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Modeling and statistical analysis of the impact of environmental factors on aquatic biodiversity

Anastasia Kozlova[1,2*], *Tatiana* Solovieva[1,2], *Sergei* Kurashkin[2], *Maxim* Bricotnin[1], and *Natalia* Kandaurova[1]

[1]Reshetnev Siberian State University of Science and Technology, 660037 Krasnoyarsk, Russia
[2]Bauman Moscow State Technical University, 105005 Moscow, Russia

Abstract. This work is dedicated to the analysis of aquatic ecosystems and the assessment of the impact of anthropogenic interventions on amphibian biodiversity. Special attention is given to restored and control ponds, where ecological characteristics such as pond type, vegetation cover, shore condition, and the presence of fish are studied, as well as their impact on amphibian species diversity. The work employed correlation, factor, and regression analysis methods, which revealed significant relationships between ecological characteristics and amphibian species abundance. The analysis results show that factors such as pond type, the presence of fish, and shoreline features have a significant impact on species diversity. A positive correlation was found between the presence of amphibian species and overall species diversity, while a negative correlation was observed between anthropogenic factors, such as fish and artificially created ponds, and amphibian abundance. Factor analysis identified latent variables describing the ecological structures of the data, such as pond types, vegetation, and organic sediments, and also demonstrated that the restoration of aquatic ecosystems contributes to improved biodiversity.

1 Introduction

The analysis of aquatic ecosystems and the impact of anthropogenic interventions on biodiversity is an important task for the conservation of ecosystem services and natural resources. In particular, amphibians, as indicators of ecosystem health, are highly sensitive to environmental changes, including the types of water bodies, the specifics of their restoration, and anthropogenic impacts. This dataset provides a unique opportunity to study the factors affecting amphibian species diversity in restored and control ponds. Including characteristics such as pond type, vegetation cover, shore condition, and the presence of fish, the data allow for exploring not only the relationships between these variables but also the impact of each factor on amphibian habitats.

The tasks of the work include investigating the relationship between water body characteristics and amphibian species diversity, assessing the impact of anthropogenic factors on ecosystem health, and analyzing the factors that promote or hinder the restoration

* Corresponding author: ankoz9@yandex.ru

of aquatic ecosystems. Special attention is given to correlation analysis, which helps identify key factors affecting amphibian abundance and diversity. The developed analytical methods will not only assess current ecological conditions but also provide recommendations for improving the state of water bodies to preserve and restore amphibian biodiversity.

This work is aimed at in-depth study of the factors determining amphibian species diversity and assessing the impact of various ecological characteristics of water bodies on their populations.

2 Materials and methods

Various statistical methods were used in the study to analyze the data, including correlation, factor, and regression analysis.

Correlation analysis was applied to examine the relationships between the ecological characteristics of ponds and amphibian biodiversity. Pearson's method was used for quantitative variables, allowing for the identification of both positive and negative correlations between factors such as pond type, shore characteristics, the presence of fish, and amphibian species.

Factor analysis was used to identify hidden factors affecting data structure and amphibian biodiversity. Principal component analysis with Varimax rotation revealed key factors such as pond type, vegetation, and shore characteristics [1, 2].

Descriptive statistical methods, such as mean, median, and standard deviation, were used to analyze the distribution of the species richness variable and to visualize the data through histograms and scatter plots.

Regression analysis was applied to assess the impact of various factors on amphibian species diversity, including linear and multiple regression, allowing for the identification of the most significant variables affecting the number of species present in the ponds.

The dataset used relates to the restoration of aquatic ecosystems and the assessment of amphibian communities [1]. It includes information on pond types, environmental characteristics, and the presence of various amphibian species. These data allow for the analysis of the impact of intervention on biodiversity, as well as the comparison of changes in ecosystems between restored and control ponds. Key variables include pond characteristics, such as vegetation cover, shore types, and the number of amphibian species found in different types of water bodies.

