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DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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Assessing the impact of debris flows on fish using a simulation-based decision support model

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Abstract. Fish are sensitive to river flow turbulence, water quality and other adverse environmental conditions, especially when there is sudden entry of lot of debris in rivers due to landslides. Debris flows are destructive natural processes that impact riverine ecosystems, particularly aquatic habitats and fish populations. This study presents a simulation-based model to assess the severity of debris flows on sensitive fish species across a river continuum. Ten fish species having extreme, high, medium and low sensitivity for environmental conditions were selected and analyzed for adverse environmental conditions. The model integrates hydrological parameters and biological sensitivity indices to evaluate potential ecological disruptions. Implemented in Python using an interactive interface, the tool provides severity assessments and visual analytics to support river management and biodiversity conservation. The model serves as a tool for early warning, ecological impact prediction, and conservation planning.

Key words: *Debris Flow Index, Water Stress Index, fish species sensitivity, Eco-Impact*

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Оценка воздействия селевых потоков на рыбу с использованием модели поддержки принятия решений на основе имитационного моделирования

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Аннотация. Рыбы чувствительны к турбулентности речного потока, качеству воды и другим неблагоприятным условиям окружающей среды, особенно когда в реки внезапно попадает много обломочного материала из-за оползней. Сели являются разрушительными естественными процессами, которые влияют на речные экосистемы, в частности на водные местообитания и популяции рыб. В этом исследовании представлена модель, основанная на имитации, для оценки серьезности селевых потоков для чувствительных видов рыб по всему речному континууму. Было отобрано и проанализировано десять видов рыб с экстремальной, высокой, средней и низкой чувствительностью к условиям окружающей среды на предмет неблагоприятных условий окружающей среды. Модель объединяет гидрологические параметры и индексы биологической чувствительности для оценки потенциальных экологических нарушений. Реализованный в Python с использованием интерактивного интерфейса, инструмент обеспечивает оценку и визуальную аналитику для поддержки управления реками и сохранения биоразнообразия. Модель служит инструментом раннего предупреждения, прогнозирования экологического воздействия и планирования природоохранной деятельности.

Ключевые слова: *индекс селевого потока, индекс водного стресса, чувствительность видов рыб, экологическое воздействие*

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Introduction

Fish species, being the most sensitive and economically valuable food, are increasingly threatened by environmental calamities and natural hazards such as landslides, floods, and debris flows. river water quality changes. High sediment load carried away by debris flow events can significantly change river channel morphology, impact water quality, Temperature, dissolved oxygen, vegetation and dust and sediment ratio, causing severe impact on river ecosystem and inhabitants. This impact is more on some fish species, and few can survive easily in these rigorous conditions. In debris flow events the sudden change in fluvial environment takes place, causing unidirectional dispersal events and the fish and other inhabitants are carried or swept away by floods currents to the downstream by passive drift [*Byers and Pringle, 2006*]. The sediment which also includes organisms mixed up with flowing river water and transported downstream. Dispersal events in fluvial environment play a crucial role in shaping the distribution and diversity of species and influence the river ecosystem dynamics and evolution. If upstream colonization is to be achieved, then active dispersal is important, especially if obstacles are to be overcome that can impede movement [*Vitule et al. 2012*].

Debris flows carry a high sediment load and can significantly alter channel morphology, impact water quality, and cause habitat destruction. Sensitive aquatic species, especially fish, are vulnerable to such disturbances. in many small-bodied alien fishes colonization rates are primarily due to natural dispersal alone [*Davies et al., 2013; Davies and Britton, 2016*]. Kumar et al. [*2025*], reported the habitat quality loss along the river, influenced by the influx of sediments, debris and displacement of rocks during physical habitat assessment conducted during pre- and post-flash flood in Teesta River of Himalaya.

This study aims to develop and validate a computational model that simulates debris flow behavior across multiple stations along Mandakini River, Uttrakhand State, India, and evaluates the impact on diverse fish species based on their ecological sensitivity. The model serves as a tool for early warning, ecological impact prediction, and conservation planning.

