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Global Freshwater Degradation: Contaminant Dynamics, Ecotoxicological Risks, Public Health Disparities, and Advanced Engineering and Policy Frameworks

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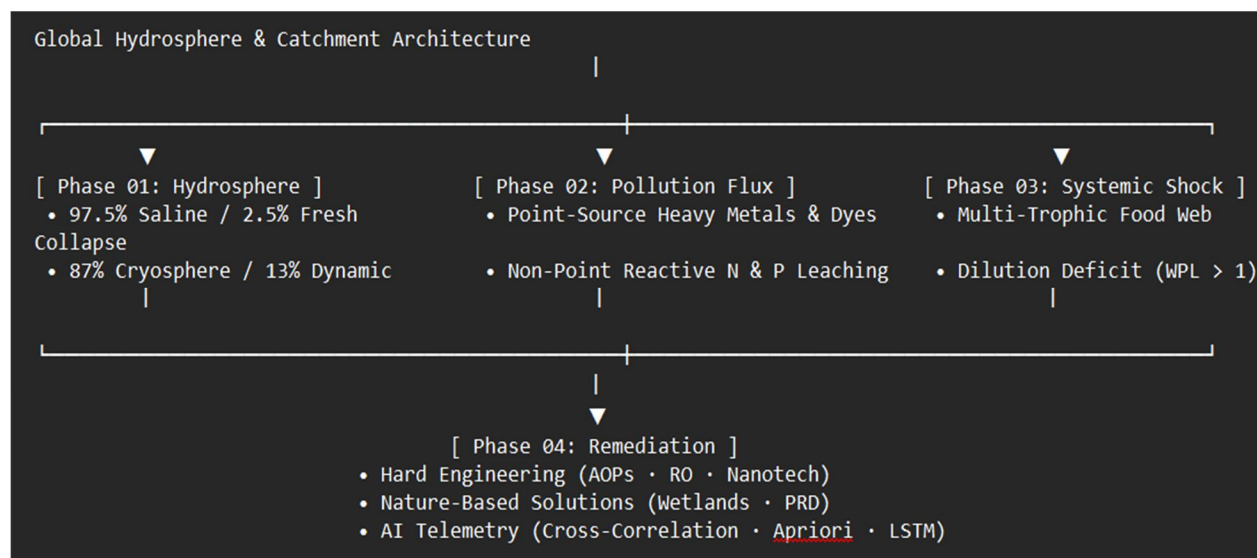
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Abstract: Freshwater security has become one of the defining systemic challenges of the Anthropocene. Although water covers more than 70% of the Earth's surface, freshwater represents only 2.5% of global reserves, with less than 1% readily accessible in lakes, river channels, and unconfined aquifers. Anthropogenic perturbations—accelerated by rapid population growth, industrialization, land-use intensification, and unmanaged waste disposal—have driven freshwater deterioration across point and diffuse interfaces.

This synthesis integrates empirical findings, spatial modeling, epidemiological cohorts, and legal frameworks across 20 foundational investigations (R1–R20). It traces the mechanistic pathways of legacy and emerging contaminants, evaluates catchment-scale nutrient cycles and the Gray Water Footprint (GWF), unpacks socioeconomic and clinical public health risks, and analyzes treatment regimes ranging from physical separations to photocatalysis and green infrastructure.

Finally, this paper interrogates institutional implementation failures, demonstrating how decentralized economic growth structures often undermine environmental governance. It outlines systemic policy pathways—including the European Union Water Framework Directive (EU WFD), non-point best management practices (BMPs), artificial intelligence tracing architectures, and community-level environmental education—essential for securing global water resilience.

Keywords: Freshwater security, Non-point source pollution, Gray Water Footprint (GWF), Eutrophication, Persistent Organic Pollutants (POPs), Environmental toxicology, Water Framework Directive (WFD), Wastewater remediation, Long Short-Term Memory (LSTM), Environmental justice.



I. INTRODUCTION: THE GLOBAL WATER CRISIS AND CATCHMENT CONNECTIVITY

Freshwater quality is fundamentally non-substitutable and constitutes the core biophysical boundary for human health, food security, and terrestrial ecosystem stability. The Earth's hydrosphere is predominantly saline (97.5%), with freshwater comprising the remaining 2.5%. Of this freshwater reserve, approximately 87% is sequestered in glaciers, polar ice caps, and permanent permafrost, leaving only ~13% (~0.3% of total global water) accessible in liquid phases via groundwater aquifers, soil moisture, lakes, and river channels. Despite constituting a minor volume of the continental surface, running freshwater channels support disproportionate shares of human water consumption, irrigation requirements, and biological diversity.

Global freshwater consumption expanded more than sixfold over the 20th century—growing at over twice the rate of human population growth—and has expanded by 600% over the past hundred years with an ongoing annual increase rate of 1.8%. The World Health Organization (WHO) and United Nations data indicate that approximately 80% of the world's population is exposed to severe threats regarding water security. Concurrently, 748 million to 1 billion individuals lack access to safe drinking water, 2.5 billion lack basic sanitation, and waterborne diseases account for roughly 14,000 avoidable deaths daily, claiming the lives of over 1.5 million children under the age of five every year.

