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Environmental Fate, Bioaccumulation, and Human Health Risks of DDT in Freshwater Ecosystems: Exposure Pathways, Trophic Transfer, and Toxicological Implications

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Abstract

Dichlorodiphenyltrichloroethane (DDT) is still an issue in freshwater ecosystems due to the limited public-health applications alongside large legacy deposits in soils, floodplains, and sediments. Its high hydrophobicity, low aqueous solubility and degradation resistance are conducive to partitioning to organic matter and biological lipids, thus facilitating bioaccumulation in freshwater biota and, in favorable food-web conditions, biomagnification. This critical review summarizes the environmental fate of DDT in inland waters, the processes that control trophic transfer, the ecological implications on freshwater biota, and the toxicological implications on human consumers. A PRISMA 2020-informed structured review of peer-reviewed freshwater literature and authoritative agency reports published between 2000 and April 2026 was compiled to gather evidence, which was supplemented by seminal earlier food-web papers. In lakes, rivers, reservoirs, wetlands, and ponds, a general trend is observed where dissolved concentrations are frequently low in comparison to sediment and tissue burdens, DDE often dominates residue profiles and represents old contamination, and troic transfer is enhanced by dietary uptake, benthic-pelagic interactions, high lipid content, and rising troic position. The main route of exposure of the general population is still freshwater fish and other lipid-containing foods, but drinking-water is generally secondary but can be important in the vicinity of local sources of contamination. Endocrine disruption, reproductive and developmental impairment, neurobehavioral effects, metabolic dysfunction, and likely carcinogenicity are toxicological evidence that implicates it. Five priorities are identified in future risk assessment: multi-compartment monitoring, stable-isotope-informed food-web analysis, metabolite-resolved interpretation, integration of ecological and dietary risk metrics, and more coordinated governance of vectors-control and freshwater surveillance. DDT must then be considered as a legacy-persisting pollutant whose ecological and public-health relevance can be most effectively interpreted in the context of the interplay between sediment storage, trophic transfer, and human consumption.

***Keywords**: DDT; freshwater ecosystems; environmental fate; bioaccumulation; biomagnification; trophic transfer; human health risk*

1. Introduction

DDT has been one of the most iconic persistent organic pollutants due to its combination of high insecticidal activity with an unprecedented environmental persistence and a long-established capacity to travel through food webs. Despite the ban or strict limitation of most agricultural applications, DDT is still listed in Annex B of the Stockholm Convention, which permits limited use as a disease-vector control agent under World Health Organization (WHO) advice when locally suitable alternatives are not available (Secretariat of the Stockholm Convention, n.d.; World Health Organization, 2011). Therefore, regulatory restriction has not been the end of environmental relevance. In most areas, the soils, floodplains, old pesticide stores, and historically treated sediments still emit DDT and its metabolites into freshwater systems years after direct application has decreased (Agency for Toxic Substances and Disease Registry [ATSDR], 2022; Rasmussen et al., 2015).

Freshwater ecosystems are especially susceptible as they combine catchment runoff, erosion, floodplain exchange, fisheries, aquaculture, and human water use. DDT is not very soluble in water and is highly lipophilic, meaning that residues are quickly bound to suspended particles, fine sediment, organic matter, and biological lipids instead of being in the dissolved state (ATSDR, 2022; Jayaraj et al., 2016; World Health Organization, 2022). This action brings about two interconnected issues. First, sediments are long-term reservoirs of contaminants that can be reactivated by storms, dredging, seasonal drawdown, eutrophication, or redox changes. Second, freshwater organisms store water, food, and sediment-related particles, which enables exposure to increase with trophic ascendancy in appropriate food webs (Arnot and Gobas, 2004, 2006; Katagi, 2010).

Interpretation revolves around transformation products. Parent DDT is more likely to be converted to DDE under more oxic conditions and to DDD under more reducing conditions; residue profiles can thus give hints to the age of contamination as well as the prevailing biogeochemical environment (Jayararaj et al., 2016; Zhou et al., 2006). Nevertheless, chemical persistence implies that transformed residues are still ecologically relevant. DDE, specifically, is highly lipophilic and often predominates in burdens in fish and higher troic levels. Since bioaccumulation is used to describe the net increase of a chemical in an organism of all exposure routes and biomagnification is used to describe increased concentration between prey and predator or between troic levels, both concepts are needed to comprehend freshwater DDT risk (Arnot and Gobas, 2004, 2006; Kelly et al., 2007).