Below are the fields of the dataset under consideration:

1. *CODE* – Code of the site.
2. *Type* – Pond type (restored or control).
3. *Restorated* – Pond restoration status (1 = restored, 0 = not restored).
4. *Constructed* – Pond construction status (1 = constructed, 0 = not constructed).
5. *RDA_POND_TYPE* – Pond type (interventional or control).
6. *utm_x*, *utm_y* – Coordinates in the UTM system.
7. *FISH* – Presence of fish (1 = present, 0 = absent).
8. *MACROPH* – Macrophyte cover (%).
9. *BANK_SLIGHTLY*, *BANK_VERY* – Percentage of shore slope with angles of 15-30° and 70-80°, respectively.
10. *SUBS_ORMUD* – Percentage of organic muds on substrates.
11. *SHORE_TREE* – Percentage of shoreline covered by trees.
12. *TERR_MIXEDWOOD*, *TERR_SCRUB* – Percentage of adjacent land with forests and shrubs.
13. *TERR_N* – Total number of natural land types.
14. *SamplingYear* – Year of data recording.

15. *Rtemporaria*, *Bbufo*, *Lhelveticus*, *Lvulgaris*, *Tcristatus* – Presence of different amphibian species (0 = absent, 1 = present).
16. *Richness* – Total number of amphibian species.

3 Results

The distribution of the variable *Richness*, as shown in Figure 1, reveals that the value 2 occurred most frequently, making up the majority of the data with 34 observations. The value 1 was observed 31 times, slightly less than value 2. The value 3 appeared 22 times, making it the third most frequent [3]. The value 0 was recorded 16 times, while the value 4 occurred only 8 times. The least common value was 5, observed only in 2 cases. This distribution suggests a predominance of low values of *Richness* in the data, which may be related to environmental characteristics, observation conditions, or the methodology of data collection. The rarity of higher values such as 4 and 5 could indicate specific conditions necessary for their occurrence.

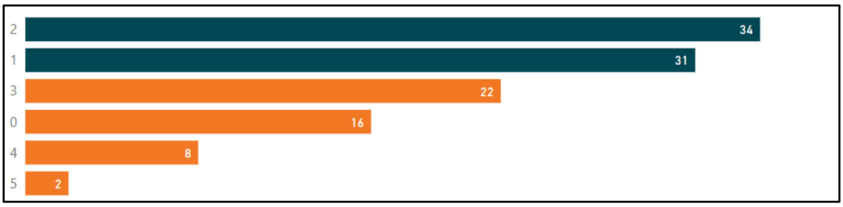

Fig.1. Number of observations for the *Richness* variable

The graph presented in Figure 2 illustrates the relationship between pond characteristics and amphibian species diversity (*Richness*). Positive correlation indicates a trend of increasing species diversity with the growth of a certain variable, while negative correlation reflects an inverse relationship.

A positive correlation is observed between the presence of amphibian species (*Rtemporaria*, *Bbufo*, *Lhelveticus*, *Lvulgaris*, *Tcristatus*) and overall species diversity (*Richness*), which makes sense since the presence of these species directly increases the total number of species. The variables *BANK_SLIGHTLY* and *SamplingYear* also show a positive correlation, which may suggest a link between ponds with a slight shore slope, later years of data sampling, and higher amphibian species diversity. A moderate positive correlation is noted for the variables *TERR_MIXEDWOOD* and TERR_N, indicating a positive effect of adjacent forest and shrub areas, as well as a greater variety of natural land types, on amphibians.

A negative correlation is identified for the variables *Type* and *Constructed*, which may mean that artificially created or restored ponds have slightly lower amphibian species diversity compared to natural water bodies. The variables *FISH* and SHORE_TREE show a more pronounced negative correlation. The presence of fish may reduce the abundance and diversity of amphibians due to predation, while high tree cover along the shoreline can alter the microclimate, which is not always favorable for amphibian breeding. A weak negative correlation is noted for the variables SUBS_ORMUD and BANK_VERY, suggesting a potential negative impact of organic muds and steep shores on amphibian habitat conditions.

