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Diclofenac and veterinary NSAIDs in river sediments and benthic macroinvertebrate communities of the Western Ghats biodiversity hotspot, India: Contamination profiles, ecological risks, and conservation implications

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Abstract
Few ecological disasters in recent South Asian history are as stark a warning as the near-collapse of Gyps vulture populations caused by a single veterinary drug. That drug — diclofenac — is now banned for livestock use in India, yet it persists in the country's rivers at concentrations that exceed safety thresholds for aquatic life. This review asks a question that has so far gone unaddressed: what are the consequences for the benthic invertebrate communities of the Western Ghats, one of the world's most celebrated freshwater biodiversity hotspots? The Western Ghats, a UNESCO World Heritage landscape running the length of peninsular India's western flank, feeds major river systems harbouring hundreds of endemic fish and invertebrate species. Its rivers are increasingly loaded with non-steroidal anti-inflammatory drugs (NSAIDs), antibiotics, and other pharmaceuticals from hospital effluents, domestic sewage, and pharmaceutical manufacturing discharge — yet the sediment compartment, where benthic organisms live and feed, has been almost entirely overlooked in monitoring campaigns. Drawing on Indian and international pharmaceutical ecotoxicology literature, this paper synthesises what is known about NSAID occurrence in Indian freshwaters, considers the ecotoxicological evidence for harm to bottom-dwelling invertebrates, and lays out why existing knowledge is grossly insufficient for managing the risk. Diclofenac and co-occurring NSAIDs exceed predicted no-effect concentrations in multiple Indian river systems, but biota-sediment accumulation factors for any native tropical invertebrate taxon have yet to be reported. We argue that this gap is not a technical footnote — it represents a substantive failure of environmental protection for a biologically irreplaceable river network, and we outline a four-phase research agenda to begin addressing it.

Keywords: Diclofenac, NSAIDs, benthic macroinvertebrates, Western Ghats, pharmaceutical ecotoxicology

Introduction

There is something quietly alarming about looking at a drug packet. Diclofenac — an anti-inflammatory sold over the counter across India for joint pain, fever, and injury — is the same compound that drove three species of Gyps vultures to the brink of extinction in the 1990s. When cattle treated with the drug died and their carcasses were consumed by vultures, the birds suffered fatal renal gout within days. Populations that had numbered in the tens of millions collapsed by over 95% within a single decade (Oaks *et al*., 2004; Swan *et al*., 2006) [20, 24]. India banned veterinary diclofenac in 2006 [24]. And yet the drug keeps showing up — in Indian rivers, in sediments, in monitoring data collected years after the prohibition. The question driving this review is not whether diclofenac is still present in Indian freshwaters (it clearly is), but what it is doing to the invertebrate communities that live on and in the river bottom, where the drug accumulates and persists.

Pharmaceutical pollution of freshwater systems has become a genuinely global problem. Wilkinson *et al*. (2022) [26] sampled 258 rivers across 104 countries and found active pharmaceutical ingredients in 25.7% of sites at concentrations considered hazardous to aquatic life. India features prominently in such data, partly because of its enormous pharmaceutical manufacturing sector and partly because of chronic underinvestment in sewage treatment infrastructure. NSAIDs — diclofenac chief among them — are among the most frequently detected and ecotoxicologically concerning drug classes in these systems. Global annual diclofenac consumption has been estimated at around 1,443 tonnes, and its persistence in aquatic environments reflects both high usage volumes and incomplete removal by conventional wastewater treatment (An *et al*., 2025; Küster & Adler, 2014) [14].

What makes this problem particularly serious in the Western Ghats context is the exceptional biological value of the rivers at stake. The Ghats — a mountain range stretching roughly 1,600 km down India's western peninsula — are recognised internationally as one of eight global biodiversity hotspots and a UNESCO World Heritage Site. The rivers draining this landscape, including the Kaveri (Cauvery), Periyar, Chalakudy, Aghanashini, and Tungabhadra, harbour over 288 freshwater fish species (approximately 118 endemic) and contain 50% of India's amphibian fauna, most of which occurs nowhere else on earth (WWF India, 2024; Myers *et al*., 2000) [18, 27]. What lives in these rivers matters globally, not just regionally.