This review combines two perspectives that are typically divided: environmental fate and public-health relevance. In particular, it focuses on (i) the entry, distribution, and retention of DDT in freshwater ecosystems; (ii) the processes that regulate bioaccumulation, biomagnification, and trophic transfer; (iii) the ecological impacts of freshwater biota; and (iv) the implications of freshwater exposure pathways on human consumers, particularly via fish and other aquatic foods. It is not only to reiterate the fact that DDT is persistent, but to clarify why persistence is biologically and socially significant when the storage of sediment, food-web structure, and human consumption converge.

2. Review Methodology

The current article was not intended to be a quantitative meta-analysis but a structured critical review based on PRISMA 2020 reporting principles (Page et al., 2021). In April 2026, literature assembly was performed based on peer-reviewed freshwater studies available in PubMed-indexed records, publisher archives, and citation chaining, along with authoritative international documents of WHO, ATSDR, the International Agency for Research on Cancer (IARC), and the Stockholm Convention Secretariat. Search terms were combined as DDT or organochlorine insecticides and freshwater, river, lake, reservoir, pond, or wetland and bioaccumulation, biomagnification, trophic transfer, food web, human health, or risk assessment.

The studies were included when they dealt with freshwater matrices or freshwater-related biota and reported one or more of the following: presence of DDT and/or its major metabolites; sediment-biota interactions; bioaccumulation or trophic-transfer relationships; ecological impacts that were applicable to freshwater receptors; or implications of human exposure to DDT through drinking-water or edible aquatic life. Earlier studies that were considered seminal were retained in cases where they offered conceptual or empirical basis in the interpretation of biomagnification measures in aquatic food webs. Studies that were marine-only, papers that did not have an analyte-specific relevance, and studies that did not have implications of freshwater exposure were eliminated unless they provided directly transferable mechanistic understanding. Since the evidence base is heterogeneous in terms of matrices, reporting units, tissue basis, metabolite grouping, and trophic characterization, the synthesis is qualitative and comparative, but not statistical.

TABLE 1. *FRAMEWORK USED TO IDENTIFY, SCREEN, AND SYNTHESIZE EVIDENCE FOR THE PRESENT REVIEW.*

Review component	Specification used in this review
Review type	Structured critical review with PRISMA 2020-informed reporting logic; no quantitative meta-analysis because of matrix and metric heterogeneity.
Time window	Primary emphasis on literature published from 2000 to April 2026, supplemented with seminal earlier food-web studies.
Evidence sources	Peer-reviewed freshwater studies, PubMed-indexed records, publisher-hosted journal pages, and official WHO, ATSDR, IARC, and Stockholm Convention documents.
Core search concepts	DDT / organochlorine insecticides + freshwater system terms (lake, river, wetland, reservoir, pond) + transfer/risk terms (bioaccumulation, biomagnification, trophic transfer, food web, human health, risk assessment).
Inclusion criteria	Freshwater matrices or freshwater-associated biota; DDT, DDE, or DDD residues; food-web or sediment linkages; ecological and/or human-health interpretation.
Data extracted	System type, geography, matrices and taxa sampled, analytes, trophic indicators, residue pattern, principal ecological message, and relevance for human exposure or management.
Synthesis approach	Comparative narrative synthesis emphasizing environmental fate, trophic transfer mechanisms, ecological consequences, and human-health implications.

3. Environmental Fate and Exposure Pathways in Freshwater Ecosystems

Freshwater DDT contamination arises from both direct and indirect pathways. Direct contemporary use is now narrowly constrained to vector-control settings, yet indirect release from old stockpiles, contaminated soils, irrigation return flows, urban drainage, and historically treated floodplains remains environmentally important (Secretariat of the Stockholm Convention, n.d.; World Health Organization, 2011). In agricultural and peri-urban catchments, rainfall-driven erosion and runoff can remobilize residues long after primary application has ceased, producing exposure pulses during stormflow, seasonal flooding, or drawdown cycles (Akoto et al., 2016; Rasmussen et al., 2015; Zhou et al., 2006). This catchment-memory effect is especially important in shallow ponds, wetlands, and littoral lake zones where land-water coupling is strong and even low dissolved concentrations can accompany high particulate or sediment-associated burdens.

