



Original Research Paper

Metapopulation Dynamics of Endangered Amphibians in Fragmented Wetland Networks

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Key Words

Metapopulation dynamics, Habitat fragmentation, Amphibian conservation, Wetland connectivity, Patch occupancy, Colonization–Extinction Dynamics, Landscape ecology.

Abstract

Habitat fragmentation is one of the major threats to global amphibian extinctions, particularly for low-dispersal wetland-dependent species. The research questions this study seeks to answer is the metapopulation dynamics of threatened amphibians in a fragmented wetland landscape, and to assess the effects of patch isolation, size, and patch connectivity on patch occupancy, colonization, and extinction. The surveys were conducted across 48 wetlands over 5 years (2019-2024), with mark-recapture and environmental DNA (eDNA) sampling used to estimate population parameters. Using a spatially explicit metapopulation model, a mean patch occupancy of 0.62 ± 0.08 (SE) across the study period was found, with annual colonization and extinction probabilities of 0.27 and 0.19, respectively. The wetland size was strongly positively correlated with occupancy ($\beta = 0.41$, $p < 0.001$), and the isolation distance negatively affected colonization rates ($\beta = -0.36$, $p = 0.004$). The occupancy patterns (R^2) were explained by connectivity indices ($R^2 = 0.58$). It is important to note that wetlands within 500m of neighboring patches had a 34% greater chance of persistence than those in more isolated regions. Simulation results suggested that a 20% improvement in linkage would decrease the likelihood of extinction by about 15% over 10 years. On the other hand, a further loss of habitat at the current rate of destruction (about 3%/year) is expected to reduce the overall metapopulation's viability by 40% in 15 years. Such results underscore the vital role of preserving functional connectivity and of focusing on larger habitat patches in conservation planning. Endangered amphibian species require strategic restoration of wetland corridors and mitigation of fragmentation effects to improve future persistence in evolving landscapes.

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Introduction

Metapopulation processes explain how species survive through a network of spatially disconnected populations (subpopulations) linked by dispersal. Instead of existing as a single continuous population, individuals are distributed across habitat patches, with local extinctions and recolonizations over time. That framework is particularly relevant for habitat patches with relevant habitats fluctuating in space and time, such as wetlands (Smith et al., 2026). The classical metapopulation model is based on a balance between immigration and

extinction, but current literature suggests that metapopulation dynamics are also influenced by stochasticity, variability, and spatial structure (Mathwin et al., 2024; Bertassello et al., 2021). Finally, amphibians spend parts of their life cycle in water and on land, so the hydroperiod's variability, their fidelity to breeding habitat, and their limited dispersal capacity are key factors in metapopulation dynamics. Empirical models have shown that dynamic wetland conditions can lead to shifts in habitat occupancy, with persistence not only dependent on habitat quality but also on the persistence of the habitat (Bertassello et al., 2022).

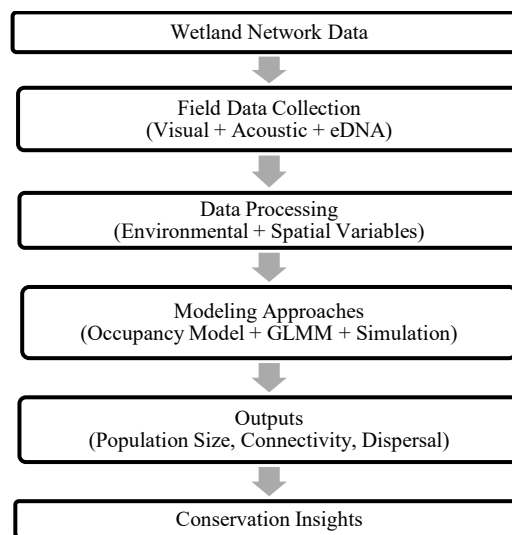


Figure 1: Framework for Analyzing Amphibian Metapopulation Dynamics in Fragmented Wetlands

The research framework is depicted in figure 1, with data from wetland networks as the starting point, leading to field surveys and analyses using models such as GLMMs and simulations to represent, for example, amphibian occurrence. The diagram stresses how the environmental and spatial raw data will be transformed into information on the three key components - population size, connectivity, and

dispersal patterns - of a population, and ultimately turned into the conservation-based knowledge for managers of endangered amphibians.

