*Iranian Journal of Animal Biosystematics* (IJAB)
Vol.21, No.2, 135-143, 2025
DOI: 10.22067/ijab.2025.93593.1103

IJAB

ISSN: 1735-434X (print); 2423-4222 (online)

RESEARCH ARTICLE Open access

# New insights into the distribution and ecological modeling of the Paghman Mountain Salamander *Paradactylodon mustersi* (Caudata: Amphibia) in Afghanistan

Mohammad Hassan Jafari[1], Seyed Saeed Hosseinian Yousefkhani[2,3]✉, Hiva Faizi[4], Ghulam Dastgeer Khawrin[5]

[1]*Department of Biology, Faculty of Education, Baghlan University, Baghlan, Afghanistan*
[2]*Department of Animal Science, School of Biology, Damghan University, Damghan, Iran*
[3]*Institute of Biological Science, Damghan University, Damghan, Iran*
[4]*Department of Biology, Faculty of Science, Razi University, Kermanshah, Iran*
[5]*Kabul Education University, Kabul, Afghanistan*

**Abstract**
This study provides new insights into the distribution and ecological modeling of the Paghman Mountain Salamander (*Paradactylodon mustersi*), an endemic species in Afghanistan, based on field surveys across 53 strategically selected localities in high-altitude streams from March to September 2024. We confirmed the species' presence in all surveyed sites, reflecting targeted sampling of suitable habitats rather than widespread abundance, consistent with its Endangered status (IUCN Red List). Using MaxEnt modeling with cross-validation to minimize overfitting, we identified key environmental variable influencing habitat suitability, as precipitation patterns (BIO13 at 46.1%), with excellent predictive accuracy (AUC = 0.945). The species showed presence in disturbed secondary growth habitats, suggesting some resilience to habitat alteration, though this requires further investigation. Ongoing monitoring and targeted conservation strategies are critical to ensure the long-term survival of this threatened species amidst pollution and climate change pressures. However, ongoing monitoring and targeted conservation strategies are essential to ensure the long-term survival of this threatened species amidst changing environmental conditions.

**Keywords:** Amphibian, habitat requirements, Conservation biology, water quality, pollution.

**Received**: *21 May 2025*

**Revised:** *11 July 2025*

**Accepted**: *13 July 2025*

## INTRODUCTION

The Paghman Mountain Salamander, *Paradactylodon mustersi*, is an endemic amphibian of the family Hynobiidae, found exclusively in the highland streams of Afghanistan's Hindu Kush mountain range. Initially described as *Batrachuperus mustersi* by Smith (1940), its taxonomic status has been debated, with Dubois and Raffaëlli (2012) questioning the validity of *Paradactylodon* due to the lack of a clear diagnosis and proposing the monotypic genus *Afghanodon* for this species (Böhme & Jablonski, 2022). We adopt *Paradactylodon mustersi* based on its broader use in recent literature. The species occurs in the Paghman mountains on the southern slopes of the Hindu Kush, including three tributaries of the Paghman Stream, as well as Gardan Diwal in the Koh-i-Baba Massif, Salang Pass, Sanglakh in Maidan Province, and Dasht-i-Nawar, representing five or fewer threat-defined locations with an extent of occurrence of 2,847 km² (Wagner et al., 2016)

✉Corresponding Author: *s.hosseinian@du.ac.ir*

**HOW TO CITE THIS ARTICLE:**
Jafari, M. H. , Hosseinian Yousefkhani, S. S. , Faizi, H. and Dastgeer Khawrin, G. (2025). New insights into the distribution and ecological modeling of the Paghman Mountain Salamander Paradactylodon mustersi (Caudata: Amphibia) in Afghanistan. *Iranian Journal of Animal Biosystematics*, *21*(2), 135-143. doi: 10.22067/ijab.2025.93593.1103