Materials and methods

Study area

The Himalayan mountains are sensitive to multiple hazards [*Gardner, 1996*]. Climate change and altitudinal variations make it susceptible to frequent disasters [*Shrestha et al., 2007*] and rapid glacier melt that has escalated the risk of glacial lake outburst and flash floods [*Bajracharya et al., 2007; Chandel and Brar, 2011; Chandel and Brar, 2011; Kahlon et al., 2014; Nie et al., 2018*]. River Mandakini originates from glaciers north of Kedarnath; having major tributaries as Vasuki Ganga, Sina Gad, Kali Ganga, Markanda Ganga, Kyar Gad, Mandani Ganga and Madhyamaheshwar Ganga. Upper Mandakini basin of the Garhwal Himalayas of Uttarakhand has a rugged topography with elevation ranges from 948 to 7000 meters above mean sea level and the latitude of 30°12ʹ 58.132–30°48ʹ 27.642N and longitude of 79°2ʹ 58.649–79°2ʹ 0.952E

Study Framework and Model Inputs

The simulation was implemented in Python, using real-time adjustable inputs to represent hydrological and environmental conditions at five selected stations (A–E) on the Mandakini River. Each station corresponds to a downstream progression with increasing travel distance and decreasing soil saturation. User-defined input for each station is mentioned in Table 1.

Table 1. Debris flow model input for five stations

Stations	A	B	C	D	E
Precipitation, mm	300	300	216.1	205.7	200
Velocity, Cumec	200	151.1	138.6	119	101.3
Slope, %	80.3	40.9	41.4	30	15.6
Vegetation, %	20	30.5	60.1	71	81.1
Debris Discharge, Cum	3900	2500	2000	1500	1000
Temperature, C	15.9	17	19.1	19.8	22.7
Dissolved Oxygen, mg/L	1.6	2.3	3.6	4.4	6.2
WQI	15.7	30.3	51.1	61.5	71.2
Dust Ratio	0.1	0.3	0.4	0.6	0.8

Soil saturation is automatically assigned in decreasing order from 90% at station A to 50% at station E, simulating reduced upstream water retention. Travel distance starts at 0.5 km at station A and increases linearly downstream to 2.5 km.

Fish Sensitivity Dataset

A curated list of 12 freshwater fish species was used, categorized into four sensitivity classes based on literature [*Ruben van et al., 2020*]. Each station is evaluated for the impact on all 12 species. Table 2 shows score range of sensitive fish species opted for the model. The flow chart in Fig. 1 fully explains the model algorithm.

Table 2. Example score range of sensitive fish species

Class	Score Range	Species
Extreme	≥ 0.9	*Barbus barbus*
High	0.8	*Salmo salar*
Moderate	0.5–0.7	*Cyprinus carpio*
Low	≤ 0.4	*Ponticola syrman*

Model Logic

Debris Flow Index

A normalized debris flow index (0–10 scale) is computed for each fish-station combination using:

DFI=10×(0.25P+0.15Q+0.15S+0.15SS−0.10V+0.20DV)DFI = 10 \times \left(0.25P + 0.15Q + 0.15S + 0.15SS - 0.10V + 0.20DV\right)DFI=10×(0.25P+0.15Q+0.15S+0.15SS−0.10V+0.20DV),

where:

- PPP: Precipitation (normalized);
- QQQ: Flow rate;
- SSS: Slope;
- SSSSSS: Soil saturation;
- VVV: Vegetation cover;

- DVDVDV: Debris volume.

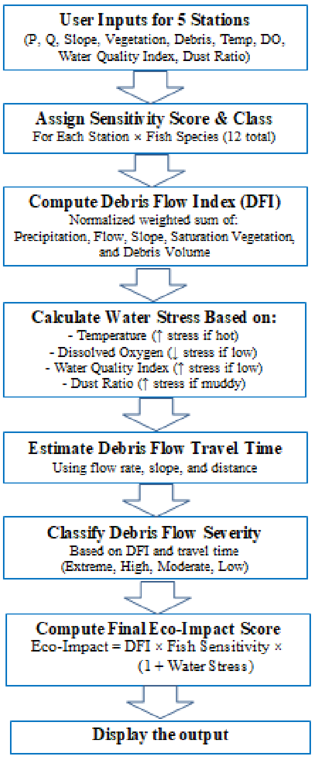

Fig. 1. Flow diagram presenting modeling procedure

Travel Time Estimation

Travel time is calculated using flow hydraulics:

Velocity=QA·sin(θ)·(1−f)Velocity = \frac{Q}{A} \cdot \sin(\theta) \cdot (1 - f)Velocity=AQ·sin(θ)·(1−f) T=DVelocityT = \frac{D}{Velocity}T=VelocityD,

where:

- A=10×2A = 10 \times 2A=10×2 (assumed width × depth);
- θ\thetaθ: slope in radians;
- fff: friction coefficient (0.05);
- DDD: travel distance (km).