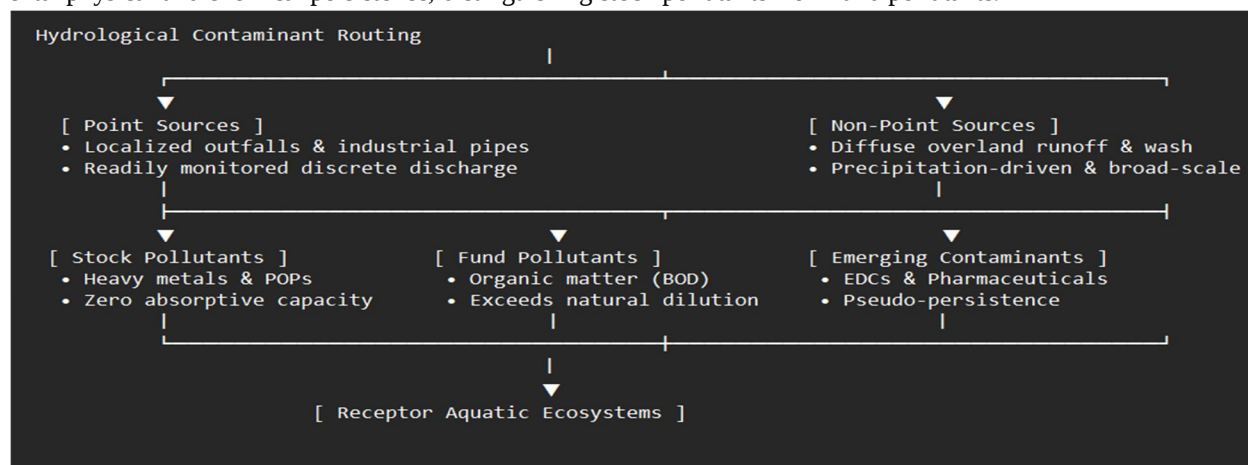
Geographic disparities further exacerbate this vulnerability. In India, which supports 16–18% of the global population on 2.4% of the land area, only 4% of the planet's renewable water resources are available, rendering over 70% of domestic surface waters unfit for human consumption. Similarly, China sustains 20% of the global population with approximately 5–6% of global renewable freshwater, complicated by severe spatial mismatches: North China accounts for 64% of national territory but only 19% of water reserves, while the Yangtze River and southern basins contain 81% of water resources.

At the macro-ecological scale, pristine catchments naturally operate under a paradigm of nutrient parsimony. Undisturbed terrestrial ecosystems tightly lock up limiting elements, particularly phosphorus and nitrogen, cycling them internally and discharging near-zero nutrient concentrations into headwater streams. Pristine running waters depend instead on allochthonous carbon inputs (woody debris, leaf litter) processed through fungal and shredder-macroinvertebrate food webs. Anthropogenic activity acts as a pervasive disturbance, stripping stabilizing terrestrial buffers and replacing conservative ecosystems with "leaky" agricultural and urbanized landscapes.

Catchment-water body relationships parallel that of a house and its waste receptacle: virtually every land-use perturbation across a drainage basin propagates downstream. Compounding this issue is the high dilution cost of waste assimilation: approximately 8 liters of pristine freshwater are required to assimilate the contaminant load of a single liter of domestic/industrial wastewater to acceptable standards. Consequently, water pollution cannot be modeled as isolated, single-contaminant occurrences, but as a systemic degradation of hydrological and biological integrity across landscapes.

II. CONTAMINANT CHARACTERIZATION: POINT AND NON-POINT SOURCE DYNAMICS

Water contaminants are broadly demarcated into point sources (discrete, identifiable conduits such as municipal wastewater outfalls, industrial effluent pipes, and offshore ditch discharges) and non-point sources (diffuse, unconfined runoff across agricultural fields, atmospheric deposition, failed septic beds, and extensive urban storm surfaces). Contaminants behave according to their fundamental physical and chemical persistence, distinguishing stock pollutants from fund pollutants.



- **Stock Pollutants:** Substances with negligible or zero environmental absorptive capacity. These include synthetic xenobiotics, heavy metals (*As*, *Cd*, *Pb*, *Hg*), and persistent plastics that accumulate monotonically over time, imposing permanent multi-generational ecological burdens.
- **Fund Pollutants:** Constituents for which the receiving aquatic environment possesses a non-zero assimilative or dilutive capacity, such as degradable organic matter, heat, and biogenic nutrients, provided the injection rate does not exceed the system's kinetic decomposition threshold.

A. Industrial and Municipal Effluents

Industrial manufacturing represents an intensive point-source polluter. Untreated textile dyeing and leather tanning effluents are notorious for extreme pollutant loads, characterized by high biochemical oxygen demand (BOD_5), high chemical oxygen demand (COD), elevated concentrations of dissolved salts, and high pH swings driven by bulk applications of caustic soda and soda ash. In Bangladesh's Turag River basin, direct discharge of industrial effluent causes dissolved oxygen (DO) to collapse to lethal extremes (0.76 mg/L, far below the required ≥ 6 mg/L baseline), while hardness reaches 1816 mg/L, COD spikes to 78 mg/L, and turbidity reaches 97.2 NTU.