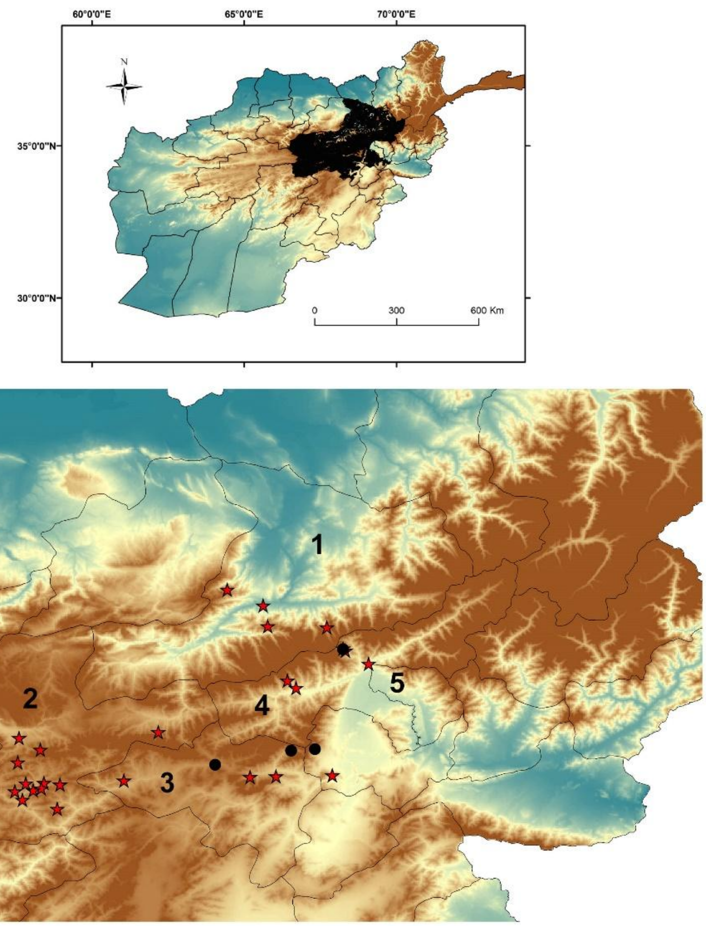


**FIGURE 1.** Study area and current distribution of *Paradactylodon mustersi* across Afghanistan, based on fieldwork (Stars refer to the newly identified localities) and literature (Black circles). 1) Baghlan; 2) Bamyan; 3) Wardak; 4) Parwan; 5) Panjshir.

### Habitat and morphology

*Paradactylodon mustersi* inhabits glacier-formed valleys, primarily in the Paghman streams area of Kabul Province, at elevations of 2,440–3,750 m above sea level (Wagner et al., 2016). It thrives in cold, fast-flowing streams with water temperatures between 0 and 14 °C (Ayobi et al., 2022). The salamander's morphological characteristics include a dark olive-brown to yellowish-olive body speckled with tiny pigmented dots and well-developed limbs, enabling effective navigation in its aquatic environment (Reilly, 1983). Recent surveys (2017–2021) confirmed its presence across tributaries of the Paghman stream and extended its known range to Panjsheer Province, highlighting its adaptation to high-altitude aquatic ecosystems (Ayobi et al., 2022).

### Threats and research gaps

Classified as Endangered (EN) by the IUCN Red List, *P. mustersi* has an estimated population of 1,000–2,000 adults, threatened by habitat disturbance from water pollution, agricultural expansion, and water diversion (Wagner et al., 2016; AmphibiaWeb, 2020[1]; Ayobi et al., 2022). Prolonged political instability in Afghanistan has limited zoological research, with comprehensive assessments of its distribution and

[1] AmphibiaWeb. 2020. *Paradactylodon mustersi*. Retrieved from https://amphibiaweb.org/species/3872 (accessed 30 Nov. 2025)

ecology last conducted nearly 40 years ago (Reilly, 1983; Stuart et al., 2008). Understanding its ecological requirements and distribution patterns is critical for developing effective conservation strategies to ensure the long-term survival of this unique species.

The taxonomic classification of the Paghman Mountain Salamander as *Afghanodon mustersi* or *Paradactylodon mustersi* remains debates in scientific community. The species, described as *Batrachuperus mustersi* (Smith, 1940) and was reassigned to the monotypic genus *Afghanodon* by Dubois and Raffaëlli (2012) due to the lack of a clear diagnosis for *Paradactylodon*. However, Böhme and Jablonski (2022) advocate for the genus *Paradactylodon*, based on morphological traits (e.g., limb structure) and genetic evidence indicating closer phylogenetic ties to other *Paradactylodon* species within the Hynobiidae family. We adopt *Paradactylodon mustersi* following its broader use in recent literature (e.g., Wagner et al., 2016; Ayobi et al., 2022), though ongoing phylogenetic studies are needed to resolve this classification.