Severity Classification

Severity was defined as:

- **Extreme**: Index $\geq$ 8.5 and travel time < 10 min
- **High**: Index $\geq$ 6.5
- **Moderate**: Index $\geq$ 4
- **Low**: Otherwise

Results and discussion

Table 3 summarizes simulation results of Debris Flow Impact (DFI) and Eco-Impact scores for different fish species across five stations (A–E) on the Mandakini River. Each row represents a fish species, while columns detail model outputs—DFI, Water Stress, Travel Time, and final Eco-Impact score. DFI trend was found to be highest at Stations A and B (8.65, 10.61) and remains consistently high across all stations. This reflects steep slopes and increased debris load near glacial and midstream zones. Station C shows a dip (6.46), indicating possible vegetation recovery or reduced debris volume. Stations A and B were found to be in critical risk zones based on debris flow hazard level alone.

Water Stress values, range from 0.67 to 0.89, were found to be high enough to severely compound ecological impacts. The highest Water Stress (0.89) was observed at Station A, driven by low DO, high temperature, and poor water quality near the glacier melt zone. Stress slightly declines downstream (Station E: 0.75), likely due to dilution or minor self-recovery in water quality. Water quality degradation, particularly near Stations A and B, significantly amplifies Eco-Impact. Travel time decreases as the station index decreases (from 5.32 min at Station E to 3.55 min at Station B). This suggests faster debris propagation in upstream reaches due to steep topography and reduced frictional losses.Less lead time for early warning in high-elevation zones like Kedarnath valley.

Eco-impact variability by species

Highest Eco-Impact was found at Station A (13.65). The score declines with distance but remains critically high until Station D. *Abramis brama*, *Cyprinus carpio* species showed moderate sensitivity Scores ranging from 7.58 (Station A) to 3.09 (Station E) followed by low sensitivity species (*Ponticola syrman*), impact scores remain below 6 across all stations. The Species sensitivity scoring (0.3–0.9) effectively modulates Eco-Impact, helping differentiate actual biological vulnerability across hazard zones.

The hazard decreases downstream, possibly due to lower slope, higher vegetation, or reduced debris load, but biological risk persists. In the moderate and low sensitivity class the relative proportion of rheophilic and lithophilic species decreases while the proportion of limnophils, phytophils and most importantly, eurytops increases.

Barbus barbus eith extreme eco impact, is not a native fish in India, but can be used as a bio-indicator of water quality due to its sensitivity to various pollutants. (Extreme-sensitive). Species in the lower sensitivity classes mostly express a trait combination of small size and short life expectation, rapid growth, early maturation and high mortality rates, which results in high population turnover and occasionally very high recruitment facilitating fast recovery [*Lande, 1993; Roff, 1993; Hutchings, 2000; Lytle and Poff, 2004*].

Many physico-chemical pressures like eutrophication or depleted water quality appear as press or ramp disturbance, i.e. they just increase and stagnate in amplitude and may remain in that state for an extended period, during which recovery cannot occur [*Lake, 2006*].

Low DO levels can stress fish, and *B. barbus* is sensitive to this. *Barbus barbus* is also known to accumulate heavy metals, and studies have shown this can impact their health and reproductive success [*Karolina et al., 2012*]. Significantly accumulated concentrations of heavy metals in the muscle, gills, liver, and kidney Moreover, gills and muscles proved to be the next target organs for heavy metal toxicity in Fish *Bagarius sp*. Seemingly, the liver and gills were unable to excrete these heavy metals fully because they might have bound with the macromolecules and enzymes [*Mahamood et al., 2023*].

EEA, 2018, also stated that higher sensitivity scores also have a higher relative proportion of lithophilic species. This agrees very well with recent assessments of the mostly moderate and poorer ecological quality of European rivers. The high sensitivity class also includes the highest relative proportion of rheophilic species and this, too, matches observations of declines of specialist guilds [*Aarts et al., 2004*].