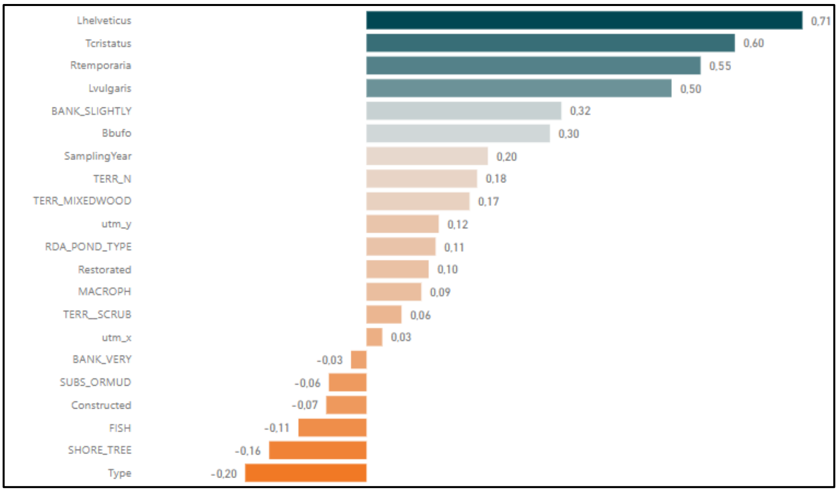

Fig.2. Correlation of variables with the *Richness* field

The results of the study highlight the importance of factors such as the presence of specific amphibian species, pond type, shoreline characteristics, presence of fish, and environmental features in shaping species diversity [4, 5]. To gain a deeper understanding of the identified relationships, further research is needed that takes into account the specifics of ecosystems. Creating and restoring water bodies considering hydrological, vegetation, and ecological characteristics are promising measures for the conservation of amphibian biodiversity [6]. Special attention should be given to studying the impact of anthropogenic factors on the ecological conditions of water bodies.

The factor analysis, the results of which are presented in Figure 3, identified several latent variables that describe the main structures in the data [7].

Factor 1 has high positive loadings on the variables *Type* (0.83), *RDA_POND_TYPE* (0.77), and SUBS_ORMUD (0.69), indicating its association with pond types and organic substrate characteristics. Moderate loadings are observed for the variables *MACROPH* (0.35) and SHORE_TREE (0.30), which may reflect the influence of macrophytes and shoreline vegetation. A negative loading for *SamplingYear* (-0.83) suggests a possible change in ecological parameters over time. Among amphibians, the largest negative loading is shown for *Rtemporaria* (-0.51), highlighting the factor's link to biodiversity.

Factor 2 is characterized by high positive loadings on biodiversity indicators: *Richness* (0.89), *Lhelveticus* (0.84), and *Rtemporaria* (0.55). This indicates that this factor describes amphibian diversity [8]. Moderate loadings for *Tcristatus* (0.40) and *Lvulgaris* (0.32) confirm its role in describing the biological component of the environment.

Factor 3 is focused on pond restoration characteristics. The variable *Restorated* has a high positive loading (0.91), while *Constructed* shows a negative loading (-0.89). This may reflect differences between restored and constructed water bodies. Moderate positive loadings for *MACROPH* (0.31) and BANK_VERY (0.30) indicate the influence of vegetation and steepness of the shore.

Factor 4 is associated with the presence of fish and other water environment characteristics. High positive loadings for *FISH* (0.78) and SHORE_TREE (0.54) point to the influence of these parameters on the data structure. Moderate loadings for *Bbufo* (0.73) and negative loadings for *Tcristatus* (-0.40) highlight the link to biodiversity.