Globally, over 80% of municipal wastewater is discharged into receiving water bodies without undergoing adequate secondary or tertiary treatment. In urbanized sectors, domestic sewage contributes between 75% and 80% of total conventional water pollution. Untreated domestic sewage dumps massive volumes of labile organic waste, pathogenic microbes (*E. coli*, *Salmonella*, *Vibrio cholerae*), and synthetic surfactants into surface waters.

The microbial breakdown of these oxygen-demanding wastes by aerobic heterotrophs rapidly consumes dissolved oxygen, driving the aquatic system into acute hypoxia and generating volatile, odorous gases such as hydrogen sulfide (H_2S) and ammonia (NH_3).

B. Persistent Organic Pollutants (POPs)

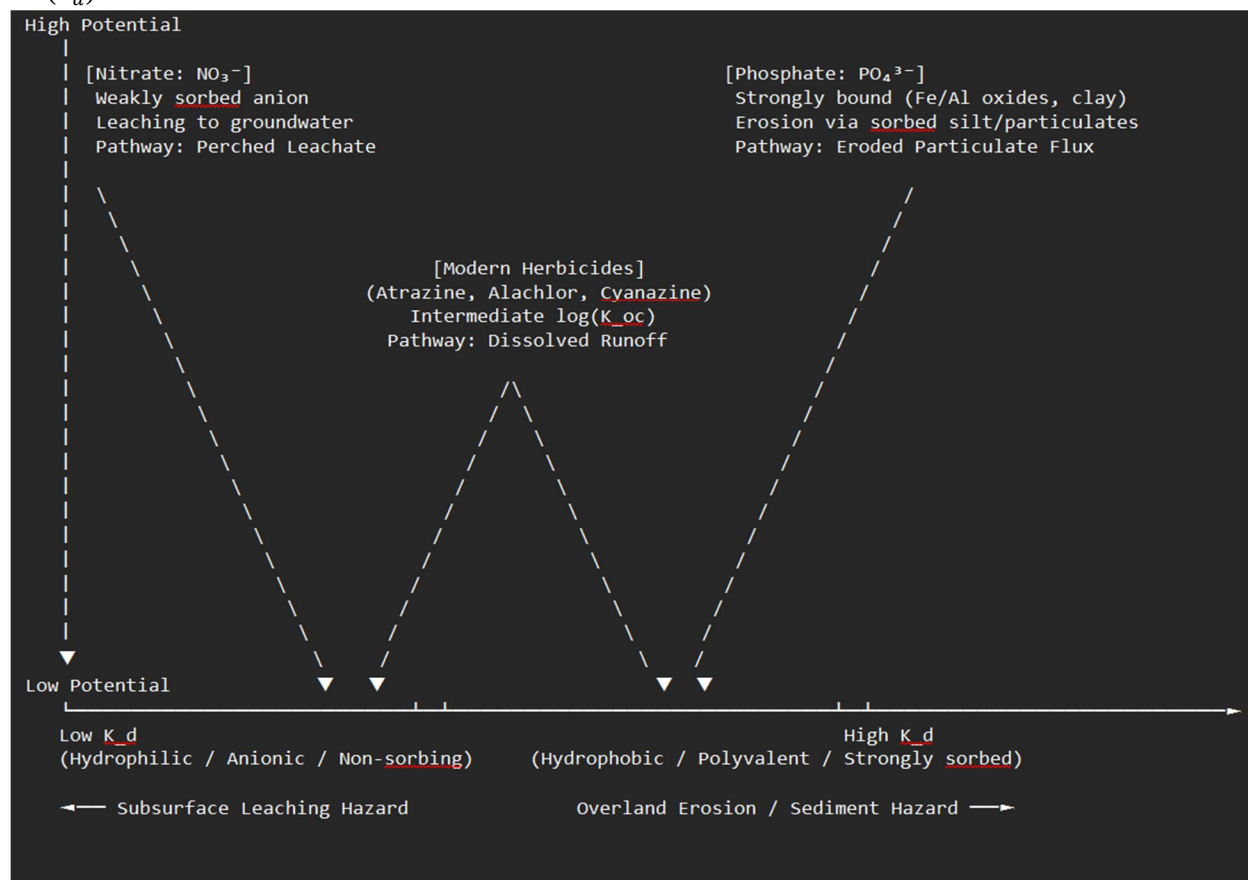
Persistent Organic Pollutants (POPs)—regulated under the Stockholm Convention—resist environmental photolysis, chemical hydrolysis, and biological degradation, undergoing extensive trophic biomagnification.