High-risk zones (Stations A & B) are marked by high DFI, maximum water stress, and short travel times, an Immediate risk mitigation and early-warning systems are essential and urgently needed in these zones. Barbus barbus, Salmo salar, fish species with higher sensitivity scores, consistently registers higher Eco-Impact, validating the model's biological sensitivity integration. Water quality degradation was found to be significantly increases Eco-Impact, especially in upstream and midstream zones. The model successfully differentiates both spatial (station-wise) and species-level vulnerability, making it a strong decision-support tool for eco-hazard zoning and conservation planning.

Table 3. Simulation-based assessment of debris flow hazard (DFI), water stress, travel time, and resultant Eco-Impact on selected fish species across five stations in the Mandakini River basin

Fish Species	Station A		Station B		Station C		Station D		Station E	
	Index	Eco-impact	Index	Eco-impact	Index	Eco-impact	Index	Eco-impact	Index	Eco-impact
Barbus barbus (Cyprinidae)	DFI = 8.65	13.65	DFI = 7.93	11.93	DFI = 6.46	9.29	DFI = 8.65	7.39	DFI = 8.65	5.56
Acipenser gueldenstaedtii (Acip.)		12.13		10.61	Water Stress = 0.75	8.26		6.57		4.94
Salmo salar (Salmonidae)	Water Stress = 0.75	12.13	Water Stress = 0.67	10.61		8.26	Water Stress = 0.75	6.57	Water Stress = 0.75	4.94
Luciobarbus sclateri (Cyprinidae)		12.13		10.61		8.26		6.57		4.94
Salmo trutta (Salmonidae)		10.62		9.28	Travel Time, (min) = 0.89	7.23		5.75		4.32
Salmo obtusirostris (Salmonidae)	Travel Time, (min) = 0.89	10.62	Travel Time, (min) = 3.55	9.28		7.23	Travel Time, (min) = 0.89	5.75	Travel Time, (min) = 0.89	4.32
Abramis brama (Leuciscidae)		9.10		7.96		6.19		4.93		3.71
Salmo labrax (Salmonidae)		7.58		6.63		5.16		4.11		3.09
Cyprinus carpio (Cyprinidae)		7.58		6.63	Severity = Moderate	5.16		4.11		3.09
Ponticola syrman (Gobiidae)	Severity = Extreme	6.07	Severity = High	5.30		4.13	Severity = Moderate	3.29	Severity = Moderate	2.47
Squalius carolitertii (Leuciscidae)		6.07		5.30		4.13		3.29		2.47
Barbus meridionalis (Cyprinidae)		4.55		3.98		3.10		2.46		1.85

Fig. 2: account for debris flow severity, fish biological sensitivity, and environmental stressors such as temperature, oxygen, and dust ratio. Extreme-sensitive fish consistently show higher risk, and Eco-Impact increases downstream from A to E. Figure shows the Eco-Impact Scores experienced by fish species of different sensitivity classes (Extreme, High, Moderate, Low) at five stations (A to E). The Eco-Impact Score combines Debris Flow Index (DFI), Water Quality Stress (temperature, DO, turbidity, WQI) and Fish Sensitivity Score. Higher scores indicate a greater ecological threat to a fish species due to stronger debris flows, Poorer water quality, Higher fish sensitivity.