Amphibians are the most threatened of all vertebrates, and fragmentation has been identified as the main driver of their decline. Wetland networks, originally continuous habitats, are being divided by urbanization,

agriculture, and water regimes. This makes it impossible for a functional link between populations to be established so that population dispersal and gene flow become limited. It has been shown that a reduced population survival and extinction risks can have profound effects in fragmented areas (particularly for species with low dispersal), and reduce the populations drastically (Andersen et al., 2023). What's more, fragmented, urban landscapes might also further reduce accessible movement corridors, hence affecting metapopulation interactions more than in natural forests (Jeon et al., 2024). Fragmentation also reduces genetic variability because interpopulation reproduction, inbreeding, genetic drift, and loss of genetic fit all increase the possibility of extinction (Wendt et al., 2021). In addition, efficient restoration of wetlands is often not achieved because it ignores the standing of the metapopulation, since population persistence of the species is dependent on the landscape in which it dwells rather than on individual wetlands (Hamer et al., 2021).

This research paper attempts to study the metapopulation of threatened amphibians in forested wetlands through the integration of landscape science, measurements, and occupancy. In particular, it attempts to measure the effects of patch size, connectivity, and environmental variability on the colonization extinction process and long-term persistence. The study will use recent improvements in stochastic and spatial models to measure the effects of hydrologic change and landscape attributes on population persistence (Mathwin et

al., 2023; Mathwin et al., 2024). The paper also explores another example of functional connectivity, as it relates to the stability of metapopulations, and the breaking point at which fragmentation leads to irreparable losses. In so doing it is hoped that the research will provide a deeper understanding of the mechanisms that interplay between ecology and space to enable amphibian persistence in anthropogenically modified systems.

This paper explores the increasing impact of habitat fragmentation on biodiversity loss, particularly for amphibians which are considered a sensitive indicator. It is vital to understand the impact of wetland fragmentation on persistence for conservation efforts.

This paper adds to the literature by synthesising the concept of metapopulation, empirical and modelling studies to determine the factors contributing to amphibian persistence. It offers management information for conservation, notably for designing connected wetland areas and for improving habitat manipulations.

The remainder of this paper is structured to discuss the amphibian metapopulation process in fragmented wetlands in a systematic fashion. This is followed by a review in section II, summarizing the relevant literature on metapopulation theory, impacts of fragmentation and conservation planning. Section III is "Methods", which provides information about the study site, data collection, and data analysis. In section IV, results are discussed in terms of population, connectivity, and dispersal effects, with quantitative analyses and presentations. Section V highlights discussion, reporting the

findings on ecologically-related problems of conservation and management. Finally, the section VI conclusion reiterates the main findings and suggestions for new studies and management.

Literature Review

Opportunities to advance the study of amphibian metapopulation dynamics have focused on the role of structure and variability on population persistence. At first, there were simple population extinctions and recolonizations; in recent years, the literature has also taken into account disease, demography and topography. For instance, the effects of age structures truncated by disease or disrupted by other factors established severe consequences in metapopulation persistence by affecting patch dynamics and reproduction (Heard et al., 2024). Similarly, other experiments focusing on amphibian communities in complex wetland habitats, such as in the Amazon in oxbow lakes, demonstrate that environmental gradients, especially vegetation structure and hydroperiod have significant effects on a network's processes and Patterns of species occurrence (de Matos et al., 2022). New developments in network-based methods have also highlighted the centrality of nodes, showing that populations in highly connected patches make outsized contributions to total genetic diversity and stability (Snead et al., 2024). All these results indicate that both local ecological processes and larger spatial interactions determine metapopulation dynamics. The extremely unfavorable climatic conditions affecting the metapopulation dynamics of endangered

amphibians in fragmented wetland networks are extreme weather events that disrupt hydrological stability and wetland connectivity (Poornimadarshini, 2024). Anthropogenic pollution also disrupts trophic relationships and water quality, which determine the survival and distribution of amphibians among habitats. The metapopulation dynamics and ecological connectivity do not fully explain the persistence of species in fragmented wetland webs unless the metapopulation dynamics are studied (Van der Sluis & Chardon, 2025). The availability of new techniques in the monitoring of the molecular and field-based techniques has enlarged the ability to assess the population structure and distribution patterns to understand the dynamics of species in fragmented environments in a better way (Wolfenson et al., 2024). The quality of habitats and species responses to anthropogenic land-use in wetland ecosystems remains to be impactful and it is evident that the metapopulation processes under an environment with increasing human modifications must also be evaluated (Aouadi et al., 2021).