This study aims to provide new insights into the distribution and ecological modeling of *P. mustersi*, emphasizing the importance of ongoing research and conservation efforts in Afghanistan's unique ecosystems. We assessed *P. mustersi*'s abiotic water parameters of the endangered species habitat.

## Material and Methods

### Field Surveys and Data Collection

Field surveys were conducted from March to September 2024 across 53 newly identified localities to assess the population of the Paghman Mountain Salamander (*P. mustersi*). The specific field activities conducted in each province include Baghlan Province (Six localities), Bamyan Province (31 localities), Panjshir Province (Two localities), Parwan Province (Six localities) and Wardak Province (Nine localities) (Figure 1 and Appendix 1). Presence records for the Paghman Mountain Salamander (*P. mustersi*) were obtained through direct fieldwork and literature (Ayobi et al., 2022). In total, 53 presence records were gathered and georeferenced.

Species Distribution Modelling (SDM): To predict current distributions, bioclimatic variables were derived from observational data available in WorldClim version 2.1 (Fick & Hijmans, 2017), with a spatial resolution of 30 arc seconds (~1 km²). Nineteen bioclimatic variables (Table 1) for the present and altitude were downloaded and clipped for Afghanistan at the same spatial resolution. The data were converted to ASCII format using DIVA-GIS version 7.5 (Zhang et al., 2021). A jackknife analysis was performed to assess the contribution of bioclimatic variables, and model fit was evaluated using the area under the receiver operating characteristic curve (AUC). The layers were cropped using ArcGIS (ESRI) to focus on the study area within Afghanistan.

All nineteen bioclimatic layers and altitude were analyzed by ENMTools 1.3 (Warren et al., 2010) to evaluate the pairwise correlation and then select the layers with lower correlation than 0.75. The following variable were selected: BIO3; BIO4; BIO11; BIO13; BIO14. Species distribution modeling was conducted using MaxEnt version 3.4.1 software (available at http://www.cs.princeton.edu/schapire/Maxent/). This software was utilized to simulate and predict the potential geographical distribution probability of *Paradactylodon mustersi* under current conditions (Coban et al., 2020; Ye et al., 2020). During the modeling process, 70% of the occurrence data samples were randomly selected as training data, while the remaining 30% were reserved for testing. A total of 10,000 randomly generated background points were used (Zhang et al., 2021). The regularization multiplier was set to 0.1 to prevent overfitting (Phillips & Dudik 2008), and linear, quadratic, and hinge features were included in the model. A total of 100 runs were conducted for model building (Flory et al., 2012), employing the Jackknife method in the environmental parameter settings while keeping other parameters at their default values. Model evaluation was performed using threshold-independent receiver operating characteristic (ROC) analyses, with AUC values used to estimate model accuracy (Elith et al., 2006). Model performance was classified as failing (0.5–0.6), poor (0.6–0.7), fair (0.7–0.8), good (0.8–0.9), or excellent (0.9–1), with higher AUC values indicating better model performance. The lowest training presence threshold define as 0.2, namely the species can tolerate a wider range of habitat conditions, even those with lower suitability scores.

**TABLE 1.** Description of predictive bioclimatic variables used in this study.

| | | | |
|---|---|---|---|
| BIO1 | Annual Mean Temperature | BIO10 | Mean Temperature of the Warmest Quarter |
| BIO2 | Mean Diurnal Range [Mean of Monthly (Max Temp – Min Temp)] | BIO11 | Mean Temperature of the Coldest Quarter |
| BIO3 | Isothermality | BIO12 | Annual Precipitation |
| BIO4 | Temperature Seasonality | BIO13 | Precipitation in the Wettest Month |
| BIO5 | Maximum Temperature of the Warmest Month | BIO14 | Precipitation in the Driest Month |
| BIO6 | Minimum Temperature of the Coldest Month | BIO15 | Precipitation Seasonality |
| BIO7 | Temperature Annual Range | BIO16 | Precipitation in the Wettest Quarter |
| BIO8 | Mean Temperature of the Wettest Quarter | BIO18 | Precipitation in the Warmest Quarter |
| BIO9 | Mean Temperature of the Driest Quarter | BIO19 | Precipitation in the Coldest Quarter |