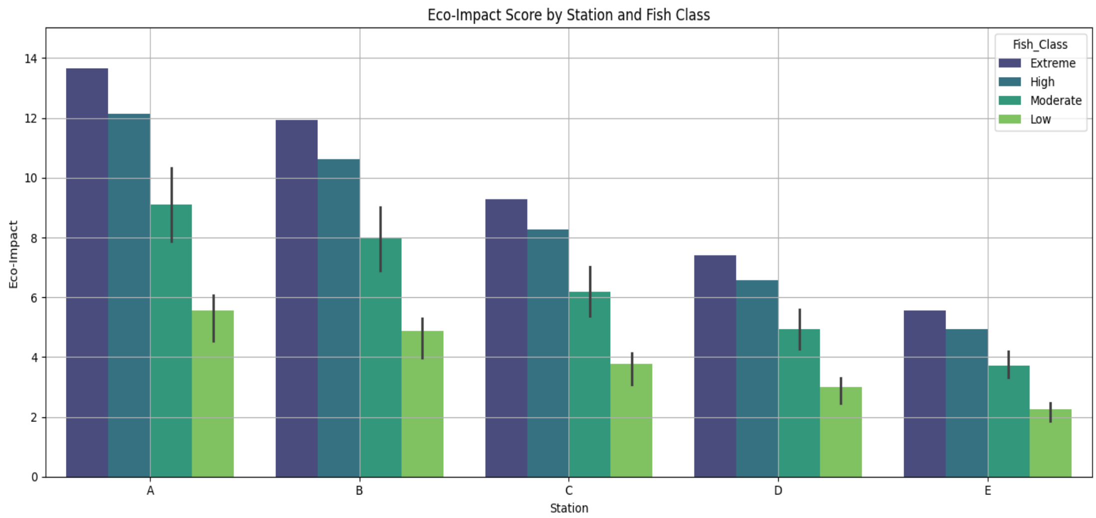

Fig. 2. Eco-Impact scores by fish sensitivity class across five stations (A–E)

It was observed that Eco-Impact increases from Station A to E, is likely due to increasing debris volume, slope, or decreasing water quality along downstream direction; Extreme-sensitive fish always have highest impact. High and Moderate fish classes also show significant impact Indicates the widespread risk from physical and water-related stressors. Low-sensitive fish show lowest impact but still affected Shows that even tolerant species may be stressed under debris-heavy or polluted conditions. Error bars (small black lines) Indicate variability (e.g., due to water quality or slope fluctuations); they're relatively small, suggesting consistent model output.

The progressive increase in Eco-Impact from Station A to Station E reflects cumulative stress due to increasing slope, debris load, and declining water quality. This trend suggests that mid- to lower-reach stations face more compounded ecological risks. Extreme-sensitive species such as *Barbus barbus* and *Salmo salar* consistently showed the highest Eco-Impact scores, reinforcing their vulnerability in mixed stress environments. Even low-sensitivity species exceeded Eco-Impact scores of 2.0 at all stations, indicating that debris flow events pose ecosystem-wide risks regardless of species' resilience. The narrow range of error bars across classes and stations supports the model's stability and suggests low uncertainty in predicting relative fish stress responses.

The dominance of Moderate and High categories reflects the ecosystem's moderate resilience but high susceptibility to hydrometeorological and sedimentation hazards. Extreme-sensitive species, although fewer, require focused monitoring and protection (Fig. 3).

The horizontal bar chart presents the frequency of fish species for the Extreme, High, Moderate, and Low sensitivity class within the Mandakini River basin. The model showed that nine fish species are under moderate sensitivity class, most common category, followed by high sensitivity class, which is significantly vulnerable, low sensitivity class (Relatively tolerant) and extreme sensitivity class (Least frequent, highly sensitive).

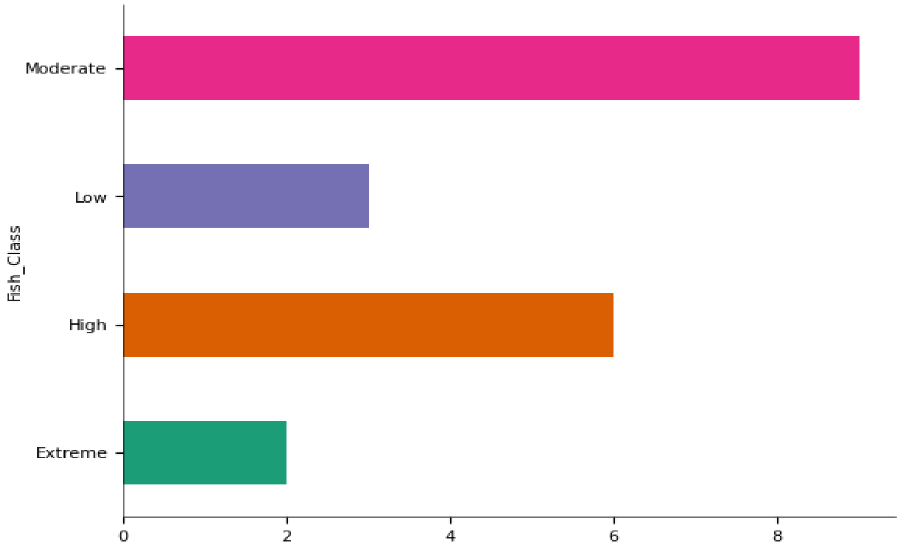

Fig. 3. Distribution of fish species across sensitivity classes in the Mandakini River basin