Physicochemical properties explain why DDT behaves differently from more water-soluble contaminants. WHO lists DDT as having very low solubility in water and high lipophilicity, which promotes sorption to organic matter, suspended particles, and biological lipids (World Health Organization, 2022). Sediments therefore function as both sinks and secondary sources. Once buried, residues can persist for years and later re-enter the biologically active zone through resuspension, bioturbation, channel disturbance, or changes in redox conditions (ATSDR, 2022; Zhou et al., 2006). This is why water-only monitoring often underestimates ecological significance: the most important exposure compartments may be periphyton, detritus, benthic particles, or consumer tissues rather than bulk water.

Transformation further complicates interpretation. DDE frequently dominates residue profiles in water, sediments, and fish from systems with old or weathered contamination, whereas elevated parent DDT may point toward relatively recent or continuing input (Hu et al., 2010; Siriwong et al., 2009; Zhou et al., 2006). Yet a simple ratio-based interpretation should be used cautiously, because redox conditions, microbial activity, particle transport, and residence time differ among sediments, porewater, suspended solids, and biota. In practice, metabolite patterns are most informative when combined with hydrological context and multi-compartment sampling.

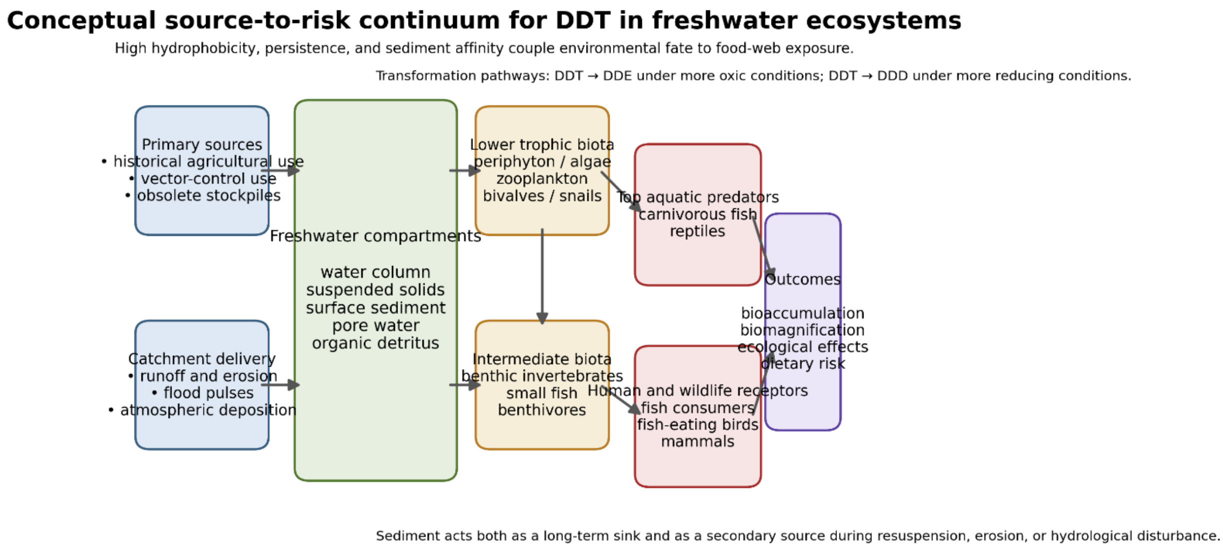

FIGURE 1. ***CONCEPTUAL SOURCE-TO-RISK CONTINUUM LINKING LEGACY SOURCES, SEDIMENT STORAGE, TROPHIC TRANSFER, AND ECOLOGICAL OR DIETARY RISK IN FRESHWATER ECOSYSTEMS.***

Exposure wise, the most important transition is the one between the environmental compartments and the food web. Primary producers and periphyton obtain residues of dissolved and particulate stages; benthic invertebrates obtain residues of sediment and detrital organic matter; and fish obtain both benthic and pelagic pathways via diet. This makes upper consumers less sensitive to water concentration and more sensitive to assimilation efficiency, trophic position, and lipid-normalized body burden (Arnot and Gobas, 2004; Kelly et al., 2007; Mackay et al., 2016). This food-web mediation describes why DDT is still of concern to human health even in areas with low or intermittent drinking-water levels.