Habitat fragmentation disrupts connectivity among wetland patches and limits subpopulations' ability to disperse and become isolated. This seclusion decreases the potential of recolonization after local extinctions and may result in long-term losses. Models of graph-theoretical and landscape resistance have been widely applied to measure connectivity and have shown that small barriers can considerably increase the cost of movement for amphibians (Heintzman & McIntyre, 2021). Fragmentation also alters population structure and breeding

success, though it limits access to favorable environments. Experimental research combining dispersal and breeding data reveals that fragmented pondscapes are frequently characterized by a lack of functional connectivity, despite the apparent proximity of patches to each other (Reyes-Moya et al., 2022). In addition, the fragmentation is combined with other stressors like climate variations and diseases, which aggravate its adverse impact. The resulting collective action tends to cause a reduction in occupancy, a decrease in genetic exchange, and an increased extinction risk across metapopulations. The conservation of amphibians is threatened by habitat fragmentation in the human-altered landscapes, which requires adaptive mechanisms to preserve connectivity of the populations to each other. The use of more advanced geospatial modeling methods can assist in the forecasting of habitat shift and evaluation of the threat to wetland ecosystems, which can sustain amphibian species (Cheng & Wei, 2025).

The conservation of amphibians in disrupted landscapes has progressively been on improving connectivity, and the planning of efficient networks of habitats. Multi-species approaches have also been included in the planning of protected areas to ascertain that conservation efforts address the needs of a variety of taxa having varied ecological needs (Donaldson et al., 2021). Connection-based management (such as reestablishing the dispersal corridors and stepping-stone habitats) was also found to be essential to the stability of the metapopulation. Also, combining graph theory with ecological

data enables the determination of main patches of habitats that comprise the connectivity hubs, which can then be prioritized to be preserved or restored (Reyes-Moya et al., 2022). The strategies described here go beyond traditional strategies to account for the factors operating at a landscape level and the bi dynamics of amphibian breeding sites. Nature-based restoration strategies such as wetlands recovery have demonstrated benefits to habitat quality and survival of amphibian metapopulations (Sahu & Dewangan, 2025).

The literature review reveals that amphibian metapopulations are extremely vulnerable to variations in connectivity, environmental variation, and demographic conditions. Fragmentation is always another significant tool as a limitation to dispersal and persistence, and network-based methods offer useful techniques in determining the essential habitats. These observations are directly informative to the current study, which builds on the existing models and further investigates the interaction between spatial configuration and environmental dynamics to explain the effect of these factors on the persistence of amphibians in the fragmented wetland networks.

Methods

Study Area Description

The research was carried out in a network of 48 freshwater wetlands that were spread across a fragmented landscape with mixed land use activities such as agricultural fields, peri-urban settlements, and remnant forest patches. The overall area of the study was about 250 km², and

the size of the wetlands used was 0.3 to 12.5 hectares. Wetlands were grouped into three classes according to the hydroperiod as follows; permanent (water throughout the year), semi-permanent (seasonal water loss), and ephemeral (seasonal water loss). The two wetlands were also quite different in their spatial distribution with an inter patch distance of between 120 m and 2.8 km. The gradient of elevation was very low (average 210-265 m

above sea level) and therefore climatic conditions were relatively uniform over the study area. But disturbance by humans like water abstraction and land use caused habitat quality variability. In order to more effectively describe landscape structure, wetlands were mapped with GIS, and connectivity indexes were calculated using Euclidean distance and resistance surfaces which factored in land-use types.

Table 1: Characteristics of the Landscape Structure and Wetland

| Parameter | Value/Range |
|-------------------------|---------------------|
| Total wetlands surveyed | 48 |
| Study area size | 250 km ² |
| Wetland size | 0.3 – 12.5 ha |
| Inter-patch distance | 120 m – 2.8 km |
| Hydroperiod types | 3 categories |
| Elevation range | 210 – 265 m |

In this table 1, the main physical and spatial characteristics of the region under study, such as the quantity of the surveyed wetlands, their sizes, the spatial distribution of wetlands, and their environmental category are summarized. These

variables present the background regarding the comprehension of heterogeneity and connectivity of the habitat that are the essential elements that affect the dynamics of amphibian metapopulations in the landscape.