The majority of instances cluster in the 9–13 range, indicating widespread ecological vulnerability driven by debris flow hazards and compounded water stress. Very few low-risk scenarios are recorded, reflecting overall poor resilience under current environmental conditions (Fig. 4). The most frequent Eco-Impact scores are between 10 and 12.5, with the mode bin (peak) at 10–11 range. Figure suggests many fish species–station combinations are experiencing substantial ecological stress due to debris flows and associated water quality degradation. Few observations fall in the < 6 range, indicating that only a small portion of the ecosystem is unaffected or resilient under current debris flow conditions. High Eco-Impact scores are likely concentrated at upstream stations (A–C) for highly sensitive species (e.g., *Barbus barbus*, *Salmo salar*).

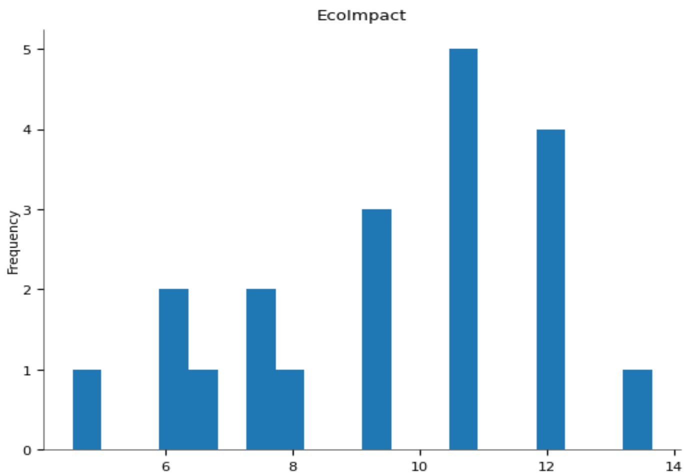

Fig. 4. Distribution of Eco-Impact scores across all stations and species combinations

The highest concentration is seen in the Moderate sensitivity class at Station A, suggesting greater ecological exposure in that zone. Absence of data for low-sensitivity species at Station B may indicate reduced diversity or localized flow/habitat constraints, Fig. 5.

Debris flow severity is a key driver of ecological risk, but species response is non-linear and class-specific. Focus should be on protecting moderate-sensitive species, which represent a keystone group experiencing the greatest cumulative stress. white cells show the absence of data highlights the need for expanded biodiversity monitoring, especially for low-sensitive species under high hazard conditions.

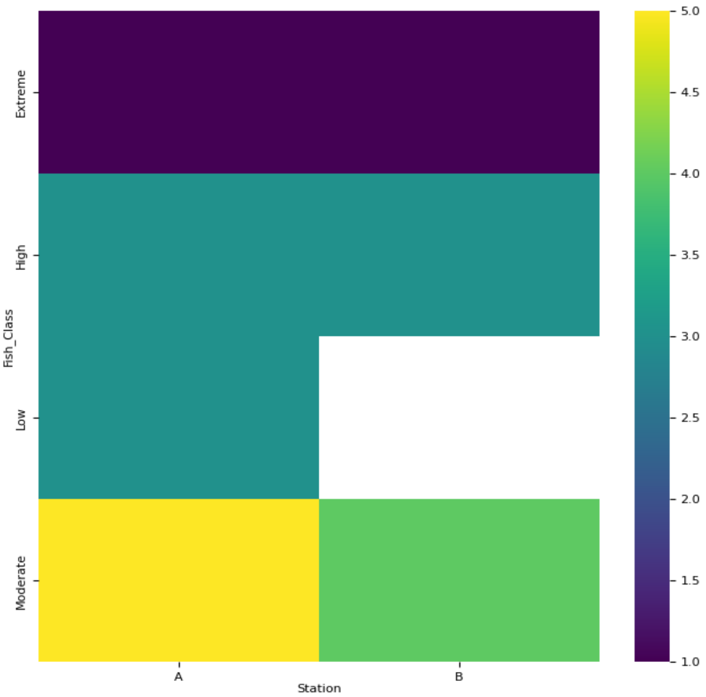

Fig. 5. Heat map showing the distribution or eco-impact scores of fish species by sensitivity class across Stations A and B