Benthic macroinvertebrates — the mayflies, stoneflies, caddisflies, worms, freshwater crabs, and snails that inhabit the river substrate — are the organisms most directly exposed to sediment-bound pharmaceutical residues. They cannot move away from a contaminated patch the way a fish can. They live embedded in the sediment-water interface through multiple seasons, feeding on biofilms and organic

matter that may carry pharmaceutical loads, and they form the primary dietary base for endemic fish. If pharmaceutical contamination disrupts benthic communities in Western Ghats rivers, the ecological consequences will propagate upward through food webs that have developed over millions of years of evolutionary isolation. Despite all of this, the pharmaceutical exposome of Western Ghats benthic communities has attracted essentially no dedicated research attention. This paper tries to articulate why that matters and what needs to be done.

Three questions organise the discussion that follows: What do we know about NSAID contamination in Indian freshwaters, and specifically in Western Ghats catchments? What does the ecotoxicological literature tell us about the risks to benthic macroinvertebrate communities? And what are the most critical knowledge gaps that must be addressed before meaningful ecological protection can be designed for this system?

The Western Ghats as a Freshwater Biodiversity Hotspot

It is easy to discuss the Western Ghats in superlatives, because the data genuinely support them. Though the Ghats cover less than 6% of India's land area, they contain more than 30% of all plant, fish, herpetofauna, bird, and mammal species recorded from the country (WWF India, 2024) [27]. The endemism figures are even more striking: 53% of fish species, 62% of reptile species, and 65% of amphibian species found here are found nowhere else (Molur *et al*., 2011) [17]. The IUCN has recently reaffirmed the Western Ghats as a critical hotspot for endangered freshwater species, with 25% of global freshwater taxa at high extinction risk (IUCN, 2025).

The river systems of the Ghats vary considerably in character, from the large and agriculturally burdened Kaveri basin to the smaller, comparatively pristine streams of the Aghanashini catchment in coastal Karnataka. The Kaveri originates in the Brahmagiri Hills and travels eastward through Karnataka and Tamil Nadu before emptying into the Bay of Bengal — a journey through one of India's most intensively farmed and industrialised corridor landscapes. A study by researchers at the Indian Institute of Technology Madras found diclofenac, carbamazepine, and caffeine at most sampling stations along the Kaveri and its tributaries, with pharmaceutical concentrations significantly higher during low-flow conditions than during monsoon (Subedi *et al*., 2021) [23]. The dry-season concentration effect is an important ecological point: benthic invertebrates experience their worst pharmaceutical exposures precisely when reduced river flows offer no dilution.

The Periyar River tells a different story, flowing through some of the most intact forest in the Ghats — including the core zone of the Periyar Tiger Reserve — before reaching the heavily industrialised Kochi urban area. A recent investigation using high-resolution mass spectrometry found pharmaceutical pollutants in Periyar sediments near hospital zones in Kerala, identifying multiple emerging contaminants in what the authors described as the first comprehensive pharmaceutical screening of these sediments (Tomy & Jameson, 2024) [25]. The fact that contamination reaches even the sediments of a river flowing through a protected area is a sobering reminder that protected area boundaries do not stop effluent-laden tributaries.

Two rivers deserve special mention because of their biological distinctiveness and their current absence from the pharmaceutical monitoring literature. The Chalakudy River, running through the Anamalai Hills in Kerala, has the highest documented fish diversity of any Western Ghats river — 98 species — including multiple endemics found in no other system. The Aghanashini River in Karnataka is one of very few large rivers in peninsular India that remains free-flowing along its entire course, supporting rich assemblages of aquatic insects documented by Sreekantha *et al*. (2018) [22]. Neither system has any published data on pharmaceutical residues in their sediments or benthic biota. Given the conservation stakes involved, this is a striking omission.