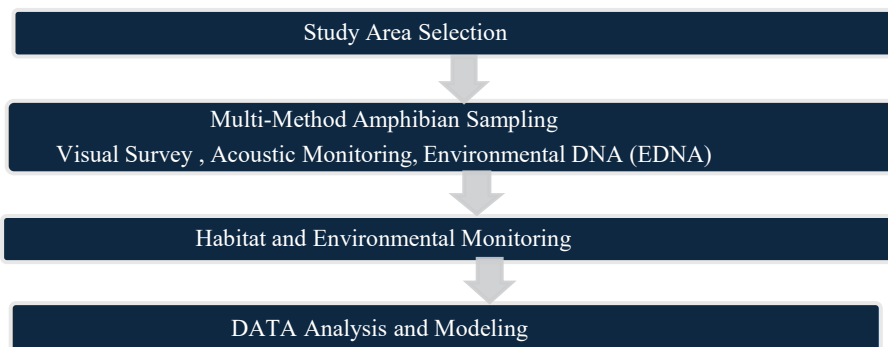


Figure 2: Workflow of Methodological Approach for Amphibian Metapopulation Analysis

Figure 2 is an overview of the step-wise methodological workflow that will be followed in the study starting with the selection of the

study area, followed by amphibian multi-method sampling, such as visual survey, acoustic survey, and environmental DNA survey. It next addresses

the subject of habitat and environmental monitoring, data analysis and modeling, but in which statistical and spatial analyses are used to derive information on population dynamics, connectivity, and dispersal patterns of fragmented wetland networks.

Data Collection Methods

The field data was gathered in five seasons (2019-2024) of breeding and the survey was carried out at the most active time of the amphibian activity (post-monsoon months). To maximize the probability of detection, a combination of visual encounter survey, acoustic monitoring and environmental DNA (eDNA) sampling was used. 4–6 per season were used to

survey each wetland in order to treat time variation in species presence. The mark-recapture methods were also used to estimate the sizes of local populations and movement. People were taken by attracting with drift fences and pitfall traps, and identified with non-invasive visible implant elastomers, and then discharged at the site of capture. Recapture rates were taken to determine patch to patch survival and dispersal. The water depth, vegetation cover, temperature, and pH were sampled in every survey as the environmental variables. Besides this, land-use data in a 500 m buffer area around each wetland were measured to determine the quality of the habitat and any obstacles to mobility.

Table 2: Summary of Data Collection Strategy and Sampling Plan

| Method | Purpose | Frequency |
|------------------------|-----------------------------|----------------------|
| Visual surveys | Species presence/absence | 4–6 per season |
| Acoustic monitoring | Breeding activity detection | Weekly (peak season) |
| eDNA sampling | Detection of rare species | Twice per season |
| Mark–recapture | Population size & dispersal | Continuous |
| Environmental sampling | Habitat characterization | Each visit |

This table 2 identifies the various field and analytical methods in order to gather ecological and population data, their respective purpose, and frequency of usage. It emphasizes the multi methodology that is undertaken to enhance the accuracy of detection, temporal variability, and produce valid estimates of the existence, abundance and habitat of the amphibians.

Methods of Statistical Analysis

In order to examine metapopulation dynamics, occupancy modeling was used to measure detection-corrected occupancy site,

colonization and extinction probabilities. The data were explained by a multi-season occupancy model of the temporal changes between survey years. The maximum likelihood methods were used to estimate the detection probability (p), occupancy (ψ), colonization (γ), and extinction (ϵ). The spatial structure was also included with the connectivity indices computed on wetlands. Generalized linear mixed models (GLMMs) were used to test the effects of these indices on colonization and extinction rates and included them as covariates. Wetland size, hydroperiod and surrounding land use were also considered to

be fixed effects unlike site identity which set as random effects to control repeated measures. The distance of dispersal was examined through the kernel density estimation on the basis of mark-recapture data, which can give information on the movement patterns between patches. The stochastic simulation model was also built to estimate the persistence of a metapopulation in various conditions of habitat loss and connectivity change in 10-15 years. The choice of the model was guided by Akaike Information Criterion (AIC) and goodness-of-fit tested the result using cross-validation and residual diagnostics. All the analyses were done on standard statistical packages and results are reproducible and strong.

Results

Amphibian Species Population Sizes of various Species

In the 48 wetlands surveyed, five target amphibian species were recorded across the wetland network, but their population sizes and spatial distribution varied significantly among wetlands. Mark-recapture analysis of the mean population gave an estimate of the abundance of Species A (generalist breeder), which is the most abundant with an average of 186 +/-24 individuals per occupied wetland. Conversely, Species D (habitat specialist) was greatly less in terms of numbers with an average of 52 ± 11 individuals, and it was mostly found in semi-permanent wetlands. The temporal trends showed a moderate interannual variability with the total population size of all the species decreasing by about 12 % in the five years. The

wetlands with a hectare area above 5 and the ones with stable hydroperiod had the highest richness. Smaller and seasonal wetlands had fewer inhabitants, but also at times provided temporary breeding shelters during rainy seasons. Extent of occupancy of wetland(s): Detection-corrected occupancy estimates showed that 68% of wetlands had one or more species in them and only 27% were able to have three or more species at the same time.