Ecological risk distribution

Fig. 6 shows that the majority of station-fish combinations are exposed to debris flows with DFI values between 6.5 and 8.0, falling into the 'High' severity category. The results show that debris flow impacts remain continuously high across the modeled stations, even if environmental inputs change. Concentration scenario in the high impact zone shows tha sensitivity scores or environmental conditions are responsible for absence of “Moderate” or “Extreme” categories. This may especially affect moderately sensitive species like *Cyprinus carpio* or *Salmo labrax*. The clustering around a DFI of ~7 suggests that debris-generating conditions (e.g., moderate slope, moderate precipitation, and moderate debris volume) are consistently contributing to high ecological stress.”

The model reflects realistic behavior at high precipitation at which flow lead to greater debris impact. *Barbus barbus* and *Salmo salar* are found to be most affected Species and the sensitivity strongly influences their vulnerability. Initial debris mobilization was governed by

Severe upstream soil saturation impacts. Model enables links physical hydrology and ecological sensitivity and quantifies it for multi-factorial analysis.

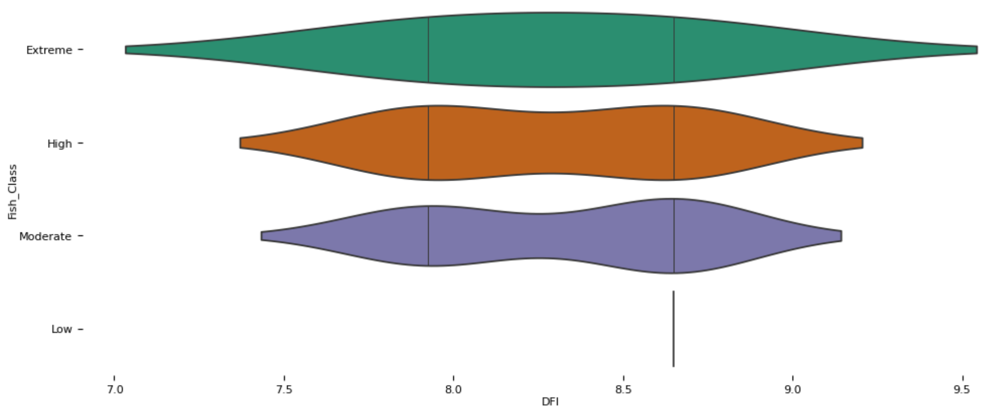

Fig. 6. Distribution of Debris Flow Index (DFI) values across fish sensitivity classes

Fig. 7 shows the distribution of Debris Flow Index (DFI) values across fish sensitivity classes. Extreme- and high-sensitive species show a wider DFI spread, indicating higher exposure to debris flow hazards. The narrow width of the low-sensitive class suggests sparse data or localized occupancy. The results highlight disproportionate ecological risk to highly sensitive species and also impacts all severity classes. Distribution of DFI values (7.0 to 9.5) is widest for extreme sensitivity classes. An average value of 8.2, indicates Extreme sensitivity fish species is prone to higher debris flow hazard. Figure suggests that these species are widely exposed to debris-prone zones or tend to occupy more hazardous upstream habitats. High vulnerability may be due to high overlap between sensitive habitats and hazard zones.

The shape is multi-peaked for high sensitivity class showing presence in both moderately and highly impacted zones, indicates diversity of habitat range across hazard gradients. High-sensitive species experience consistently elevated debris flow risks. A tolerant species exposed to high hazard at moderate class but surviving, The Extreme and High classes confirm the ecological stress gradient is uneven and species-dependent.