Diclofenac and NSAIDs in Indian River Systems: Sources, Pathways, and Occurrence

1. Where the Drugs Come From

The entry routes for pharmaceuticals into Indian rivers are reasonably well understood, even if the downstream consequences are not. Pharmaceutical manufacturing is the single most concentrated point source. The Patancheru-Bollaram industrial estate near Hyderabad, which hosts dozens of active pharmaceutical ingredient manufacturers, released drugs including diclofenac and ciprofloxacin into the Musi River — a tributary of the Krishna — at concentrations that researchers found orders of magnitude above levels therapeutic in humans (Fick *et al*., 2009) [10]. Hospital effluents represent a different kind of problem: geographically dispersed but continuous, with effluent streams carrying a broad spectrum of drugs that vary with ward type, patient population, and season. In the Western Ghats region, major hospital complexes in Kochi, Thiruvananthapuram, Bengaluru, Mysuru, and Mangaluru all drain, directly or indirectly, into river catchments supporting endemic aquatic fauna.

Domestic sewage is the most diffuse but probably the largest volumetric source. Most Indian cities do not have sewage treatment capacity commensurate with their populations, and many operate plants at a fraction of their design efficiency. Even well-functioning conventional STPs remove only a portion of most pharmaceuticals from effluent streams — diclofenac removal rates at Indian facilities are reported well below the 70-90% achievable with advanced treatment (Naik *et al*., 2022) [19]. Agricultural runoff adds another dimension: dairy and draught cattle — animals integral to rural livelihoods throughout the Ghats — continue to receive NSAID treatment despite the veterinary ban, and their urine, dung, and carcasses contribute diclofenac to the landscape even in areas remote from urban point sources (Cuthbert *et al*., 2016) [5].

Diclofenac's chemistry places it in an interesting environmental position. With a log Kow of approximately 4.5 and a pKa of 4.15, it is predominantly anionic at the pH ranges typical of Western Ghats rivers (7-8), which limits its direct binding to particulate organic matter. However, its transformation products behave differently. Photodegradation generates compounds including 4'-hydroxydiclofenac and 2- [(2-

chlorophenyl)amino]benzaldehyde, and risk modelling suggests some of these metabolites may pose greater ecotoxicological hazard than the parent drug (Cédat *et al*., 2021). Most river monitoring, including what limited Indian data exists, measures only the parent compound — meaning reported contamination levels likely understate the true pharmaceutical burden in sediments and pore water.

2. What Monitoring Data Show

The Wilkinson *et al*. (2022) [26] global study placed Asia among the most contaminated regions for pharmaceutical river pollution, and Indian sampling sites repeatedly appeared in the upper concentration ranges. Six pharmaceuticals — azithromycin, caffeine, diclofenac, naproxen, norfloxacin, and sulfamethoxazole — were found at levels exceeding predicted no-effect concentrations for aquatic organisms at multiple Indian locations (Naik *et al*., 2022) [19]. In some Asian surface water samples, diclofenac concentrations have exceeded 8,000 ng/L (An *et al*., 2025), though concentrations in Western Ghats rivers specifically span a wide range depending on proximity to point sources and seasonal flow conditions.

The Kaveri River study by Subedi *et al*. (2021) [23] found diclofenac at most sampling stations during both pre- and post-monsoon periods, with concentrations peaking during lower-flow conditions. This pattern has a direct implication for benthic ecology: the organisms most exposed to pharmaceutical-laden sediment pore water face their highest concentrations precisely during the dry season, when the river provides no hydraulic refuge through dilution or lateral flushing. In the Ganga River system, diclofenac and five other pharmaceuticals exceeded safety thresholds, with the authors noting a conspicuous lack of understanding about how these compounds move between the water column, sediment, and groundwater (Kaur *et al*., 2025) [13]. For the Western Ghats river network — which feeds into entirely different catchment systems and hosts fundamentally different biological communities — the equivalent data simply do not exist.