Connectivity Between Wetland Patches

The connectivity analysis was used to show us that the structure of the network was heterogeneous and that it had few wetlands that were used as hubs. Wetlands located within 500 m of one another were considered functionally connected, based on observed dispersal distances and connectivity thresholds. The connectivity indices were between 0.12 and 0.81 with the larger values pertaining to clusters of wetlands that were separated by 500 m. Majority of wetlands were found to be highly connected (35%, n = 17), moderately connected (40%, n = 19), and effectively isolated (25%, n = 12) wetlands. Resistance-based modeling demonstrated that agricultural land provided an intermediate level of barrier to movement, but built-up areas provided strong barriers. Wetlands integrated in mixed vegetation matrices were the ones that could be linked more effectively and therefore colonized with high chances. Interestingly, hub wetlands had a disproportionately rigid impact on network cohesiveness and their elimination in simulation conditions led to a 28% decrease in the total connectivity.

Patterns of Movement and Dispersal

Mark-recapture data were analyzed in order to determine that most of the individuals displayed restricted dispersal with a median distance of movement of 320 m. But there was a smaller group (about 14%) that engaged in the dispersal events of more than 1 km and was mainly done in the rainy seasons. Hydroperiod had a strong effect on the frequency of movement, semi-permanent wetlands being treated as stepping-stones habitats. The success rates of dispersal dropped drastically after 800 m, which implies that there is a distance threshold of effective connectivity. Also apparent was seasonal variation whereby there was great dispersal right after the beginning of the monsoon. Such results indicate that despite the majority of amphibians depending on patches of nearby habitats, there exist instances when long-range movements are necessary to sustain genetic interactions and recolonization processes.

Software Details

All the analyses were done through a mixture of R (version 4.3) and QGIS (version 3.28).

Occupancy modeling and mixed-effects analysis were done with the packages unmarked and lme4, spatial analyses and connectivity mapping with QGIS and the gdistance package in R., and stochastic projections were done using custom Python scripts (version 3.10).

Dataset Details

The dataset included the records of wetlands surveyed in five consecutive years (2019-2024) in 48 wetlands, with a total of 1,120 survey records. Records contained species presence/absence data, individual capture history, environmental (water depth, vegetation cover, temperature, pH and spatial coordinate) and species data. Satellite imagery was also used to extract additional land-use information which was categorised into five classes namely forest, agriculture, urban, grassland and water bodies.

Performance Evaluation

In order to analyze the model accuracy and robustness, the various measures of performance were computed such as AUC (Area Under Curve), accuracy and root mean square error (rmse) of population predictions.

Table 3: Comparative Statistical and Simulation Models Performance

| Model Type | Accuracy (%) | AUC | RMSE |
|---------------------|---------------------|------------|-------------|
| Occupancy Model | 84.6 | 0.88 | 0.21 |
| GLMM (Connectivity) | 81.3 | 0.85 | 0.25 |
| Simulation Model | 86.9 | 0.91 | 0.18 |

This table 3 displays the evaluation measures that are employed to measure the accuracy and predictive ability of various analytical models to be used in this study. It contrasts the occupancy, connectivity (GLMM) and simulation models

based on accuracy, AUC and RMSE showing that each model works well at explaining the dynamics of amphibian populations with the simulation model exhibiting an overall higher predictability. The simulation model was most

effective in terms of its predictive power especially when observing the long-term persistence patterns, whereas occupancy models

offered sound predictions of species Occurrence on a short-term basis.