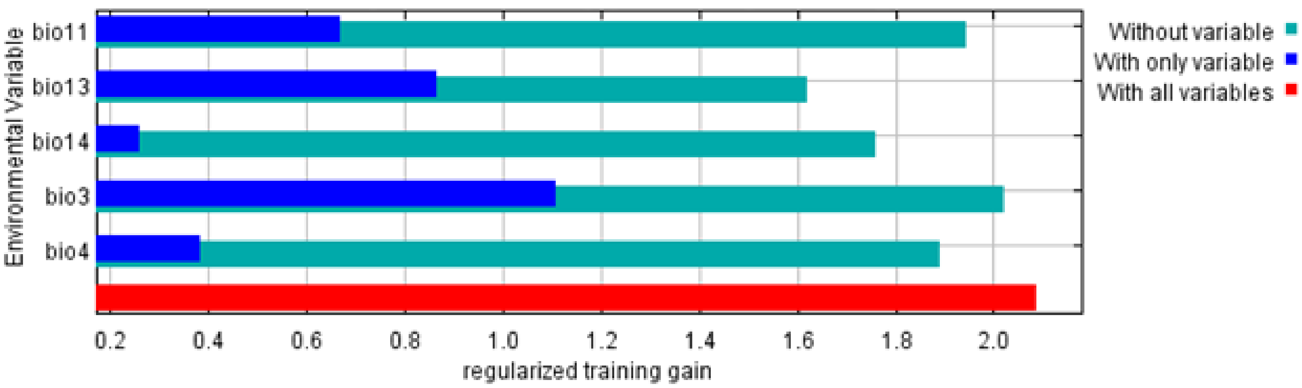


**FIGURE 2**. Results of Jckknife of regularized training gain for *Paradactylodon mustersi*.

## RESULTS

Field surveys conducted across 53 newly identified localities from March to September 2024 yielded critical data on the distribution and ecological requirements of the Paghman Mountain Salamander (*P. mustersi*). The surveys confirmed the presence of the species in all surveyed locations, contributing valuable presence records for future conservation efforts.

### Environmental Variable Contributions

To understand the ecological factors influencing the distribution of *P. mustersi*, a species distribution model was developed using MaxEnt. The analysis revealed the percent contribution and permutation importance of various environmental variables, which are summarized in Table 2 and Figure 2. BIO13 (Precipitation in the Wettest Month) was identified as the most effective variable on habitat suitability, contributing 46.1% to the model's predictive power and demonstrating a permutation importance of 43.6%. Mean Temperature of the Coldest Quarter (BIO11) followed closely, with a percent contribution of 14.2% and a permutation importance of 13.7%, indicating its relevance in understanding the species' habitat preferences. Other precipitation variable also played crucial roles, BIO14 (Precipitation in the Driest Month), which had a percent contribution of 14.0% and a relatively high permutation importance of 26.0% and BIO3 (Isothermality) contributed 13.2% with a permutation importance of 13.3%. Other factor as Temperature Seasonality (BIO4) shows minimal contributions to habitat suitability, with contribution of 12.5%.

The performance of the habitat suitability model was evaluated using the Area Under the Curve (AUC) metric. The mean AUC value was found to be 0.945, indicating excellent predictive accuracy for

