules.

In a dryland river basin, there was a variation of the riparian plant composition in relation to the hydrological gradient. Drying was linked to the decline of wetland and native plant communities and the rise of annuals (Reynolds & Shafroth, 2017). This is consistent with the idea that continuous water shortage results in drought-resistant communities.

Functional Traits and Species Filtering

Functional traits give a good way to understand vegetation adaptations to change. Seed size, dispersal method, root depth, ability to grow clonally, stem flexibility, flooding tolerance, and drought tolerance are examples of traits that affect the survival of plants under changed water regimes. Species with wide tolerance will increase in abundance while specialists will decrease. This may lead to functional homogenization of ecosystems even when some functional groups remain. Regulation of northern rivers was found to reduce species richness and for plant guilds intolerant of waterlogging, performance at regulated sites was poor (Bejarano et al., 2018).

V. Consequences for Plant Succession

Successional Pathways Under Natural Hydrology

The concept of wetland succession has been explained to entail a series of vegetation successions through sediment deposition and soil formation. In areas that have shallow waters or waters that recede periodically, there may be colonization of pioneer herbs and sedges in exposed substrates. With time, emergent plants tend to increase in number while other plant forms such as shrubs and even trees may develop on raised and less inundated grounds. The process of wetland succession is neither uniform nor always a linear phenomenon.

Succession Under Prolonged High Water

However, if the water levels are maintained at a high level for a long time, the recruitment of terrestrial and hydrophytic plant species may be limited. Existing emergent vegetation may get stressed due to prolonged submergence if beyond their tolerance, whereas submerged and floating-leaved plant species may enjoy an advantage due to light availability and favorable water conditions. High-water levels for several seasons can limit the establishment of seedlings as well as survival of the plant species requiring bare soil for germination.

Succession Under Persistent Low Water

Prolonged low water levels can result in exposing previously submerged areas and allow the establishment of terrestrial herbs, grasses and woody plant species. If there is any alteration in the hydrological regime, these species can become established and alter the course of succession. Re-submergence of the area cannot lead to an immediate return of the previous vegetation due to changes in seed bank and propagule availability.

Regulation and Alternative Stable States

The concept of an alternative state applies in the context that when a wetland moves from one observable community pattern to another and stays in that pattern even as the original hydrological conditions recover partially. This might occur because of interactions between vegetation, sediment entrapment, organic accumulation, light and water depth. For instance, high density of emergent vegetation leads to sediment entrapment and organic accumulation, thus causing substrate elevation and conditions favorable for emergent plants to be reinforced. On the other hand, the removal of submerged vegetation might reduce complexity and sediment stability.

Long-term monitoring in the Three Gorges Reservoir water level fluctuation area shows significant changes in riparian plant community structure in a new regulated environment, including reduced number of observed species in consecutive years (Jian et al., 2018). This is an example of how prolonged hydrological change might alter vegetation development process for several years ahead.

The pathway shown below represents the general direction of change. This does not represent a universal prediction since the real response depends on species pool, geomorphology and water quality among others in figure 1.

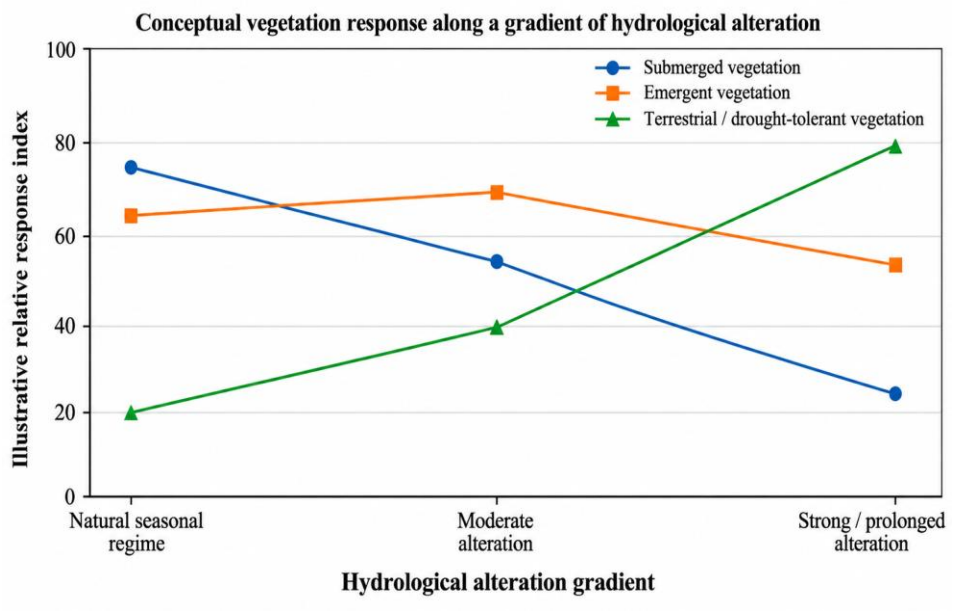


Figure 1: Conceptual Vegetation Responses Along a Gradient of Hydrological Alteration. The Index Values are Illustrative and are not Derived from Field Measurements.

VI. Wider Ecological Consequences

Biodiversity and Habitat Structure

Vegetation supplies food, nesting material, shelter and habitat complexity to both aquatic and terrestrial species. An alteration in the balance between submergent, emergent and terrestrial vegetation will affect the availability of habitats for invertebrates, fishes, amphibians and water birds. An increased presence of dense terrestrial vegetation can decrease the open water area whereas the removal of emergent vegetation can decrease nesting sites or refuge areas. The nature of the response of biodiversity is case-specific, but the replacement of a specialized native vegetation community with a limited number of tolerant species leads to decreased ecological uniqueness.