- **Organochlorine Pesticides (OCPs):** Historically applied across intensive agriculture, compounds such as hexachlorocyclohexanes (HCHs: α -, β -, γ -, and δ -isomers) and dichlorodiphenyltrichloroethane (DDT and its primary degradation metabolites DDE and DDD) remain widespread. Between 1950 and 1983, China alone applied 4.9 million tons of HCHs (33% of global consumption) and 0.4 million tons of DDT (20% of global consumption). Although technical DDT was banned in agriculture in 1983, secondary production continued for use in dicofol formulation and marine anti-fouling paints.
- **Diagnostic Isomer Ratios:** Ratios of specific chemical isomers serve as geochemical tracers to differentiate between historical residues and illicit or ongoing inputs:
 - **HCH Source Apportionment:** Technical HCH formulations possess an α -HCH/ γ -HCH ratio between 3.7 and 11, whereas purified lindane ($\geq 99\%$ γ -HCH) yields ratios between 0.2 and 1.0 due to the rapid environmental degradation of γ -HCH. Ratios observed in China's Yellow River, Huaihe River, and Guanting Reservoir range from 0.20 to 1.0, signaling contemporary lindane applications, whereas lakes like Taihu (ratio = 3.9) exhibit historical signatures of technical mixtures.
 - **DDT Source Apportionment:** Technical DDT exhibits an o,p' -DDT/ p,p' -DDT ratio of 0.2 to 0.3, whereas dicofol formulations show elevated ratios of 4.8 to 9.2 (averaging ~ 7). Ratios exceeding 5.0 in the Jiangsu reach of the Huaihe River, Taihu Lake, and Guanting Reservoir confirm substantial modern dicofol contamination. Concurrently, values of the ratio p,p' -DDT/(p,p' -DDE + p,p' -DDD) < 1.0 indicate aged, historically weathered residues across 85% of evaluated Chinese water bodies, whereas values > 1.0 in shipping conduits (e.g., Deep Bay) point directly to fresh inputs from anti-fouling hull paints.
- **Polychlorinated Biphenyls (PCBs) and Flame Retardants:** Approximately 10,000 tons of commercial PCBs were produced in China between 1965 and 1974 for dielectric fluids in capacitors and power transformers. Improper disposal and containment leaks maintain PCB surface water concentrations far above international baselines. In the Haihe River, PCB concentrations range from 311 to 3110 ng/L, exceeding the Chinese regulatory drinking water limit (20 ng/L) by up to 380-fold, while coastal seawater across 90% of monitored Chinese island shores exceeds the US EPA Continuous Concentration Criterion of 30 ng/L.

- **E-Waste Leaching:** Informal electronic waste recycling centers—exemplified by Guiyu, Longtang, and Taizhou—process millions of tons of domestic and imported e-waste, emitting an estimated 70,600 tons of polybrominated diphenyl ethers (PBDEs, notably deca-BDE-209) and up to 6800 g of toxic polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs; up to 240 g I-TEQ) annually into surrounding aquatic networks.

C. Agrochemical Transport Mechanisms and the Soil Partitioning Paradox

Agriculture dominates global freshwater withdrawals, accounting for approximately 70% of total abstractions. The mobilization and ultimate environmental fate of agricultural non-point source contaminants depend on the compound-specific soil-water distribution coefficient (K_d).



The soil-water partition coefficient, K_d , defines the mass ratio of target contaminant adsorbed to soil solids relative to that remaining dissolved in porewater at equilibrium:

$$K_d = \frac{C_{\text{solid}}}{C_{\text{solution}}}$$

- 1) **High Partitioning ($K_d \gg 1$):** Hydrophobic pesticides (legacy organochlorines) and mineral phosphates (PO_4^{3-}) bond strongly to soil minerals and organic matter. Their primary transport route is surface erosion via detached particulate sediment.
- 2) **Intermediate Partitioning ($K_d \approx 1 - 10$):** High-volume modern herbicides (triazines such as atrazine, and chloroacetanilides such as alachlor and metolachlor) exhibit moderate water solubility and moderate soil sorption. They are transported primarily within the dissolved aqueous phase of overland storm runoff.
- 3) **Low Partitioning ($K_d \ll 1$):** Unadsorbed anionic compounds—most notably nitrate (NO_3^-)—remain unretarded in soil solution, bypassing surface filtration and leaching downward into tile drainage networks and deep groundwater aquifers.

This partitioning behavior creates an operational trade-off in soil conservation policy. Soil erosion initiatives—such as the US 1985 Farm Security Act—have historically relied on cultural and structural best management practices (conservation tillage, contour cropping, terracing) designed to minimize soil loss and enhance soil moisture retention.

While these practices successfully decrease particulate sediment transport and sediment-bound phosphorus loadings, increased infiltration through permeable soils directly accelerates the leaching of soluble nitrates and mobile herbicides into underlying aquifers. Consequently, erosion control alone cannot safeguard water quality unless combined with strict nutrient application limits, cover cropping, and residue nutrient crediting.