Benthic Macroinvertebrates as Sentinels of Pharmaceutical Contamination

1. Why the Sediment Zone Is Different

River ecologists sometimes describe benthic macroinvertebrates as living at the intersection of the water column and the sediment archive. That framing captures something important about pharmaceutical exposure. Compounds that partition even partially into sediment or particulate matter are delivered continuously to benthic organisms through multiple vectors: pore water seeping up through the substrate, fine particulate material settling from above, biofilm ingestion, and prey consumption. This cocktail of exposure routes means that measured pharmaceutical concentrations in overlying water substantially underestimate the doses experienced by sediment-dwelling organisms (Paltiel *et al*., 2016) [21].

The available European data illustrate the point concretely. Caddisfly larvae (Hydropsyche sp.) and leeches (Erpobdella octoculata) sampled from a Czech stream receiving treated sewage effluent both contained measurable diclofenac in their tissues, demonstrating that food web pathways — not just direct aqueous exposure — are meaningful pharmaceutical delivery routes for benthic consumers (Paltiel *et al*., 2016) [21]. Biota-sediment accumulation factors (BSAFs) measured across a range of pharmaceutical compounds in chironomid larvae, EPT nymphs, and oligochaetes in European and North American systems, while low in absolute terms, are ecologically significant when organisms are exposed continuously across their entire life history (de Solla *et al*., 2016 [6]; Cédat *et al*., 2021).

Western Ghats rivers support diverse and well-characterised (in taxonomic terms) benthic assemblages. EPT insects — Ephemeroptera, Plecoptera, Trichoptera — are the gold-standard bioindicators of river health globally, and the Ghats rivers host numerous endemic representatives of these groups. The Kaveri River catchment was assessed using standard North American and European biomonitoring indices by Hannaford *et al*. (1997) [11], who found the methods broadly applicable despite the different tropical fauna — suggesting that index frameworks developed elsewhere can be meaningfully deployed here, and that adding pharmaceutical residue analysis to such campaigns would be technically and conceptually straightforward. That integration has not happened. Not a single published study has combined pharmaceutical sediment monitoring with macroinvertebrate community assessment in a Western Ghats river system.

2. Toxicological Evidence for Harm

Diclofenac inhibits cyclo-oxygenase (COX) enzymes, blocking prostaglandin synthesis. Because COX pathways are evolutionarily conserved across a wide taxonomic range — not just in vertebrates but in many invertebrate groups — non-target aquatic organisms are genuinely susceptible to pharmacological effects from environmental diclofenac concentrations (Fabbri & Capuzzo, 2010) [9]. This is not merely theoretical. Mesocosm experiments — conducted under conditions far more ecologically realistic than standard single-species laboratory tests — have detected community-level effects on zooplankton and macroinvertebrates at diclofenac concentrations of just 1 µg/L, with no-observed-effect concentrations (NOECs) at the population level falling below 0.1 µg/L (Escher *et al*., 2021) [8]. Strikingly, the effects observed in mesocosm conditions were more severe than what standard laboratory bioassays would have predicted, underscoring a consistent problem in pharmaceutical risk regulation: laboratory NOECs poorly capture real-world ecological sensitivity.

Studies on sediment-dwelling crustaceans have been instructive. When exposed to sublethal diclofenac concentrations of 50 µg/L, the harpacticoid copepod Bryocamptus pygmaeus — which spends its entire life among riverbed sediment grains — showed significant disruption to six of eight monitored behavioural parameters (Di Lorenzo *et al*., 2021) [7]. Interstitial copepods of this kind regulate nutrient cycling and microbial dynamics in the hyporheic zone; behavioural impairment translates directly to functional disruption in a habitat that most river biomonitoring programmes completely ignore. In the amphipod Hyalella azteca, metabolomic profiling after diclofenac exposure revealed disrupted amino acid metabolism, altered energy allocation, and elevated

oxidative stress biomarkers — changes that would compromise growth and reproductive fitness even when acute mortality is not observed (Mehler *et al*., 2021) [16].