Factor 5 is characterized by a high loading for *BANK_SLIGHTLY* (0.80), indicating its association with shoreline slope characteristics. Moderate positive loadings for *Lvulgaris*

(0.57) and *Tcristatus* (0.53) may reflect the influence of slope on amphibian habitat conditions [9].

Factor 6 is focused on the diversity of natural territories. A high positive loading for TERR_N (0.75) and moderate loadings for *Rtemporaria* (0.47) emphasize the impact of surrounding landscapes on biodiversity.

Factor 7 is associated with the steepness of the shore. A high negative loading for BANK_VERY (-0.73) indicates the link between this factor and steep shorelines [10-12]. Moderate positive loading for *TERR_MIXEDWOOD* (0.48) may reflect the role of mixed forests in the adjacent territory.

Name	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6	Factor 7
BANK_SLIGHTLY	-0,12	0,01	-0,01	0,15	0,80	0,23	0,17
BANK_VERY	0,10	0,01	0,30	0,11	-0,17	0,06	-0,73
Bbufo	0,15	0,19	-0,10	0,73	0,18	-0,04	-0,40
Constructed	0,22	0,01	-0,89	0,07	-0,05	-0,02	0,04
FISH	0,06	-0,16	-0,09	0,78	-0,01	0,06	-0,05
Lhelveticus	-0,05	0,84	0,03	-0,13	0,07	-0,12	0,12
Lvulgaris	0,01	0,32	0,13	-0,07	0,57	-0,15	0,07
MACROPH	0,35	0,23	0,31	-0,28	-0,22	0,16	0,40
RDA_POND_TYPE	0,77	0,21	-0,34	0,12	-0,10	0,25	-0,03
Restorated	-0,16	0,05	0,91	-0,05	0,04	-0,05	-0,06
Richness	-0,07	0,89	0,03	0,03	0,38	0,17	-0,08
Rtemporaria	-0,51	0,55	0,02	-0,05	-0,17	0,47	0,13
SamplingYear	-0,83	0,13	0,35	-0,23	0,09	-0,14	0,04
SHORE_TREE	0,30	-0,15	0,09	0,54	-0,20	0,33	0,29
SUBS_ORMUD	0,69	-0,15	0,09	-0,23	0,11	0,21	0,04
Tcristatus	0,25	0,40	0,02	-0,40	0,53	0,20	-0,12
TERR__SCRUB	-0,70	-0,05	-0,08	-0,11	-0,04	0,31	-0,10
TERR_MIXEDWOOD	0,22	0,23	0,31	0,00	0,22	-0,22	0,48
TERR_N	0,26	0,03	-0,05	0,11	0,21	0,75	-0,13
Type	0,83	-0,13	-0,35	0,23	-0,09	0,14	-0,04

Fig. 3. Factor Loadings

For *Rtemporaria* (Fig. 3, a), the proportion of observations where the variable value equals 1 is 46.9%, while the proportion of observations where the value equals 0 is 53.1%. This suggests that approximately half of the data belongs to category 1, and the other half to category 0. Such a distribution indicates a balance between the two states or categories for this species or characteristic.

For *Bbufo* (Fig. 3, b), the situation is somewhat different, as the proportion of observations with a value of 1 is 70.8%, while the proportion with a value of 0 is 29.2%. This indicates a predominance of category 1, which may suggest that this state or characteristic is more frequent for *Bbufo*. In this case, the distribution is unbalanced, which could influence data interpretation, such as in modeling or probability analysis [13-18].