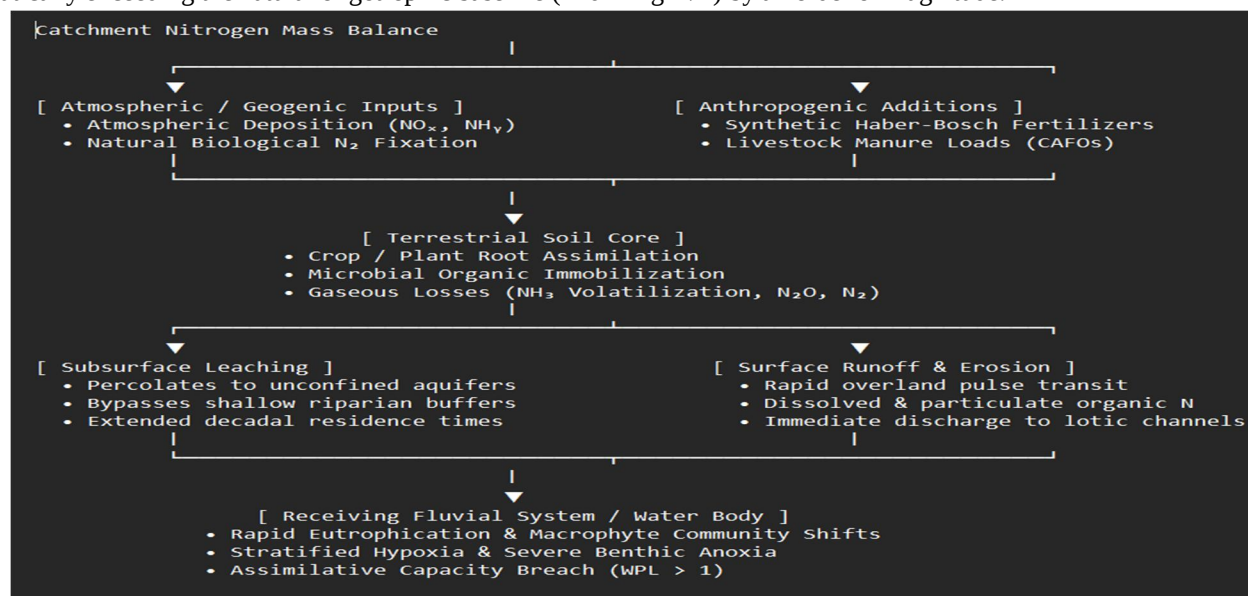
D. Emerging Contaminants

Modern aquatic monitoring has revealed a diverse group of emerging contaminants that escape conventional municipal and industrial wastewater facilities:

- **Pharmaceuticals and Personal Care Products (PPCPs):** Excreted through urine and feces or flushed directly, active pharmaceutical ingredients (antibiotics, non-steroidal anti-inflammatory drugs, steroid hormones, analgesics) continuously enter surface waters via domestic and hospital sewage outfalls. These biologically active residues alter endocrine systems, trigger behavioral shifts in non-target aquatic organisms, and exert selective pressures that foster multi-drug antibiotic resistance in ambient aquatic microbes.
- **Per- and Polyfluoroalkyl Substances (PFAS):** Widely manufactured for waterproof coatings, fluorinated surfactant firefighting foams, and fluoropolymer processing, compounds such as perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) possess high chemical stability due to extremely strong carbon-fluorine bonds. Unlike traditional lipophilic POPs, PFAS bind selectively to proteins and accumulate in serum, liver, and kidney tissues. In China, domestic manufacturing of PFOS expanded substantially after Western phase-outs, producing over 47 tons annually by 2005. PFAS concentrations in the Yangtze River reach up to 260 ng/L (near Shanghai), with concentrations in urban municipal tap waters reaching 78 ng/L.
- **Microplastics and Synthetic Surfactants:** Secondary fragmentation of mismanaged consumer plastic debris, paired with primary microbead discharges, yields ubiquitous microplastic particles (< 5 mm) throughout marine and freshwater systems. Microplastics function as hydrophobic vector substrates, concentrating persistent organics and toxic heavy metals from the surrounding water column and facilitating their transfer into lower trophic fauna. Surfactants (anionic, cationic, and non-ionic forms) derived from industrial clean-in-place protocols and household detergents degrade aquatic plant cuticles, lower surface tension, reduce gas exchange, and introduce toxic alkylphenol breakdown intermediates into the water column.

III. CATCHMENT-SCALE NUTRIENT DYNAMICS AND THE GRAY WATER FOOTPRINT

Anthropogenic alteration of the global nitrogen cycle has flooded catchments with reactive nitrogen (N_r), outpacing the natural buffering and denitrification capacity of terrestrial ecosystems. Modern high-intensity agricultural systems leach reactive nitrogen at rates of roughly $25 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$. This leaching maintains baseflow stream concentrations at or above $10 \text{ mg NO}_3\text{-N/L}$, systematically exceeding the natural oligotrophic baseline (< 0.4 mg N/L) by an order of magnitude.