For the aquatic insects that form the backbone of Western Ghats benthic communities, experimental data on NSAID effects are thin. Much of what exists relates to other pharmaceutical classes. Fluoxetine, for example, has been shown to alter the behaviour and physiology of damselfly larvae, and Martin *et al*. (2024) [15] demonstrated that antidepressant contamination reshaped freshwater community structure and slowed recovery from predation pressure. If a single drug at realistic concentrations produces such effects, the implications of the complex pharmaceutical mixtures typical of Indian rivers — which simultaneously exceed PNECs for diclofenac, azithromycin, norfloxacin, and others — are difficult to predict from existing data (Naik *et al*., 2022) [19]. Mixture toxicity interactions among NSAIDs and antibiotics on EPT insects native to the Western Ghats remain essentially unexplored territory.

The Diclofenac Ban: What It Achieved and What It Did Not

India's 2006 ban on veterinary diclofenac manufacture is, by any measure, a significant policy achievement. It came directly from scientific evidence — the documentation by Oaks *et al*. (2004) and Swan *et al*. (2006) [20, 24] that vulture deaths were caused by diclofenac residues in cattle carcasses — and it was enacted relatively quickly for a regulatory system that often moves slowly. Nepal and Pakistan followed. The RSPB, the Bombay Natural History Society, and the Peregrine Fund had all been pushing for the ban, and their advocacy shaped both the scientific framing and the political timing.

What the ban did not achieve was elimination of diclofenac from Indian rivers. The reason is partly straightforward: human diclofenac consumption was never banned and remains very high, and its metabolites pass through inadequate sewage treatment into water bodies. But there is also a veterinary compliance problem. Multi-dose human pharmaceutical vials continued to be diverted for cattle use after 2006, because they were pharmacologically identical and cheaper than licensed alternatives. It was not until 2015 that regulatory action limited multi-dose human formulation vials — effectively closing the largest loophole (Cuthbert *et al*., 2016) [5]. Enforcement of pharmaceutical effluent standards remains weak; Subedi *et al*. (2021) [23] noted that the Karnataka State Pollution Control Board samples river water quarterly and only during daytime, while effluent discharge from pharmaceutical units frequently occurs overnight.

Perhaps the most fundamental gap in evaluating the ban's effectiveness is the absence of any longitudinal monitoring study that has tracked diclofenac concentrations in Western Ghats river sediments and associated biota before and after 2006. It would be difficult to find a more directly tractable policy-evaluation question for aquatic ecotoxicology in India. Sediment cores from reservoir catchments with measurable sedimentation rates could in principle provide a temporal archive extending back to the pre-ban era; paired with contemporary sediment and biota sampling, such cores would offer the first real evidence base for assessing whether the prohibition has actually reduced pharmaceutical burden in aquatic habitats. That study has not been done.

Knowledge Gaps and a Proposed Research Agenda

1. What We Do Not Know

The most immediate knowledge gap is simply baseline data. For the Kaveri and Periyar rivers we have fragmentary water column data and, for the Periyar, one sediment screening study near hospital zones. For the Chalakudy, Aghanashini, Tungabhadra, and the dozens of other ecologically significant tributaries of the Western Ghats, there is nothing. Sediment-phase concentrations — which govern the exposure experienced by benthic taxa — have not been systematically measured in any Western Ghats river system. Given that sediments act as long-term reservoirs, slowly re-releasing sorbed compounds during bioturbation or flood events, this is not a minor gap in the data.

The second gap is the absence of any BSAF data for Indian tropical invertebrates. European values cannot simply be assumed to transfer. Higher ambient temperatures in tropical systems accelerate metabolic rates, affecting both uptake kinetics and biotransformation capacity. The food quality and organic content of tropical river sediments differ substantially from temperate benchmarks. Life history parameters — generation time, larval duration, feeding strategy — vary between Western Ghats EPT taxa and the European chironomids and amphipods on which most pharmaceutical accumulation data are based. Without taxon-specific accumulation data, risk assessments for this system are built on assumptions that have not been validated.