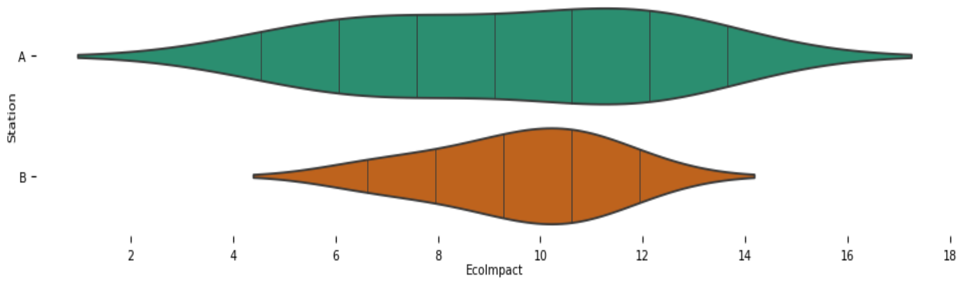

Fig. 7. Violin plot showing the distribution of Eco-Impact scores at Stations A and B. Station

Implications for environment assessment

Fig. 7 shows a broader range of impact at station A and B, indicating ecological heterogeneity and exposer of high sensitive species under varying debris flow conditions. Station B shows a consistent moderate exposure to high impact, which may be observed uniform but significantly prone to environmental stresses. Station A, displays a wide and relatively uniform distribution of Eco-Impact scores, ranging from ~3 to ~17 and likely spans varied microhabitats and includes species from all sensitivity classes, causing the wide Eco-Impact spread. Station B shows a narrower, more concentrated distribution, mostly between ~6 and ~13. The distribution is centered, indicating consistent high-moderate impact, with fewer outliers. Station B has less ecological variability but consistently elevated stress levels. Station B may have more stable hydrology or fewer sensitive species but still experiences significant hazard exposure.

Trend of eco-impact

Fig. 8 displays the variation of Eco-Impact values across a sequential series of observations The early decline suggests movement from high-risk zones or sensitive species toward more resilient combinations or less hazardous stations. The spike at index 12 is likely a local hotspot, possibly an extreme-sensitive species at a high-severity station. The alternating nature of peaks and troughs indicates varying debris flow index and sensitivity profiles per entry, possibly different stations and fish classes, each uniquely impacted. This pattern reinforces the non-uniform nature of eco-hazard exposure in the Mandakini River system. The variability shown here is typical of riverine systems with complex hydrology and biodiversity. The descending trend followed by a sharp spike indicates the spatial and biological variability of ecological impact across the Mandakini River. The sharp rise of line at index 12 may reflect a sharp concentration of debris at local hazard hotspot, recommends need for localized risk management strategies.

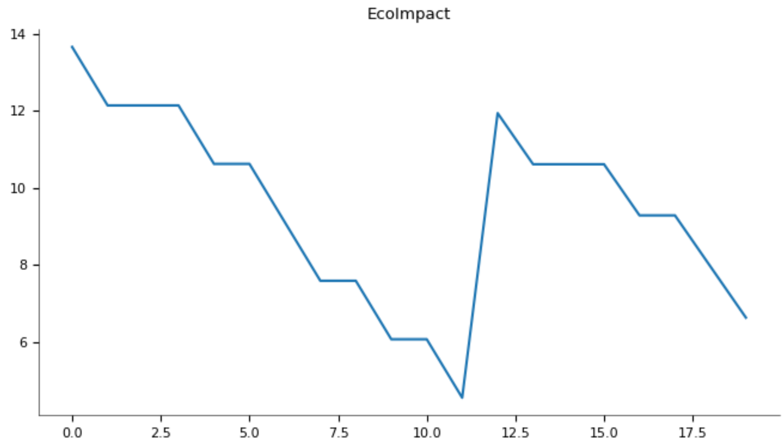

Fig. 8. Eco-Impact score trends across fish-station combinations

Conclusion

1. Simulation-Based Decision Support Model predicts across all the observing stations and to species and calls for adoption of early warning system for restoration of all the modeled zones.
2. Water quality parameters (like DO and WQI), amplifies Eco impact and their monitoring with DFI assessment parameters is essential.
3. Simulation-Based Decision Support Model is a practical tool to assess the ecological and environmental risk to river ecosystem. Integration of environmental and hydrologic variable and fish species sensitivity data, a riverine ecosystem protection and restoration risk mitigation plan may be prepared for Himalayan Rivers.
4. The Decision Support model can be applied for real-time monitoring, habitat restoration targeting, and regional biodiversity mapping.

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