4. Bioaccumulation, Biomagnification, and Trophic Transfer

The difference between bioaccumulation and biomagnification is the key to the interpretation of DDT. Bioaccumulation is the overall concentration of a chemical in an organism of all exposure pathways, such as uptake of water, food, and sediment-bound particles. Biomagnification is the concentration increase between prey and predator or, at the food-web level, with increasing trophic position. A number of related measures are applied in practice. The bioconcentration factor (BCF) is the uptake by water alone under controlled conditions; the bioaccumulation factor (BAF) is the uptake by all exposure routes under field conditions; the biomagnification factor (BMF) is the uptake by a predator and prey matched; and the trophic magnification factor (TMF) is the uptake by a food web as a whole (Arnot

In the case of DDT, dietary uptake is generally more significant with increasing troic level since predators feed on prey that already harbors lipid-associated residues. However, biomagnification is not universal. It is determined by food-web length, trophic connectivity, growth dilution, metabolic transformation, age of organism, and lipid dynamics (Arnot and Gobas, 2004, 2006; Kelly et al., 2007). Inland waters are particularly sensitive to benthic-pelagic coupling. Contaminated sediment and detritus can be strongly exposed to benthic invertebrates and benthivorous fish, but can be diffusely exposed to pelagic planktonivores. Generalist predators that feed in both compartments can thus combine multiple contamination pathways and attain greater burdens than predicted by a single habitat pathway (Kidd et al., 2001; Windsor et al., 2019).

These controls are depicted by field studies across continents. Evans et al. (1991) found especially high biomagnification of DDE between plankton and fish in an offshore food web in Lake Michigan, showing that DDT-related compounds can be food-web active despite a direct use decrease. Kidd et al. (2001) demonstrated in Lake Malawi that trophic level and carbon source interacted to determine DDT biomagnification, and that stable isotopes were important to differentiate benthic and pelagic transfer. Hu et al. (2010) reported the accumulation patterns of organochlorine pesticides in the Baiyangdian Lake freshwater food web in North China, and Siriwong et al. (2009) identified DDT derivatives in the entire aquatic food web of an agricultural region in central Thailand. Collectively, these studies suggest that trophic transfer is most intense in areas where sediment-related exposure, long food chains, and lipid-rich consumers intersect.

TABLE 2. *REPRESENTATIVE FRESHWATER STUDIES SHOWING HOW DDT RESIDUES MOVE AMONG COMPARTMENTS, FOOD WEBS, AND HUMAN DIETARY PATHWAYS.*

Study / location	Matrices or biota	Main finding on DDT transfer	Freshwater significance
Evans et al. (1991) - Lake Michigan, USA	Plankton, mysids, amphipods, deepwater fish	DDE showed strong biomagnification from lower food-web compartments to fish.	Classic evidence that DDT metabolites remain food-web active in freshwater systems.
Kidd et al. (2001) - Lake Malawi, East Africa	Benthic and pelagic food webs	Trophic level and carbon source both influenced DDT burdens and biomagnification.	Demonstrates why stable isotopes are valuable for pathway-specific interpretation.
Hu et al. (2010) - Baiyangdian Lake, China	Water, invertebrates, and freshwater food-web taxa	Accumulation varied among taxa, with trophic transfer evident across the food web.	Shows how shallow eutrophic lake structure shapes residue distribution.
Siriwong et al. (2009) - Rangsit agricultural area, Thailand	Indicator species across an aquatic food web	DDT derivatives were detected throughout the food web in an agricultural landscape.	Illustrates the continuing dietary relevance of agricultural drainage and local food use.
Akoto et al. (2016) - Tono Reservoir, Ghana	Water, sediment, and edible fish	Residues occurred in environmental matrices and fish, with associated health-risk implications.	Integrates environmental occurrence with human consumption concerns.
Gerber et al. (2016) - southern African conservation area	Apex aquatic predator tissue	Bioaccumulation was evident in a top predator, and risk assessment highlighted food-web transfer to upper consumers.	Apex consumers reveal magnified burdens not visible from water data alone.
Kaur et al. (2008) - Punjab, India	Freshwater fish species	Organochlorine residues were measurable in edible fish species from inland waters.	Relevant to food safety and fish consumption in South Asian freshwater contexts.
Cheung et al. (2007) - Hong Kong markets	Freshwater fish muscle	DDT residues varied markedly among edible fish species and tissues.	Highlights how consumer exposure depends on species choice and edible tissue burden.