Third, mixture toxicity in the context of Indian river contamination profiles remains unaddressed. Real-world pharmaceutical contamination in Indian rivers is not a single-compound problem. Multiple compounds exceeding their PNECs are present simultaneously: diclofenac alongside azithromycin, norfloxacin, sulfamethoxazole, and caffeine is a typical observed combination in Indian river surveys (Naik *et al*., 2022; Wilkinson *et al*., 2022) [19, 26]. These compounds target different biochemical pathways. Their combined effects on EPT insects, which are among the most sensitive organisms in these systems, could be additive, synergistic, or — less probably — antagonistic. We do not know.

Fourth, and perhaps most consequentially for conservation, nothing is known about how pharmaceutical contamination affects the functional ecology of Western Ghats benthic communities. Leaf pack decomposition, organic matter processing, secondary production, drift behaviour, and the trophic transfer of energy from invertebrates to endemic fish — all of these could plausibly be disrupted by pharmaceutical exposure at concentrations already documented in Indian rivers. Given the high endemism of both the invertebrates and the fish that depend on them in Western Ghats rivers, disruption of these trophic linkages would have conservation consequences with no parallel anywhere else in the world.

2. A Four-Phase Research Framework

Phase 1 should be a systematic baseline survey. The priority rivers — Kaveri, Periyar, Chalakudy, Aghanashini,

Tungabhadra — should be sampled across three hydrological phases (pre-monsoon, monsoon, post-monsoon) at sites spanning a gradient from upstream pristine to downstream urbanised. Both sediment and co-located benthic macroinvertebrate samples should be collected and analysed by liquid chromatography-tandem mass spectrometry (LC-MS/MS) for parent NSAIDs, human metabolites, veterinary metabolites, and key transformation products including hydroxydiclofenac. The goal is not a single snapshot but a spatiotemporally resolved picture of pharmaceutical loading that can reveal seasonal concentration dynamics and identify the worst-affected reaches.

Phase 2 should determine tissue-specific pharmaceutical accumulation in representative Western Ghats benthic taxa: chironomid larvae, EPT nymphs, freshwater oligochaetes, and endemic freshwater crabs of the genus Barytelphusa — which are widespread in these rivers, occupy a significant trophic position as prey for endemic fish, and have never been examined for pharmaceutical burden. Stable isotope analysis of carbon and nitrogen should be used alongside chemical residue measurements to distinguish dietary uptake from direct aqueous exposure and to trace pharmaceutical transfer across trophic levels.

Phase 3 should move into experimental ecotoxicology, exposing Western Ghats-native species to pharmaceutical mixtures at concentrations representative of Phase 1 field findings. Endpoints of ecological relevance — survival, growth, larval development and emergence, reproductive output, feeding rate, drift initiation, predator avoidance — should be measured alongside molecular biomarkers of oxidative stress, endocrine disruption, and inflammatory pathway activation. Mesocosm experiments replicating local stream conditions would allow community-level functional endpoints — leaf pack breakdown rates, secondary production, macroinvertebrate assemblage composition — to be assessed under realistic mixture exposure.

Phase 4 is the retrospective piece. Sediment cores from reservoir catchments with datable stratigraphy should be analysed for pharmaceutical residues in archived sediment layers, combined with paleoecological analysis of chironomid head capsules and other preserved invertebrate subfossils. This approach has been used successfully in temperate systems to reconstruct historical contamination but has not been attempted in India. It would allow pharmaceutical loading trends to be reconstructed across the pre- and post-ban periods, and community compositional changes to be correlated with contamination history — producing the first temporal evidence base for evaluating whether the 2006 diclofenac ban has reduced pharmaceutical pressure on Western Ghats aquatic communities.

