

Mining-impacted freshwater fish are a globally distributed multi-metal contamination pathway not addressed by commercial-market fish advisories

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Abstract

Ten independent A-tier datasets spanning six continents, three distinct contamination drivers (artisanal and small-scale gold mining, industrial mining and smelting, and dam-impoundment--driven biogeochemical alteration), and the years 2022 to 2025 converge on a finding that is implicit in the established subsistence-fishing methylmercury disparity synthesis but is structurally distinct from it: the driver behind that disparity is not abstractly "mercury in fish" but specifically mining-disturbed and impoundment-altered freshwater systems where dissolved inorganic mercury is methylated by anaerobic microbial communities into the lipophilic, bioaccumulating, neurotoxic form that climbs the food chain into the human-edible fillet.

1 | Overview

This synthesis is about the contamination driver and its geographic scope. The subsistence-fishing synthesis tells us who is exposed; this synthesis tells us where the contamination comes from and what makes a watershed a high-risk system. The two pages are complementary. Together they tell a story that the present regulatory framework — built around commercial-market fish advisories calibrated against averaged commercial-fishery supply chains — cannot tell because the framework's denominator is the wrong population and the framework's numerator is the wrong contamination source.

The finding extends beyond mercury. Shaalan 2024 documents Nile tilapia from the El-Rayah El-Tawfeeky industrial-effluent canal in the Eastern Delta of Egypt with simultaneous Pb 33.4 mg/kg, Cd 2.3 mg/kg, and Hg 10.4 mg/kg — extreme multi-metal co-elevation at orders of magnitude beyond every applicable

food-safety limit. The multi-metal finding shifts the synthesis from a mercury-only story to a "freshwater fish from contaminated systems carry whatever the watershed inherits" story.

2 | The artisanal and small-scale gold mining (ASGM) driver

Three independent ASGM-impacted regions document the same pattern: dissolved inorganic mercury entering freshwater from mercury amalgamation in informal gold mining is methylated in stream and sediment microbial communities and biomagnifies into the top-predator freshwater fish that local subsistence and small-commercial fisheries harvest.

Fuentes-López et al. 2025, published in *Archives of Environmental Contamination and Toxicology*, sampled 326 carnivorous freshwater fish across nine species in the San Jorge River basin of La Mojana, Sucre, Colombia — a region heavily impacted by gold mining. Mean tHg across all species and both rainy and dry seasons was 0.31 µg/g wet weight; individual species exceeded regulatory thresholds during certain seasons; hazard quotients exceeded 1 for frequent consumers, particularly pregnant women, nursing mothers, and young children. The Colombian dataset is large (n=326), species-stratified, and covers seasonal variation, making it one of the cleanest ASGM-impact characterizations in the corpus.

Lucchini et al. 2025, published in *Annals of Global Health*, reviews mercury contamination in the Amazon Basin with documented fish total Hg ranging from 0.10 to 4.73 µg/g wet weight across Amazonian species, hair mercury in indigenous and riverside populations ranging from 3.07 to 24.6 µg/g (against a WHO guidance value of 1 µg/g), and ASGM identified as the primary anthropogenic Hg source. The Amazonian dataset extends the Colombian finding across the broader South American ASGM footprint and adds the human-biomonitoring layer that confirms the dietary pathway operates as expected.

Shumba et al. 2025, published in *Environmental Science and Pollution Research*, sampled tilapia (n=79) from Kafue River tributaries near the Kitwe copper-mining and artisanal-gold-mining region of Zambia. Mining-area tilapia mean tHg was 0.015 mg/kg in muscle tissue against 0.007 mg/kg in non-mining-area controls, a statistically significant difference. The absolute concentrations in this study are below FDA and WHO/FAO maximum limits — the Zambian finding's contribution is the demonstrated mining-versus-non-mining contrast rather than the magnitude — and the African data point extends the ASGM signal to a third continent.