A. Gray Water Footprint (GWF) and Water Pollution Level (WPL)

To quantify the hydrological dilution volume required to assimilate anthropogenic pollutant burdens, the Water Footprint Network formulated the Gray Water Footprint (GWF). For nitrogen, the GWF (m^3/yr) is mathematically defined as the total pollutant load (Load, kg/yr) divided by the difference between the ambient receiving water quality standard (C_{max} , mg/L) and the natural background concentration (C_{nat} , mg/L):

$$GWF = \frac{\text{Load}}{C_{max} - C_{nat}}$$

Adopting an ambient water quality standard $C_{max} = 2.9$ mg N/L (aligned with aquatic ecosystem protection criteria) and a natural background concentration $C_{nat} = 0.4$ mg N/L establishes an assimilation capacity of 2.5 mg N/L.

The relative stress exerted on a river basin is evaluated using the Water Pollution Level (WPL), defined as the ratio of the basin's aggregate GWF to its actual annual runoff (R_{act} , m^3/yr):

$$WPL = \frac{GWF}{R_{act}}$$

A value of $WPL = 1.0$ indicates that the freshwater system's full biological and physical waste assimilation capacity has been completely consumed. When $WPL > 1.0$, pollutant loads exceed the sustainable assimilation threshold of the river basin, resulting in degraded water quality standards and persistent downstream pollution.

B. Global Nitrogen Fluxes and River Basin Degradation

A comprehensive global modeling assessment by Mekonnen and Hoekstra estimated that the total anthropogenic nitrogen load to global freshwater between 2002 and 2010 reached 32.6 million metric tons per year. Of this total, 75% (24.4 million tons/yr) originated from non-point agricultural leaching and runoff, 23% from municipal domestic discharge, and 2% from direct industrial point sources.

At the crop-specific level, cereal grain production accounted for 18% of the global N-related GWF (wheat 7%, maize 6%), vegetable production accounted for 15%, and oil crops contributed 11%.

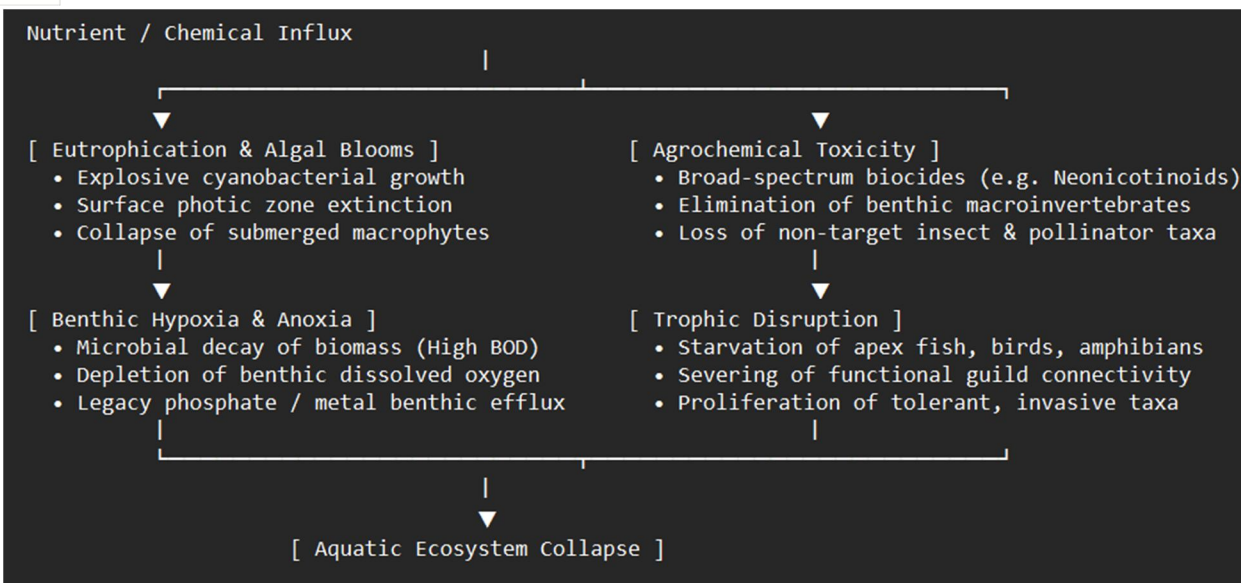
The resulting global gray water footprint for reactive nitrogen totaled $13 \times 10^{12} m^3/yr$ (13,000 billion m^3/yr). Geographically, Asia contributed roughly two-thirds (64.4%) of this global total—with China alone responsible for 45% (5875 billion m^3/yr)—followed by Europe (15.2%), North America (7.8%), and Latin America (6.2%).