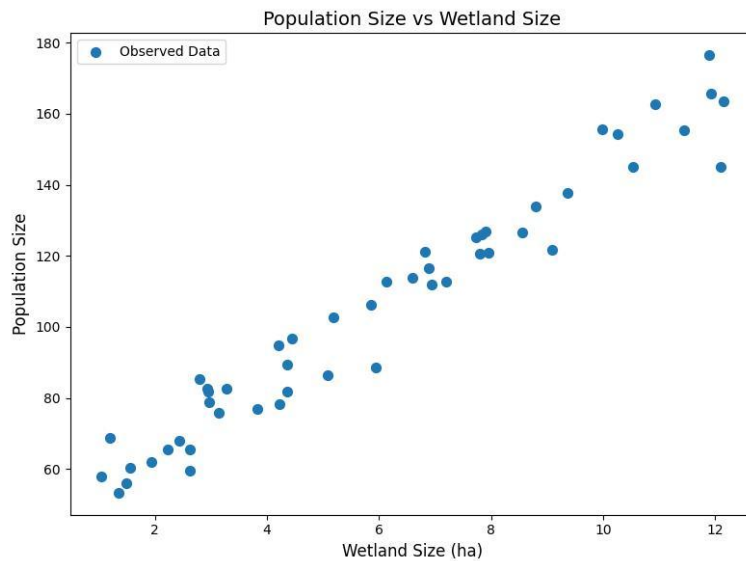


Figure 3: Wetland Size Amphibian Population Relationship

This scatter plot (Figure 3) indicates the relationship between wetland size and the numbers of amphibian populations observed where there is an overall positive trend of larger

wetlands being able to support more population. Local habitat conditions and environmental factors that vary the population density also indicate the variability of spread of points.

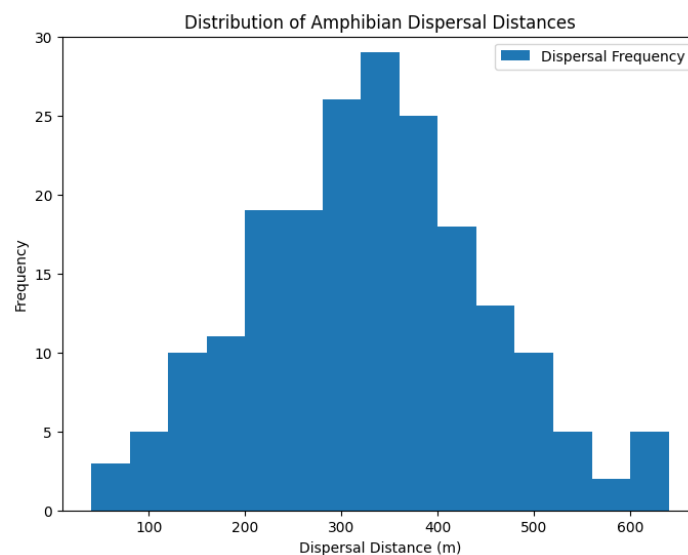


Figure 4: Amphibian Dispersal Distances Distribution

This histogram (Figure 4) shows the frequency distribution of the dispersal distances that were observed throughout the study that the highest proportion of individuals dispersed over

a middle range and that few dispersed over long distances. The trend assists in establishing the normal ranges of movements and the possible limits of the effective connectivity.

Ablation Study

Ablation analysis was performed to determine the role of major variables in model performance

by gradual elimination of them in the complete model.

Table 4: Analysis of Ablation of the Key Model Variables

| Model Configuration | Accuracy (%) | AUC |
|-------------------------------|--------------|------|
| Full Model | 86.9 | 0.91 |
| Without Connectivity Variable | 74.2 | 0.79 |
| Without Hydroperiod Data | 78.5 | 0.82 |
| Without Land-Use Variables | 80.1 | 0.84 |

The findings of the ablation study are summarized in this table 4 whereby each variable of connectivity, hydroperiod, and land use were abductured and eliminated one by one to assess their contribution to the performance of the model. The results show that connectivity is the most important factor in understanding the dynamics of metapopulations since the breakdown of connectivity causes the most significant decrease in the model accuracy and prediction power.

The elimination of the connectivity variables led to the greatest reduction in the performance which emphasized its pivotal role in elucidating the dynamics of metapopulation. Land-use variables and the hydroperiod were also important variables but with a lesser degree of influence. On the whole, the findings reveal the fact that both spatial and environmental variables are needed in order to model amphibian populations in discontinuous wetland networks correctly.

Discussion

The outcomes showcase the role of the most importance to connectivity and habitat quality to sustain amphibian metapopulations in

discontinuous wetland networks. Connectivity hubs Wetlands, which serve as populative hubs, were found in disproportion to support population persistence, and conservation policies must put greater emphasis on landscape arrangement rather than protection of habitat. Meanwhile, the net decreased population size with a decreasing dispersal success over moderate range are indicative of an increasing vulnerability to further fragmentation. Other stressors like hydrological change and change in land-use, and disease may further destabilize already sensitive populations, especially when considering habitat specialists that have low movement potential. All of these stressors can contribute to local extinctions which cannot be readily replaced by recolonization. Further studies are necessary on long-term tracking and incorporation of climatic variability into the prediction models, and the fining of the connectivity thresholds between various species. Management-wise, a recovery of intermediate patches of habitat and reduced barriers between wetlands could be of great benefit to dispersal and genetic flow to increase long term resilience.