Conservation and Policy Implications

The regulatory picture for pharmaceutical contamination in Indian freshwaters is, at present, not encouraging. India's Central Pollution Control Board operates an extensive river water quality monitoring network, but pharmaceutical compounds are not routinely included in its measurement panels. Environmental impact assessments for urban and industrial development in Western Ghats catchments do not require pharmaceutical baseline surveys. The consequence is regulatory invisibility: a pollution category known to cause ecological harm in these systems is essentially unmonitored and thus unmanaged.

The most tractable near-term intervention is mandatory pharmaceutical monitoring of rivers associated with the Western Ghats, particularly those that flow through or alongside protected areas. The Periyar Tiger Reserve, Kudremukh National Park, and Silent Valley National Park all adjoin river systems for which pharmaceutical sediment data are either absent or limited to a single study. Incorporating pharmaceutical monitoring into protected area management plans and catchment-level environmental assessment frameworks would cost relatively little compared to the ecological value at stake. The analytical infrastructure exists at universities and research institutes throughout the region.

On the treatment side, conventional STPs are not solving the problem. Diclofenac and most other NSAIDs pass through secondary biological treatment at partial removal rates at best. Advanced tertiary treatment — activated carbon adsorption, ozonation, UV photolysis, and membrane bioreactor systems — achieves substantially higher removal efficiencies for NSAIDs and has been demonstrated at scale in Europe and increasingly in parts of Asia. Urban centres discharging into Western Ghats catchments, particularly Kochi, Bengaluru, Mysuru, Coimbatore, and Thrissur, should be prioritised for STP modernisation, with pharmaceutical removal efficiency included as a performance metric alongside conventional BOD and nutrient parameters (Naik *et al*., 2022) [19].

The continued presence of veterinary diclofenac in Indian rivers more than fifteen years after the ban also points to the need for sustained post-market surveillance, accessible substitutes, and genuine community engagement. Meloxicam — an NSAID proven safe for Gyps vultures and other obligate scavengers — has been available as a veterinary alternative since the mid-2000s, but uptake in rural livestock-farming communities across the Ghats buffer zones has been uneven. Outreach targeting village-level livestock health practitioners, combined with affordable meloxicam supply chains, would address the residual veterinary diclofenac source more directly than regulatory enforcement alone. Integrating the conservation knowledge and stewardship practices of indigenous and tribal communities within the Western Ghats — who have managed these river landscapes sustainably for generations — into monitoring and management frameworks is a longer-term but essential complement to any technical intervention.

Conclusion

The diclofenac story in India carries a particular kind of irony. The near-extinction of Gyps vultures was noticed quickly because these are large, conspicuous birds whose decline was visible to any observer walking through rural South Asia. The potential decline of mayfly nymphs, caddisfly larvae, and freshwater crabs in Western Ghats rivers is not the kind of thing that makes headlines. These organisms are small, largely invisible, poorly known to the public, and embedded in river substrates that most people

never examine. Yet they are foundational to the functioning of some of the most biodiverse freshwater ecosystems on the planet.

This review has tried to make a simple argument: that pharmaceutical contamination in Western Ghats river sediments is a real and undercharacterised threat to endemic benthic invertebrate communities, that the current state of knowledge is plainly inadequate for evaluating the scale of that threat, and that a targeted research programme — baseline monitoring, bioaccumulation studies, ecotoxicological experimentation with native taxa, retrospective sediment analysis — would provide the foundation for meaningful protective action. The research agenda we have outlined is ambitious but not unrealistic; it is, if anything, the minimum required given the conservation stakes involved.

The endemic aquatic fauna of the Western Ghats cannot be protected by habitat management alone if the chemical environment in which those animals live is progressively compromised by pharmaceutical residues. Conservation biology in this region has rightly focused on deforestation, overfishing, and invasive species. Pharmaceutical ecotoxicology needs to take its place alongside these concerns — not as an abstract future problem, but as a present reality that is accumulating in the sediments of rivers that evolutionary history has made biologically irreplaceable.

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