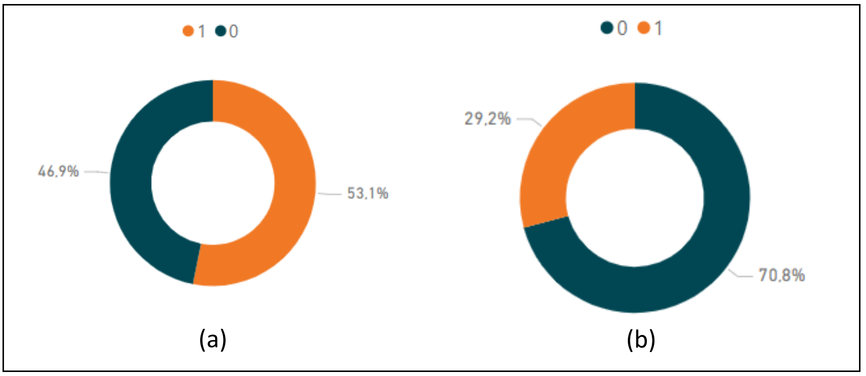

Fig. 4. Proportion of observations for categories of variables: a) *Rtemporaria*, b) *Bbufo*

The correlation analysis of Rtemporaria revealed several significant relationships. The highest positive correlation was with Richness (r = 0.546), indicating that higher species diversity is linked to more frequent occurrences of Rtemporaria. A moderate positive correlation with SamplingYear (r = 0.416) suggests increased abundance over time. The species also showed a positive correlation with scrubland areas (TERR_SCRUB, r = 0.366). Negative correlations include avoidance of areas with organic and muddy substrates (SUBS_ORMUD, r = -0.318) and a decrease in the western region (utm_x, r = -0.258) [19]. Rtemporaria is also less common in anthropogenic water bodies and areas with high fish populations.

For Bbufo, the strongest positive correlation was with FISH (r = 0.507), indicating a preference for fish-rich water bodies. It also correlated moderately with Richness (r = 0.300). Negative correlations include a decline over time (SamplingYear, r = -0.249) and a preference against restored water bodies and certain landscape types. Bbufo favors water bodies with distinct shorelines [20].

Lhelveticus showed a strong positive correlation with Richness (r = 0.713), indicating its preference for species-rich water bodies. It also had a moderate positive correlation with Rtemporaria (r = 0.304) and a negative correlation with FISH (r = -0.274), suggesting avoidance of fish-dense habitats [21]. It prefers mixed forests and moderate vegetation along shores.

Lvulgaris has a strong positive correlation with Richness (r = 0.499) and moderate correlations with Tcristatus (r = 0.271) and shore characteristics. It prefers water bodies with fewer fish (r = -0.148) and fewer trees along shores. A slight positive correlation with SamplingYear (r = 0.123) suggests a modest increase in its abundance.

Tcristatus was observed in only 35 out of 113 cases, indicating its rarity. Its strongest positive correlation was with Richness (r = 0.602), suggesting it thrives in species-rich habitats. It also prefers slightly altered shorelines (BANK_SLIGHTLY, r = 0.282) and muddy substrates (SUBS_ORMUD, r = 0.296). Negative correlations with fish (r = -0.241) and trees along shores (r = -0.204) suggest avoidance of such habitats.

4 Discussion

The provided dataset offers valuable information about the ecological conditions influencing amphibian communities in pond ecosystems, with a particular focus on restored and control ponds. The results of the correlation and factor analysis highlight the complexity of interactions between ecological variables and amphibian diversity.

One of the most significant findings is the positive correlation between the presence of individual amphibian species (e.g., *Rtemporaria*, *Bbufo*, *Lhelveticus*, *Lvulgaris*, and *Tcristatus*) and overall species diversity. This suggests that the presence of diverse amphibian species is a key factor determining the richness of amphibian communities in ponds. This positive relationship indicates that ponds with greater amphibian diversity generally have higher species richness, aligning with ecological theories on biodiversity .

Additionally, it was found that certain ecological factors, such as pond type (restored and artificial) and shoreline characteristics, influence species richness. Interestingly, restored ponds, despite their goal of ecosystem restoration, were associated with lower amphibian diversity compared to natural ponds. This may be due to incomplete habitat complexity restoration or the relatively recent establishment of these ecosystems. The correlation between pond type and artificial ponds with lower species richness suggests that artificial ponds may lack some ecological characteristics inherent in natural ponds that are critical for supporting amphibian communities.