Processes of Soil and Nutrient Cycling

Water depth controls the soil oxygen levels and redox potential which impacts microbial decomposition as well as the cycling of nutrients such as nitrogen, phosphorus, iron and sulfur. High levels of flooding can limit aerobic decomposition and encourage anaerobic decomposition, whereas periods of drying allow increased levels of oxygen availability leading to faster decomposition of organic materials in optimal conditions.

Productivity and Carbon Storage

Wetland vegetation contributes to carbon sequestration through aboveground production, belowground biomass, and organic sediment buildup. Disturbance of the hydrological regime can affect the rate of plant production as well as the balance between carbon addition and decomposition. Prolonged drying can oxidize organic soils while prolonged flooding can affect methane production and transport. Therefore, the climatic impact cannot be estimated solely on the basis of vegetation cover; the water regime, soil conditions, and pathways for greenhouse gases need to be considered.

Connectivity and Floodplain Processes

The movement of water, nutrients, sediments and organisms between river channels and wetlands is part of flood pulse. Water regulation and extraction can limit flood pulse events. Fieldwork in the Macquarie Marshes has provided insight into the connection between vegetation and water availability and timing of inundation in floodplain wetlands (Mason et al., 2022).

Constructed Versus Natural Wetlands

The importance of hydraulic conditions on water treatment and biological processes in constructed wetlands is clear from studies, however, constructed wetlands serve a different purpose compared to natural wetlands. Their results can help understand hydraulic loading and vegetation response in natural wetlands but with caution (Jiang & Chui, 2022).

VII. Management Implications

Restore a Seasonal Hydrograph Rather than a Fixed Level

Managers need to strive for keeping water levels within a suitable ecological range. Such a range might involve seasonal flooding, a steady decline in water levels, and periods of low flow to ensure recruitment and regeneration.

Establish Components of Environmental Flows

Prescriptions for environmental flow need to include not only minimum flow. Components of environmental flow are magnitude, timing, duration, frequency, and rate of change. Insofar as possible, managers need to keep occasional high flows and seasonal low water periods that ensure heterogeneous habitats and plant life cycles.

Maintain Floodplain Connectivity

Retention of connections between rivers, floodplains, and neighboring wetlands will facilitate propagation, exchange of nutrients, and sediment transport. Decisions regarding infrastructure and water allocation have to take into account the effects of decreased connectivity on vegetation recruitment and successional processes.

Monitor Vegetation and Hydrology Simultaneously

Monitoring must be done using water-level loggers, inundation mapping, vegetation transects, plant species identification, and remote sensing. Repeated measurements in more than one year are required since there can be a time delay between hydrological and vegetation changes. The indicators should include native species richness, abundance of functional groups, recruitment, invasive species cover and open water area.

Adopt Adaptive Management Approach

Water-management strategies must be tested as hypotheses. Staged release and seasonal water level targets can be implemented by managers and then monitored for vegetation effects, and the operation can be adjusted in case the expected ecological effect is not realized. Adaptive management is essential when hydrological conditions cannot be replicated due to climate variability.

VIII. Research Gaps and Future Directions

There are several gaps that prevent the successful forecasting of wetland succession in response to changes in water level management. Firstly, many studies are based on individual plant species or short-term responses, while succession takes several years and involves such processes as recruitment, mortality, and competition between plants. The creation of long-term permanent plots connected with

hydrological data is required. Secondly, the influence of changes in water level interacts with such factors as salinity, nutrient status, sediment composition, temperature, grazing, and invasions of alien plants. It is recommended to use factoral approaches or good observation models in future researches. Thirdly, it is necessary to establish the hydrological thresholds of different species regarding their germination, seedling survival and presence. Such thresholds will allow creating an environmental flow design and distinguishing a beneficial drawdown from damaging droughts. Fourthly, remote sensing can be used to detect changes in vegetation in large territories, but it is necessary to validate results in the field and distinguish between plant functional groups and changes within the dense canopy. Fifthly, comparative studies should be performed in tropical monsoonal wetlands, temperate marshes, arid floodplains, and coastal wetlands. A potentially helpful framework for the future would be the integration of hydrologic time series data, plant functional traits, seed-bank analyses, soil biogeochemical processes, and vegetation mapping. With this, scientists will be able to not only determine if there is a change in vegetation, but also what causes succession redirection.

IX. Conclusion

Changes to water level management can alter the course of wetland vegetation succession through alteration of the environmental factors determining plant establishment, development, reproduction and survival. From the literature examined, it can be concluded that the ecological consequence is not merely dependent on the flooding or drying of the wetland but on the degree, period, frequency, timing and speed of change in water levels. Long periods of flooding can hinder flood-intolerant plants and favor flood-tolerant functional types, while long periods of drawdown can make the sediments available, limit aquatic plant life and encourage terrestrial plants. Such impacts can affect not only the composition of the vegetation but also the physical characteristics of the habitat, biodiversity, the redox regime of soils, nutrient cycles, productivity, and carbon sequestration. Nonetheless, such impacts differ from wetland type to wetland type and are highly dependent on geomorphology, sedimentation processes, climate, the species' characteristics, and disturbance histories. Consequently, maintaining a single optimal level of water would not suffice to maintain all ecological functions of wetlands. What needs to be done is to maintain ecological proper variability of water levels, restore the river-floodplain linkages, and apply environmental flow to promote the stages of plant life cycle. The monitoring process needs to include not only hydrological monitoring but also the monitoring of vegetation and remote sensing in order to detect the changes in the processes of succession in advance. Future studies need to determine the hydrological thresholds for each species and assess how multiple stressors impact the successional pathways.

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