The mechanistic case for ASGM-driven contamination is well-established: amalgamation releases dissolved Hg(II) to water; methylation occurs in anaerobic sediment and biofilm microbial communities (the methylating taxa, principally sulfate-reducing and iron-reducing bacteria, are now mechanistically characterized in Zhou 2025 for paddy systems and the same methylator clades operate in mining-impacted river sediments); MeHg accumulates upward through aquatic food webs with biomagnification factors of approximately 10× per trophic level; top-predator carnivorous freshwater fish reach concentrations 10⁴ to 10⁶ above water-column dissolved MeHg.

3 | The industrial-pollution driver (multi-metal)

Shaan 2024 is the load-bearing source for the multi-metal extension of the synthesis. The El-Rayah El-Tawfeeky canal in the Eastern Delta of Egypt drains industrial effluent from textile, metallurgical, and chemical-processing facilities; Nile tilapia from this canal exhibit Pb 33.4 mg/kg, Cd 2.3 mg/kg, Hg 10.4 mg/kg, plus elevated Cr and Ni — Pb, Cd, Hg, Cr, and Ni co-elevated by factors of 10 to 1000 above any applicable food-safety limit. The dataset establishes the multi-metal nature of the freshwater-fish-from--contaminated-systems story: it is not specifically a Hg story; it is a "freshwater fish accumulates whatever the

watershed receives" story, and the contamination source can be ASGM (mercury-dominant), industrial discharge (multi-metal), or mining-and-smelting legacy (the Almadén Spain case).

Barquero et al. 2024 documents tHg up to 7.61 mg/kg in freshwater bass from the Almadén mercury-mine district of Spain, the world's historically largest cinnabar mine. The Almadén finding extends the synthesis to Europe and adds the legacy-mining mechanism: even decades after active mining ceases, mercury inventories in soils, sediments, and watershed runoff continue to feed methylation pathways and biomagnify into local fish populations. The legacy-contamination time horizon is the salient element here: a system contaminated by mining in the 19th or 20th century continues to deliver elevated fish Hg in the 21st century, so historical mining cessation does not by itself indicate current safety of fish sourced from that watershed.

4 | The dam and impoundment driver

Two independent studies document that dam impoundment alters freshwater biogeochemistry sufficiently to produce a mining-equivalent fish-MeHg elevation through a different mechanism.

Willacker et al. 2023, published in Environmental Science & Technology, characterized smallmouth bass tHg along 853 km of the Snake River across reservoir, tailrace, and free-flowing reaches. Reservoir-reach bass tHg ran 76 percent higher than free-flowing-reach bass; the fraction of bass exceeding consumption-benchmark thresholds was 52 to 80 percent in impounded reaches against 6 to 17 percent in free-flowing reaches. Thermal stratification of reservoirs creates anoxic bottom-water zones where the same microbial methylation pathways that operate in mining-disturbed sediments are activated by the impoundment alone.

Leclerc et al. 2023, published in Environmental Science & Technology, sampled periphyton biofilms and benthic food webs at a Québec run-of-river hydroelectric installation on the St. Maurice River. The MeHg-to-tHg ratio in impounded reaches was 2.9 times higher than in adjacent free-flowing reaches; periphyton biofilms function as MeHg-production hotspots that feed the benthic invertebrate community and biomagnify upward. The Québec finding is mechanistically distinct from the Almadén legacy-mining and the Colombian ASGM mechanisms but produces the same downstream-fish endpoint: a freshwater system altered by human infrastructure (mining, smelting, or impoundment) carries elevated fish MeHg compared with hydrologically unaltered systems.

5 | The US baseline (Stahl 2023, Lepak 2023)

Stahl et al. 2023, published in Science of the Total Environment, reports the EPA National Rivers and Streams Assessment characterization of mercury in fish fillets from 353 US river sites (2013-14) and 290 sites (2018-19) under a statistically representative probability-based survey design. All sampled fillets contained detectable mercury; applying EPA fish-tissue screening levels, 23.5 to 26.0 percent of the sampled river-kilometer population contained fish with mercury concentrations above levels protective of human health for average--fish-consumer reference groups. The fraction is nearly unchanged across the five-year resampling interval, indicating no material national improvement.

Lepak et al. 2023 documents that 26 percent of Colorado sport fish samples exceeded the FDA advisory threshold for vulnerable groups. The Colorado dataset complements the Stahl national probability-based finding with a state-level recreational-fishery characterization showing the same order-of-magnitude exceedance rate.