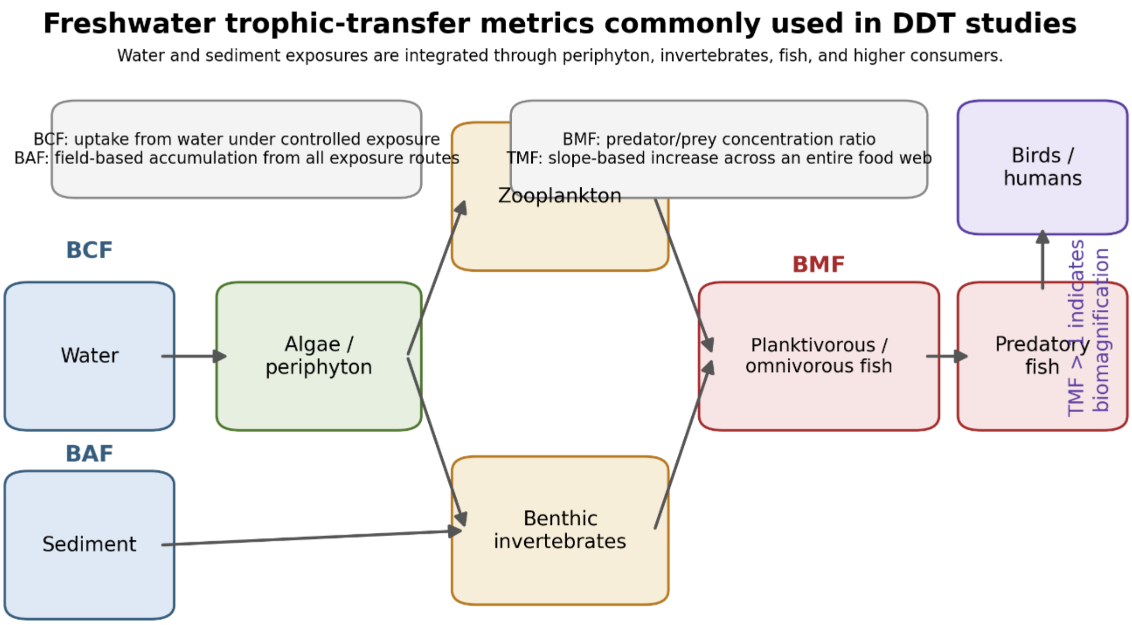

Figure 2. ***Simplified freshwater food web showing where BCF, BAF, BMF, and TMF are applied in DDT bioaccumulation studies.***

There are two implications of these patterns to interpretation. To begin with, high concentrations in predatory fish do not always imply high dissolved concentrations at the time of sampling; they are often a historical record of integration of sediment-bound and dietary exposure. Second, edible species cannot be considered interchangeable. Residue burdens depend on feeding guild, habitat use, body size, age, and lipid content, and thus food-safety assessments should sample a variety of species across trophic levels, not just a sentinel taxon (Cheung et al., 2007; Kaur et al., 2008; Walters et al., 2016).

5. Freshwater Biota Ecological Risk

Ecological significance of DDT is not limited to mere detection of residues. There is consistent experimental and review evidence that DDT and its metabolites have the potential to disrupt endocrine signaling, reproduction, development, and behavior in aquatic organisms and in the higher consumers that rely on them (Beard, 2006; Jayaratne et al., 2016; Martyniuk et al., 2020). In fish, the risk is increased since organochlorine pesticides may interact with steroidal pathways, modify reproductive physiology, and impact early-life stages, despite the lack of overt acute mortality. In wildlife, the traditional issues of eggshell thinning and reproductive dysfunction are still pertinent since freshwater food webs link contaminated fish with birds, reptiles, and mammals.