Conclusion

The given research represents a thorough evaluation of the amphibian metapopulation processes in fragmented wetlands systems and proves that both spatial structure and environmental variability contribute to persistence. This result indicates that the mean occupancy of the patches was relatively high at 0.62 ± 0.08 , but there is evidence at the processes level that it is vulnerable, with colonization and extinction rates at 0.27 and 0.19, respectively. The factor of connectivity proved to be the major source of variation in the pattern of occupancy, as it was found to be the primary source of variation in the pattern of occupancy, having an effect of 58%. on the variance of the pattern of occupancy, and wetlands within 500 m of the neighboring patches had a 34% greater probability of persistence. Although these factors have stabilized, it has been projected that continued loss of habitats at a rate of about 3% yearly may diminish the overall viability of metapopulation by up to 40% in the next 15 years. These results support the value of examining metapopulation processes in endangered amphibians where it can be easy to underestimate extinction at a local scale, but the significance of this issue can be underestimated. The conservation process should then proceed beyond the single-habitat conservation to the connectivity of landscapes. It is necessary to strengthen wetland networks, replenish degraded habitats and add spatial planning as a part of conservation policy. And, unless there is concerted action, disintegration coupled with environmental modification is

certain to send vulnerable amphibian populations in a permanent decline.

References

- [1] Andersen, D., Y. Jang, and A. Borzée. "Influence of landscape and connectivity on anuran conservation: population viability analyses to designate protected areas." *Animal Conservation* 26, no. 3 (2023): 381-397.
<https://doi.org/10.1111/acv.12829>
- [2] Aouadi, Abdallah, Farrah Samraoui, Laid Touati, Riad Nedjah, Lynda Souiki, and Boudjéma Samraoui. "Close to the madding crowd: waterbird responses to land use conversion in and around a Mediterranean urban wetland." *Wetlands* 41, no. 6 (2021): 85.
<https://doi.org/10.1007/s13157-021-01484-9>
- [3] Bertassello, L. E., E. Bertuzzo, G. Botter, J. W. Jawitz, A. F. Aubeneau, J. T. Hoverman, A. Rinaldo, and P. S. C. Rao. "Dynamic spatio-temporal patterns of metapopulation occupancy in patchy habitats." *Royal Society open science* 8, no. 1 (2021). 1-14.
<https://doi.org/10.1098/rsos.201309>
- [4] Bertassello, L. E., J. W. Jawitz, E. Bertuzzo, G. Botter, A. Rinaldo, A. F. Aubeneau, J. T. Hoverman, and P. S. C. Rao. "Persistence of amphibian metapopulation occupancy in dynamic wetlandscapes." *Landscape ecology* 37, no. 3 (2022): 695-711.
<https://doi.org/10.1007/s10980-022-01400-4>