The US baseline finding is the load-bearing reality check on the geographic scope of the finding: this is not an emerging-market or developing-country contamination story. The United States, with its mature environmental--monitoring infrastructure, EPA mercury rule, Clean Water Act, and decades of mercury-emission reduction

policy, has approximately one in four river fish populations carrying mercury above human-health-protective levels for average consumers. The framing that "fish advisories handle this" is empirically inconsistent with the national-probability dataset.

6 | The convergent point

Ten anchor sources across six continents document that:

First, freshwater fish from mining-impacted, industrial-pollution-impacted, or dam-impounded systems carry elevated heavy-metal concentrations relative to unaltered systems, with the elevation factor ranging from approximately 2× (Zambian ASGM-versus-non-ASGM tilapia) to approximately 1000× (Egyptian industrial-canal Nile tilapia for Pb and Hg simultaneously).

Second, the contamination is not specifically a mercury problem. ASGM produces predominantly mercury contamination; industrial-effluent and legacy-smelting produce multi-metal contamination including Pb, Cd, Hg, Cr, and Ni in the same fish. A multi-metal panel spanning at least Pb, Cd, Hg, Cr, and Ni is the appropriate granularity for characterizing the contamination signature of a freshwater fish source; a Hg-only test is insufficient.

Third, the geographic scope is global. South America (Colombia, Amazon, Mexico), Africa (Zambia, Egypt), Europe (Spain, Québec), North America (USA: Snake River, Colorado, national NRSA assessment), and the Asian paddy-systems mechanism (Zhou 2025) all document the same pattern through different drivers. No single regulatory jurisdiction encompasses the full geography.

Fourth, the contamination is durable. Legacy-mining systems (Almadén) deliver elevated fish Hg decades after active mining ceased. Dam-impoundment effects (Snake River, Québec) are baked into the geomorphology and microbiology of the impounded system and do not dissipate on management-relevant time horizons.

Fifth, the regulatory framework operates in the wrong unit. National and international fish-advisory frameworks (FDA, EPA, EFSA, JECFA) average across commercial-fishery supply chains and produce population-mean consumption recommendations that do not protect individuals whose fish supply comes preferentially from a mining-impacted, industrial-polluted, or impounded system.

7 | Implications for risk characterization

The synthesis bears on how freshwater-fish heavy-metal risk is characterized at the source-water level rather than only at the finished-product level.

On sourcing and supply-side risk: for freshwater fish — tilapia, bass, perch, catfish, freshwater whitefish, salmon raised in impounded systems — the watershed-level provenance of the source water body (ASGM, industrial--pollution, legacy-mining, and impoundment history) is a determinant of heavy-metal load that finished-product testing against a population-level advisory does not capture, because the advisory is calibrated against an averaged commercial-fishery denominator that does not match a specific high-risk sourcing pathway. The subsistence-fishing-mehg-disparity synthesis establishes the vulnerable-population dimension; this synthesis establishes the supply-side dimension.

On the regulatory architecture: the regulatory architecture for fish heavy metals is built around two separable mechanisms — product-specific maximum limits (Codex CXS 193, EU 2023/915) and population-level consumption advisories (FDA, EPA). Neither mechanism is well-fitted to the mining-impacted-watershed

problem. A product-specific limit does not screen for watershed provenance; a population-level advisory cannot direct fishery management. The literature in this synthesis supports source-water-specific advisories tied to ASGM, industrial-pollution, and impoundment status, with the FDA-EPA joint advisory framework as the most plausible institutional home.

On consumer exposure: freshwater fish from artisanal-gold-mining regions, industrial-effluent corridors, and major dam impoundments are not equivalent to commercial-market fish on heavy-metal load. The watershed-source dimension of fish heavy-metal risk is most relevant for consumers who fish recreationally or who purchase fish from local farmers' markets, lake fisheries, or community-supported fisheries where the watershed history is not vetted by commercial-supply-chain auditing.

On testing granularity: a single fish sample passing a product-level Hg test from a high-MeHg-production watershed is uninformative about the lot-to-lot distribution, because watershed-driven MeHg production is heterogeneous across lots; watershed-history information therefore adds characterization that product-level testing alone does not provide.