The presence of fish in ponds, which negatively correlated with amphibian species richness, is another important conclusion. Fish, especially predatory species, can have a detrimental impact on amphibian populations as they may consume larvae and adult amphibians. This finding is consistent with previous ecological studies showing the competitive and predatory pressures of fish on amphibians in freshwater ecosystems. Similarly, the negative correlation between amphibian diversity and the amount of shoreline vegetation (SHORE_TREE) suggests that dense tree cover along pond shores may alter the microclimate in a way that is unfavorable for amphibian breeding, potentially lowering water temperature or changing light conditions.

Regarding habitat preferences, the analysis highlighted the role of surrounding landscapes, such as mixed forests (*TERR_MIXEDWOOD*) and shrub zones (TERR_SCRUB), in supporting amphibian biodiversity. These environments likely provide suitable conditions for amphibians, including shelter, food, and breeding sites. Positive correlations with these types of landscapes emphasize the importance of surrounding landscape features for maintaining amphibian populations.

Factor analysis revealed several latent variables that help explain the internal structure of the dataset. Factor 1, which links pond type, organic substrates, and specific shoreline characteristics, reflects ecological conditions that distinguish restored and natural ponds. Factor 2, associated with amphibian diversity, highlights the importance of species richness and specific amphibian species in the ecosystem. These results indicate that amphibian diversity depends not only on pond characteristics but also on the broader ecological context, including surrounding lands and the presence of specific ecological features.

The species analysis of *Rtemporaria*, *Bbufo*, *Lhelveticus*, and *Lvulgaris* showed differences in habitat preferences for each species. For instance, *Rtemporaria* was strongly positively correlated with species richness and showed a preference for areas with shrub vegetation. In contrast, *Bbufo* preferred ponds with higher fish numbers, which may indicate higher tolerance for predation. On the other hand, *Lhelveticus* showed a negative correlation with the presence of fish, indicating a preference for fish-free environments, and was associated with ponds located in mixed forests.

In conclusion, the results of this dataset provide valuable insights into the complex interactions between ecological variables and amphibian diversity in pond ecosystems. The data suggest that both biotic (e.g., species presence) and abiotic (e.g., pond type, fish presence, shoreline characteristics) factors play a crucial role in shaping amphibian communities. These findings emphasize the importance of maintaining diverse and suitable habitats for amphibians and highlight the need to carefully consider ecological factors, such as the presence of fish, shoreline vegetation, and surrounding land use, for successful restoration and conservation of amphibian populations in freshwater ecosystems. Future research should continue to explore these relationships and consider the long-term dynamics of amphibian populations in restored ecosystems.

5 Conclusion

The study of aquatic ecosystems and amphibian species has revealed that factors such as pond type, its characteristics, shoreline vegetation, fish presence, and substrate significantly influence amphibian species diversity. The positive correlation between overall amphibian species diversity and ecosystem condition confirms the importance of these factors for maintaining ecological stability. However, anthropogenic impacts, such as artificial pond restoration, may negatively affect the population of some species.

Particular attention should be given to the role of vegetation and fish, which, as the results show, can reduce amphibian populations. Vegetation communities, such as macrophytes, on the other hand, contribute to creating more favorable conditions for amphibians by providing shelter and improving their habitat.

The analysis conducted using factor analysis revealed that latent variables, such as waterbody characteristics and biodiversity, play a key role in determining ecosystem processes. The influence of time is also significant, as changes throughout the year affect the abundance and diversity of amphibian species.

Thus, the study highlights the importance of a comprehensive approach to pond restoration, taking into account all ecological factors and monitoring ecosystem changes to maintain and increase biodiversity. These results can serve as a foundation for the development of effective conservation measures and strategies for preserving amphibian communities in aquatic ecosystems.

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