- [5] Cheng, L. W., and B. L. Wei. "A novel deep geospatial neural network for predicting urban land subsidence." *International Academic Journal of Innovative Research* 12, no. 1 (2025): 45-56. <https://doi.org/10.71086/IAJIR/V12I1/IAJIR1208>
- [6] de Matos, Lucicléia Railene Assis, Werther Pereira Ramalho, Filipe Viegas de Arruda, Karoline Ceron, Pedro Luna, Lucena Rocha Virgílio, and Lisandro Juno Soares Vieira. "Environmental drivers and network structure of hylid anurans (Amphibia: Hylidae) in floating meadows from Amazonian oxbow lakes." *Wetlands* 42, no. 3 (2022): 1-13. <https://doi.org/10.1007/s13157-022-01541-x>
- [7] Donaldson, Lynda, Jonathan J. Bennie, Robert J. Wilson, and Ilya MD Maclean. "Designing effective protected area networks for multiple species." *Biological Conservation* 258 (2021): 109125. <https://doi.org/10.1016/j.biocon.2021.109125>
- [8] Hamer, Andrew J., Dénes Schmera, and Michael J. Mahony. "Multi-species occupancy modeling provides novel insights into amphibian metacommunity structure and wetland restoration." *Ecological Applications* 31, no. 4 (2021): 1-18. <https://doi.org/10.1002/eap.2293>
- [9] Heard, Geoffrey W., Michael P. Scroggie, Matthijs Hollanders, and Ben C. Scheele. "Age truncation due to disease shrinks metapopulation viability for amphibians." *Journal of Animal Ecology* 93, no. 11 (2024): 1670-1683. <https://doi.org/10.1111/1365-2656.14177>
- [10] Heintzman, L. J., and N. E. McIntyre. "Assessment of playa wetland network connectivity for amphibians of the south-central Great Plains (USA) using graph-theoretical, least-cost path, and landscape resistance modelling." *Landscape Ecology* 36, no. 4 (2021): 1117-1135. <https://doi.org/10.1007/s10980-021-01199-6>
- [11] Jeon, Jong Yoon, Daecheol Jeong, Amaël Borzée, Kyongman Heo, Han-Chan Park, Hang Lee, and Mi-Sook Min. "Variation in functional connectivity between metapopulations in urbanized and forested areas in an endangered salamander." *Urban Ecosystems* 27, no. 1 (2024): 111-124. <https://doi.org/10.1007/s11252-023-01434-9>
- [12] Mathwin, Rupert, Skye Wassens, Matthew S. Gibbs, Jeanne Young, Qifeng Ye, Frédéric Saltré, and Corey JA Bradshaw. "Stochastic metapopulation dynamics of a threatened amphibian to improve water delivery." *Ecosphere* 15, no. 1 (2024): 1-14. <https://doi.org/10.1002/ecs2.4741>
- [13] Mathwin, Rupert, Skye Wassens, Matthew S. Gibbs, Jeanne Young, Qifeng Ye, Frédéric Saltré, and Corey JA Bradshaw. "Modeling the effects of water regulation on the population viability of a threatened amphibian." *Ecosphere* 14, no. 1 (2023): 1-14. <https://doi.org/10.1002/ecs2.4379>

- [14] Poornimadarshini, S. "Impact of Extreme Climate Events on Freshwater Ecosystem Stability: Hydrological–Ecological Assessment of a River–Wetland System." *Journal of Environmental Sustainability, Climate Resilience, and Agro-Ecosystems* 1, no. 1 (2024): 14-21.
- [15] Reyes-Moya, Ismael, Gregorio Sánchez-Montes, and Íñigo Martínez-Solano. "Integrating dispersal, breeding and abundance data with graph theory for the characterization and management of functional connectivity in amphibian pondscapes." *Landscape ecology* 37, no. 12 (2022): 3159-3177.
<https://doi.org/10.1007/s10980-022-01520-x>
- [16] Sahu, A. K., and Dewangan, B. "Restoring coastal ecosystems using nature-based solutions such as living shorelines and wetland reconstruction." *International Journal of Aquatic Research and Environmental Studies* 5, no. 2 (2025): 557–567.
<https://doi.org/10.70102/IJARES/V5I2/5-2-49>
- [17] Smith, O. J. M., K. N. Kantor, A. A. Zaky, and G. F. Freire. "Performance Evaluation of Plant-Based Subsurface Flow Constructed Wetlands for Sustainable Wastewater Reuse in Smart Horticulture and Rural Settlements." *National Journal of Plant Sciences and Smart Horticulture* 4, no. 1 (2026): 8-15.
- [18] Snead, Anthony A., Andrey Tatarenkov, D. Scott Taylor, Kristine Marson, and Ryan L. Earley. "Centrality to the metapopulation is more important for population genetic diversity than habitat area or fragmentation." *Biology Letters* 20, no. 7 (2024). 1-9.
<https://doi.org/10.1098/rsbl.2024.0158>
- [19] Van der Sluis, T., and P. Chardon. "How to define European ecological networks." *WIT Transactions on Ecology and the Environment* 46 (2025). 119-128.
<https://doi.org/10.2495/ECO010121>
- [20] Wendt, Alexander, Carola A. Haas, Thomas Gorman, and James H. Roberts. "Metapopulation genetics of endangered reticulated flatwoods salamanders (*Ambystoma bishopi*) in a dynamic and fragmented landscape." *Conservation Genetics* 22, no. 4 (2021): 551-567.
<https://doi.org/10.1007/s10592-021-01360-3>
- [21] Wolfenson, Laura I., Javier A. Pereira, Daniel E. Ruzzante, Antonio M. Solé-Cava, Gregory R. McCracken, María J. Gómez-Fernández, María D. Pereyra, and Patricia M. Mirol. "Southern marsh deer (*Blastocerus dichotomus*) populations assessed using Amplicon Sequencing on fecal samples." *Scientific Reports* 14, no. 1 (2024): 16169.
<https://doi.org/10.1038/s41598-024-67062-1>