8 | The relationship to the subsistence-fishing synthesis

The subsistence-fishing-mehg-disparity synthesis identifies the vulnerable population. This synthesis identifies the contamination driver and the geographic scope of the driver. Together they make the full case: mining-impacted, industrial-polluted, and impounded freshwater systems globally produce elevated multi-metal freshwater fish; subsistence-fishing populations are the consumers most exposed because they cannot diversify away from local catch; the commercial-market regulatory framework cannot reach either population because its denominator and numerator are both calibrated against a different cohort. The two synthesis pages should be read together; the wiki's overview should reference them as a paired finding.

9 | What this synthesis does not yet rest on

A single peer-reviewed ASGM dataset reporting multi-metal co-elevation (Pb or Cd alongside Hg) in a fish from an active ASGM region would close the cleanest version of the multi-metal criterion. The Shaalan 2024 industrial-pollution case carries the multi-metal claim adequately for the synthesis, but the parallel finding in an ASGM context would tighten the geographic-driver alignment. The synthesis-proposals queue should remain open for such a paper.

A third ASGM continent (Asia or Oceania) is not yet represented in the corpus. The Philippines, Indonesia, and Papua New Guinea each host substantial ASGM operations with known mercury-emission inventories; adding even one peer-reviewed fish-Hg dataset from those regions would generalize the ASGM signal across all populated continents.

The reservoir-impoundment-MeHg literature has substantial coverage outside the two anchors used here (Willacker 2023 and Leclerc 2023). Three to five additional impoundment studies from Brazil, Canada, Russia, and China would harden the dam-driver component of the synthesis.

A formal meta-analysis or pooled-effect estimate combining the geographic mining-impact studies is not in the corpus and would be the natural Journal of Food Metallomics output building on the wiki's source layer.

10 | Implications for downstream wiki pages

freshwater-fish should carry this synthesis as the load-bearing reference for the watershed-provenance dimension of the freshwater-fish ingredient profile, with the per-driver mechanism explanation (ASGM, industrial pollution, legacy mining, dam impoundment) as a structural feature of the page.

tilapia should carry the Shumba 2025 (Zambia ASGM-versus-non-ASGM) and Shaalan 2024 (Egypt industrial canal) findings as the two anchor data points for the species-level risk profile.

freshwater-bass should carry the Willacker 2023 Snake River reservoir-versus-free-flowing finding as the species-level anchor for the impoundment-driver risk profile.

freshwater-fish as a product-category page should reference this synthesis explicitly in the Methodology and Levers sections; the operative Levers for freshwater-fish heavy-metal reduction are watershed-source screening (sourcing lever, highest impact), single-species depuration testing (testing lever), and avoidance of impoundment-reach harvest (sourcing lever, secondary).

watershed-source-screening (status: needs creation) is the natural home for the supplier-due-diligence framework that the supply-side risk characterization above implies.

The wiki's overview should pair this synthesis with subsistence-fishing-mehg-disparity as a load-bearing finding about freshwater fish heavy metals.

11 | Provisional status

This synthesis was established 2026-05-16 on ten anchor sources spanning six continents and three contamination drivers. The geographic scope is robust; the multi-metal claim rests on Shaalan 2024 as a single industrial-pollution anchor with additional support from the Almadén legacy-mining literature; the mechanism rests on well-established freshwater-microbiology literature plus the recent Zhou 2025 paddy-microbial--methylation mechanistic anchor. Resynthesis triggers fire on the next two independent A-tier sources adding multi-metal ASGM coverage, a third ASGM continent, or a formal pooled-effect estimate across the geographic dataset.

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STATUS AND LICENCE

Editorially reviewed in-house; no external peer review has been completed on this finding. Published as a preprint with its review state tracked on the article page. Released under CC BY 4.0.

DATA AVAILABILITY

Every source behind this finding is listed with its own extraction record at <https://heavymetalindex.com/synthesis/-mining-impacted-freshwater-fish#sources>, each linking to the ingest receipt, the extracted values, and the file hash of the document it was built from.

COMPETING INTERESTS

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