Ecological risk is usually chronic and not catastrophic in terms of field perspective. Benthic feeders may be subjected to sublethal effects due to sediment-associated residues over extended durations, causing changes in growth, reproductive fitness, or community structure. This chronic aspect is especially hard to identify when the monitoring is based on water chemistry. African and South African reviews highlight that agrochemicals in freshwater systems can be endocrine-disrupting chemicals and that organochlorine mixtures can be interacting with other stressors, such as eutrophication, metals, and habitat degradation (Horak et al., 2021; Taiwo, 2019). Thus, DDT is not to be considered a single contaminant with one endpoint of response, but a chronic stressor that is integrated into larger ecosystem change.

Apex aquatic predators are particularly valuable warning signals since they combine contamination across time and space. Gerber et al. (2016) demonstrated that an apex predator in a conservation zone still had significant organochlorine loads, highlighting that conservation status does not shield freshwater food webs against legacy contaminants. In areas where fisheries are dependent on protected wetlands or reservoirs, the same residues that are important to wildlife conservation can be important to subsistence or cultural fish consumption. This common ecological-human interface is among the most compelling reasons to have integrated freshwater risk assessment.

6. Human Exposure Pathways and Toxicological Implications

To the general population, food is the most common route of exposure to DDT-related compounds since DDT is highly lipophilic and is likely to accumulate in fatty foods and animal tissues (ATSDR, 2022; World Health Organization, 2022). Freshwater fish are thus of significance to the public-health perspective particularly in communities that depend on inland fisheries as a source of protein. In areas where fish are eaten regularly, the concentrations of the residues in the edible muscle, liver, or fatty tissues may be more important to risk assessment than bulk water concentrations. Residue burden, which is a characteristic of freshwater fish species, has been repeatedly demonstrated by market-based and reservoir-based studies to vary significantly between species, indicating species ecology and feeding habit rather than local contamination level (Akoto et al., 2016; Cheung et al., 2007; Kaur et al., 2008).

After absorption, DDT and its key metabolites are stored in adipose tissue preferentially and may last long in the body; ATSDR states that oral exposure via food and drinking-water is typically presumed to be the primary route of human exposure, and that stored body burden may be released during fat turnover (ATSDR, 2022). This continuity is of concern to transgenerational exposure since maternal burdens may lead to fetal or infant exposure during pregnancy and lactation. Despite the heterogeneity of the epidemiological literature, reviews have consistently found reproductive, developmental, neurobehavioral, endocrine, and metabolic endpoints to be the priority concerns (Beard, 2006; Eskenazi et al., 2009).

Human evidence should be used with caution since exposure histories, mixtures and confounding factors vary among study populations. However, the evidence has been overwhelming to the extent that IARC has categorized DDT as likely to cause cancer in humans (Group 2A) (Loomis et al., 2015). The Pine River Statement and its follow-up reviews also highlight the links between DDT or DDE exposure and effects such as breast cancer, diabetes, poor semen quality, spontaneous abortion, and poor neurodevelopment, but acknowledge that causality is more compelling in some endpoints than others (Eskenazi et al., 2009). The most practical implication, in freshwater terms, is that the pollution of edible aquatic organisms is a plausible and avoidable route of chronic human exposure.

TABLE 3. ***MAJOR HUMAN EXPOSURE PATHWAYS AND TOXICOLOGICAL CONSIDERATIONS RELEVANT TO FRESHWATER DDT CONTAMINATION.***

Exposure pathway or indicator	Why it matters in freshwater systems	Main toxicological concern	Selected evidence base
Consumption of contaminated freshwater fish and invertebrates	Lipophilic residues partition to edible tissues and integrate long-term food-web exposure.	Endocrine, reproductive, developmental, metabolic, and cancer-related concerns.	Akoto et al., 2016; Beard, 2006; Eskenazi et al., 2009; Kaur et al., 2008
Drinking-water from contaminated local sources	Usually a secondary route because DDT is poorly soluble, but may become relevant near heavily contaminated sources or disturbed sediments.	Chronic oral exposure with liver, endocrine, and neurological relevance.	ATSDR, 2022; World Health Organization, 2022
Maternal body burden and transfer	Stored residues in adipose tissue can be mobilized during pregnancy or lactation.	Fetal and infant developmental vulnerability; longer internal residence time.	ATSDR, 2022; Eskenazi et al., 2009
Residence near vector-control or legacy-use areas linked to inland waters	Environmental redistribution can maintain low-level chronic exposure while contaminating aquatic foods.	Combined community exposure through environment, diet, and proximity.	Secretariat of the Stockholm Convention, n.d.; Taiwo, 2019; World Health Organization, 2011