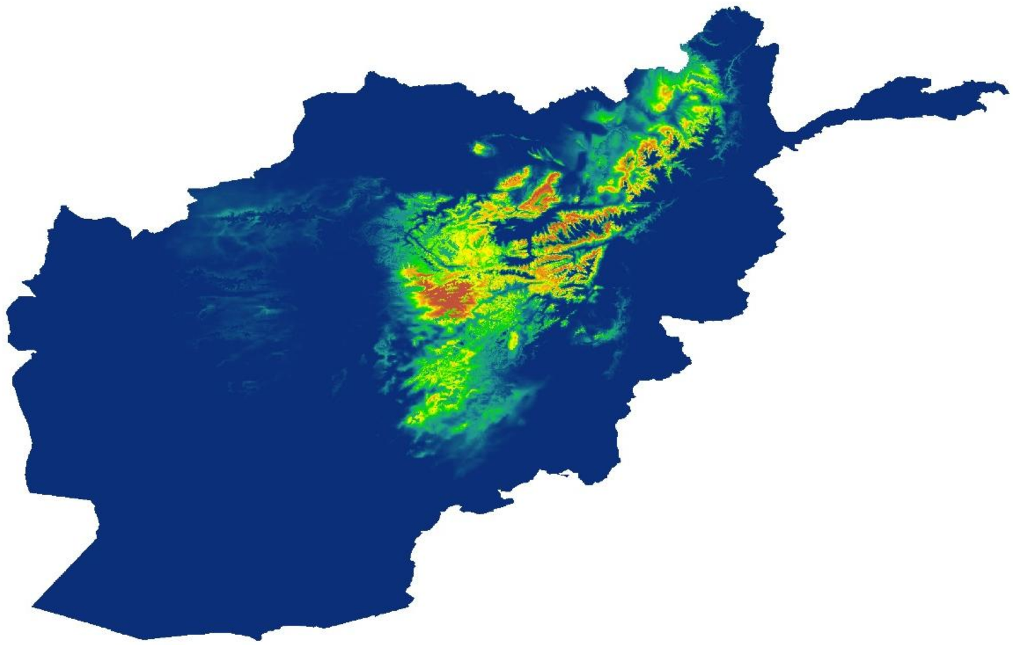

**FIGURE 3.** Habitat suitability prediction and the favorable area for *Paradactylodon mustersi* in Afghanistan under current climate conditions (Worldclim 2.1) based on the Maxent model. Red color refers to the most suitable regions (1) and the blue color shows unsuitable regions (0).

identifying suitable habitats for *P. mustersi*. This high AUC value suggests that the model effectively distinguishes between suitable and unsuitable habitats based on the environmental variables analyzed. The high suitable regions in the modeled map, clearly shows that valleys and streams is the best regions for species presence and needs more consideration (Figure 3).

## DISCUSSION

The results of this study offer critical insights into the distribution and ecological requirements of the Paghman Mountain Salamander (*Paradactylodon mustersi*) in Afghanistan, a region where amphibian ecology remains poorly documented. The confirmation of *P. mustersi* presence across all 53 surveyed localities from March to September 2024 underscores the value of systematic field surveys in generating robust baseline data for conservation in Central Asia. The MaxEnt species distribution model, with a high predictive accuracy (AUC = 0.945), effectively delineates suitable habitats, particularly valleys and streams, which are pivotal for the species' survival. These findings contribute to the broader understanding of amphibian ecology in montane environments and align with regional studies on salamander distribution patterns.

Precipitation-related variables, notably BIO13 (Precipitation in the Wettest Month, 46.1% contribution) and BIO14 (Precipitation in the Driest Month, 14.0% contribution), emerged as the primary drivers of habitat suitability for *P. mustersi*. This strong dependence on water availability mirrors patterns observed in other Middle Eastern salamanders, such as *Salamandra infraimmaculata* in Turkey and Iran, where precipitation is a key determinant of habitat suitability (Kurnaz, 2022; Vaissi, 2021a). For instance, Kurnaz (2022) reported that precipitation during the wettest periods significantly influenced the distribution of *S. infraimmaculata* in Turkey, a finding echoed in our study. Similarly, ecological niche modeling of *Neurergus derjugini* in Iraq highlighted the critical role of precipitation in sustaining stream-dependent amphibians (Khwarahm et al., 2021). The high permutation importance of BIO14 (26.0%) in our model suggests that *P. mustersi* is particularly sensitive to dry season conditions, a trait shared with

**Table 2.** Variable Contributions to Habitat Suitability Model. Bold value refers to the high contributed layer in modeling.

| Variable | Percent Contribution (%) | Permutation Importance (%) |
|---|---|---|
| BIO3 (Isothermality) | 13.2 | 13.3 |
| BIO14 (Precipitation in the Driest Month) | 14.0 | 26.0 |
| BIO13 (Precipitation in the Wettest Month) | **46.1** | **43.6** |
| BIO4 (Temperature Seasonality) | 12.5 | 3.5 |
| BIO11 (Mean Temperature of the Coldest Quarter) | 14.2 | 13.7 |

*Paradactylodon* populations in Iran, where niche evolution is shaped by precipitation gradients (Vaissi et al., 2023). These consistent patterns across taxa underscore the vulnerability of stream-associated salamanders to changes in hydrological regimes.