Chemistry, ecology and consumption behavior should thus be linked through risk assessment. Numerous freshwater investigations have begun to estimate human exposure based on fish residue concentrations, local ingestion rates, body weight, hazard quotient, or lifetime cancer risk calculations. These methods are useful, but as strong as the ecological design of these methods. One edible species sampled at one time cannot reflect seasonal hydrology, trophic diversity, or sediment reactivation. Similarly, the guideline value of DDT and its metabolites in drinking-water provided by WHO is protective of human health, although WHO does not consider the guideline value to be an environmental or aquatic-life threshold (World Health Organization, 2022). The ecological monitoring is therefore necessary in parallel with the traditional public-health thresholds to protect freshwater.

7. Risk Assessment and Management Priorities

The first step is to stop water-only surveillance and transition to multi-compartment surveillance. Freshwater DDT assessment must at least combine water, suspended sediment, surface sediment, periphyton or macrophytes, representative invertebrate consumers, and at least two fish troic levels. Recent studies on stream surveillance demonstrate the usefulness of suspended sediment and periphyton since these two compartments capture the biologically available portion of hydrophobic contaminants compared to grab water samples (Ijzerman et al., 2024). These sampling designs are especially significant in ponds, floodplain wetlands, and reservoirs where fine sediment disturbance can quickly re-link legacy contamination to the food web.

The second priority is enhanced trophic interpretation. Delta-15N and delta-13C are particularly valuable as they are stable isotopes that can be used to measure trophic position and carbon source more effectively than diet labels alone. They are essential to shallow systems where benthic and pelagic pathways are mixed, as shown by Kidd et al. (2001) and supported by global syntheses of trophic magnification and biological trait effects (Walters et al., 2016; Windsor et al., 2019). To the management, isotopic evidence assists in differentiating between a contaminated predator that is either a result of pelagic magnification, benthic sediment exposure, or a combination of both. The third priority is consistency in analytics and reporting. Parent DDT and major metabolites should be reported separately, with tissue basis and lipid normalization, with concentrations reported on a wet-weight or dry-weight basis, and biomagnification measures reported as matched predator-prey pairs or food-web regressions. In the absence of this consistency, cross-site comparison is challenging and dietary recommendations are less transferable (Arnot and Gobas, 2006; Mackay et al., 2016). Sediment management, erosion control, removal of outdated stockpiles, and local fish-consumption advisories ought to be viewed as complementary and not independent interventions. Since DDT is still applicable within limited public-health conditions, pesticide regulation and freshwater surveillance must be aligned in such a way that the policy of disease control is guided by modern environmental surveillance and not by historical presumptions only.

8. Conclusion

DDT is a persistent contaminant of freshwater ecosystems due to environmental persistence, hydrophobicity, sediment storage, and food-web transfer that enable burdens to persist beyond the time of initial use. The most intense loads are typically linked to sediments, lipid-rich organisms, and increased trophic levels across lakes, rivers, reservoirs, wetlands, and ponds. Nevertheless, biomagnification does not occur automatically and is influenced by trophic structure, carbon pathways, organism characteristics, sediment remobilization, and dietary uptake and elimination balance. The same mechanisms that amplify ecological risk provide avenues of chronic human exposure via contaminated freshwater foods.

A viable freshwater plan should thus bridge environmental destiny, trophic ecology and human health. The best foundation to future management is multi-compartment monitoring, stable-isotope-informed food-web analysis, metabolite-resolved interpretation, and integrated dietary risk assessment. DDT cannot be considered only as a historical pesticide, but as a legacy-carrying contaminant the meaning of which is most evident when the memory of sediments, the structure of the ecosystem, and human consumption are considered as a unit.

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