Temperature-related variables, including BIO11 (Mean Temperature of the Coldest Quarter, 14.2% contribution) and BIO3 (Isothermality, 13.2% contribution), also significantly influence *P. mustersi* distribution. The importance of cold season temperatures aligns with findings for *Salamandra infraimmaculata*, where cooler, high-elevation habitats were preferred (Vaissi, 2021a). In contrast, the limited contribution of BIO4 (Temperature Seasonality, 12.5%) suggests that *P. mustersi* is less affected by seasonal temperature fluctuations compared to hynobiid salamanders in western Japan, which show greater sensitivity to temperature variability (Shin et al., 2021). This may reflect *P. mustersi*'s adaptation to the stable microclimates of valleys and streams, which provide thermal and moisture refugia. Comparable studies on *Neurergus barani* and *N. strauchii* in Anatolia further support the importance of stable microhabitats for montane salamanders (Kurnaz & Şahin, 2021). The prominence of valleys and streams in our habitat suitability maps (Figure 3) reinforces their role as critical habitats, consistent with findings for other stream-breeding amphibians in the Middle East (Vaissi, 2021b).

The biogeographic context of the Paghman Mountains, characterized by arid conditions and fragmented habitats, amplifies the conservation significance of our findings. The high AUC value of our model indicates that conservation efforts should prioritize protecting valley and stream ecosystems, which serve as refugia for *P. mustersi*. This is particularly urgent given the vulnerability of montane amphibians to habitat loss and climate change, as observed in *Neurergus* species in the Zagros Mountains (Hosseinain Yousefkhani, 2021; Kurnaz & Şahin, 2021; Vaissi et al., 2023). Projections for *Salamandra infraimmaculata* suggest potential range contractions under future climate scenarios due to reduced precipitation and rising temperatures (Vaissi, 2021a; Khwarahm et al., 2021), a threat likely applicable to *P. mustersi* given its reliance on moisture-rich habitats. Additionally, studies on three rare salamanders species in East Asia indicate that climate-driven shifts in precipitation could disrupt breeding cycles of stream-dependent amphibians (Ma et al., 2020), further highlighting the need for climate-informed conservation strategies for *P. mustersi*.

Our study also underscores the utility of ecological niche modeling in data-scarce regions like Afghanistan. By integrating our findings with those from neighboring regions, such as Iran, Turkey, and Iraq, we demonstrate that *P. mustersi* shares ecological traits with other Middle Eastern salamanders, including dependence on moist microhabitats and sensitivity to climatic extremes (Vaissi et al., 2023; Kurnaz, 2022; Khwarahm et al., 2021). However, the unique environmental conditions of the Paghman Mountains, including their high-altitude streams and isolation, suggest potential niche specialization. For example, studies on the ecological niche and population genetic of two groups of *Hynobius* on Tsushima Island indicate that isolated populations often exhibit distinct ecological adaptations (Niwa et al., 2022), a hypothesis worth exploring for *P. mustersi* through genetic and population studies.

In conclusion, this study provides a robust framework for understanding the ecological drivers of *P. mustersi* distribution and emphasizes the critical role of valleys and streams as conservation priorities. By drawing parallels with regional studies on *Salamandra*, *Neurergus*, and *Hynobius* species, we highlight shared ecological vulnerabilities and the pressing need for targeted conservation in Central Asia. Future research should incorporate climate change projections and genetic analyses to assess long-term risks and enhance conservation strategies for this enigmatic species.

**ACKNOWLEDGEMENTS**

This project was partially supported by Mohamed bin Zayed Species Conservation Fund under proposal number 232531958.

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