Globally, river basins exhibiting $WPL > 1.0$ account for 17% of global ice-free land area, carry 9% of global continental runoff, and support 48% of the global human population. Major basins facing severe assimilation deficits include:

- Huang He (Yellow River): $WPL = 8.3$; agricultural runoff contributes 95% of the total nitrogen load, exceeding its waste assimilation capacity by over 800%.
- Aral Drainage Basin: $WPL = 4.0$; extensive upstream diversion and untreated sewage disposal have outpaced runoff assimilation fourfold.
- Indus River Basin: $WPL = 3.0$; intensive cereal and oil-crop irrigation coupled with domestic discharge in an arid-to-semiarid regime outstrips dilution capacity threefold.
- Xi Jiang (Pearl River Tributary): $WPL = 2.3$; dense industrial manufacturing, chemical intensive cropping, and municipal sewage drive substantial degradation.
- Yangtze River (Chang Jiang): $WPL = 2.0$; total nitrogen loads have increased more than tenfold since 1968, driven primarily by intensive vegetable, cereal, and oil-crop cultivation (96% agricultural source attribution).
- Murray-Darling Basin: $WPL = 1.8$; agricultural runoff (96% of N input) drives toxic cyanobacterial blooms across Australia's primary agricultural basin.
- Ganges River Basin: $WPL = 1.2$; high population density (343 people/ km^2) makes domestic sewage the dominant driver (56% of total N load), exceeding basin assimilation capacity by 20%.

IV. ECOTOXICOLOGICAL CASCADES AND AQUATIC ECOSYSTEM IMPAIRMENT

The introduction of excessive nutrient, chemical, and physical pollutants triggers complex ecological cascades that destabilize natural food webs.



A. Eutrophication and Hypoxia Cascades

Anthropogenic nutrient loading alters freshwater stoichiometry, shifting aquatic ecosystems from nutrient-poor baseline states into persistent cultural eutrophication. When excessive nitrogen and phosphorus reach standing or slow-moving water bodies, they trigger rapid blooms of phytoplankton and cyanobacteria (e.g., *Microcystis*, *Anabaena*). These surface algal scums attenuate sunlight, suppressing underwater photosynthetic active radiation and causing the widespread die-off of native submerged macrophytes (such as *Potamogeton* species).

When these algal blooms collapse, the sinking biomass is decomposed by aerobic heterotrophic bacteria. This process rapidly consumes dissolved oxygen throughout the water column, producing severe hypoxia ($DO < 2$ mg/L) and localized anoxia. Under anoxic conditions, benthic organisms, mollusks, and fish die from suffocation, while reducing conditions at the sediment-water interface accelerate the chemical release of previously bound iron-phosphate complexes and heavy metals back into the water column.

Cyanobacterial blooms can also produce potent secondary hepatotoxins and neurotoxins (e.g., microcystins, anatoxins) that bioaccumulate across aquatic food webs, rendering waters toxic to wildlife, livestock, and downstream domestic users.

B. Agrochemical Impacts and Trophic Collapses

Broad-spectrum biocides can disrupt non-target aquatic populations. Neonicotinoid insecticides (such as imidacloprid, thiamethoxam, and clothianidin) are highly water-soluble, environmentally persistent, and toxic to invertebrates. Runoff from agricultural fields washes neonicotinoids into adjacent wetlands, headwaters, and drainage ditches, decimating non-target aquatic insects, shredders, and emerging insects. This depletion cascades through food webs, starving insectivorous predators (bats, amphibians, waterfowl, and juvenile salmonids) and degrading ecosystem structure.

Furthermore, historical applications of persistent organochlorines continue to biomagnify up aquatic food chains. High trophic predators exhibit severe endocrine disruption, reproductive failures (such as eggshell thinning from p,p' -DDE), and biological magnification factors that exceed background aqueous concentrations by several orders of magnitude.

C. Acidification, Thermal Shifts, and Sedimentation Dynamics

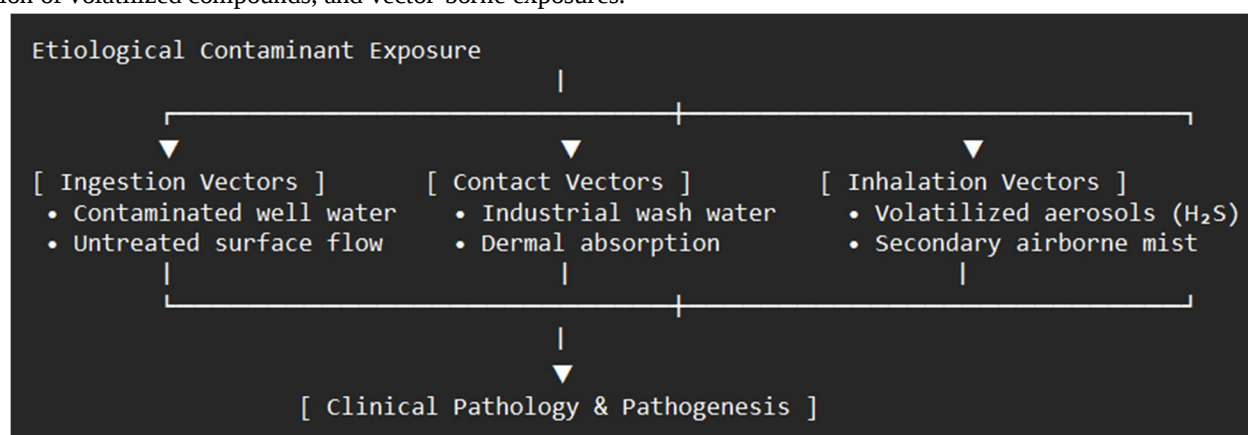
Physical and chemical alterations compound the biological pressures on freshwater systems:

- **Acidification:** Combustion emissions (SO_2 , NO_x) and industrial acid effluents lower surface water pH. Below the critical biological threshold of pH 6.0, natural bacterial and fungal decomposers decline, slowing leaf litter and organic matter breakdown and stalling catchment nutrient cycles. Below pH 5.8, acid-sensitive diatoms and green algae disappear, replaced by dense, monodominant mats of acid-tolerant filamentous algae such as *Cladophora*. Acidic conditions also accelerate the leaching of toxic free aluminum ions (Al^{3+}) and heavy metals from benthic sediments, damaging fish gills and triggering ionoregulatory failure.

- **Thermal Pollution:** Industrial cooling systems, thermoelectric boilers, and nuclear power operations discharge substantial volumes of heated water back into rivers and lakes. Elevated water temperatures reduce dissolved oxygen saturation capacity while simultaneously accelerating the metabolic and respiratory rates of ectothermic organisms. This dual impact increases physiological oxygen demand under conditions of reduced oxygen supply, disrupting spawning migrations, halting embryonic development, and killing stenothermal aquatic species.
- **Siltation and Turbidity:** Accelerated catchment erosion driven by land clearing and tillage deposits extensive suspended sediment loads into fluvial systems. Suspended sediments elevate water turbidity, attenuating light penetration, suppressing primary production, and physically abrading delicate fish gills, which can induce respiratory asphyxiation. As these sediments settle, they smother coarse gravel substrates, burying benthic macroinvertebrate communities and destroying spawning grounds for lithophilic fish species.

V. PUBLIC HEALTH HAZARDS, CLINICAL PATHOLOGY, AND SOCIOECONOMIC DISPARITIES

Water pollution poses acute and chronic threats to global public health, operating through chemical ingestion, dermal contact, inhalation of volatilized compounds, and vector-borne exposures.



A. Toxic Inorganic Pathology: Nitrate, Fluoride, and Heavy Metals

- **Nitrate Toxicity (NO_3^-):** Ingestion of excessive nitrate in drinking water initiates a three-stage toxicological sequence. Primary toxicity causes direct mucosal irritation of the stomach and intestines, resulting in vomiting, diarrhea, and gastric pain. Secondary toxicity occurs when nitrate is biochemically reduced to nitrite (NO_2^-) by gastric bacteria or salivary enzymes. Nitrite oxidizes ferrous iron (Fe^{2+}) within hemoglobin to ferric iron (Fe^{3+}), generating methemoglobin—a modified protein incapable of reversible oxygen transport. In infants under 6 months of age, whose low gastric acidity facilitates bacterial reduction of nitrate, this process causes infantile methemoglobinemia ("Blue Baby Syndrome"), resulting in cyanosis, tissue hypoxia, and potentially death at concentrations exceeding the 10 mg NO_3^- -N/L maximum contaminant level. Tertiary toxicity stems from reactions between nitrite and secondary amines in the gut, synthesizing carcinogenic *N*-nitroso compounds (NOCs) associated with elevated rates of gastric, colorectal, and bladder cancers[cite: 6, 11].
- **Fluoride Pathology (F^-):** Although trace fluoride intakes (< 0.5–1.0 mg/L) aid in remineralizing dental enamel, chronic ingestion of concentrations above 1.5 mg/L causes dental fluorosis (permanent enamel mottling and pitting). Chronic consumption at levels exceeding 3.0–6.0 mg/L induces crippling skeletal fluorosis. Fluoride functions as a biochemical antagonist to calcium, precipitating out as insoluble calcium fluoride, which mobilizes mineral reserves from the skeleton. This leads to severe bone density alterations, ligament calcification, osteosclerosis, and irreversible structural deformities of the vertebral column and pelvic girdle. Fluoride also interferes with thyroid iodine uptake, exacerbating goiter endemicity in vulnerable populations.
- **Heavy Metal Toxicity:** Heavy metals are potent, non-biodegradable systemic poisons:
 - **Arsenic (As):** Ingested through groundwater, inorganic trivalent arsenite (As^{3+}) binds to cellular sulfhydryl enzyme groups, disrupting ATP production and DNA repair. Chronic arsenicosis manifests as palmar and plantar hyperkeratosis, dermal pigmentation changes, peripheral vascular gangrene ("Blackfoot disease"), and elevated risks of lung, bladder, liver, and skin cancers.

- o **Cadmium (Cd):** Discharged from electroplating, paint, and battery effluents, cadmium accumulates selectively in renal proximal tubules. Chronic exposure through irrigated rice paddies triggers proximal tubular nephropathy, osteomalacia, and severe bone fractures, clinically termed *Itai-Itai* ("ouch-ouch") disease.
- o **Lead (Pb):** Leached from aging distribution plumbing, lead disrupts heme synthesis by inhibiting delta-aminolevulinic acid dehydratase, inducing microcytic anemia, renal dysfunction, and permanent neurodevelopmental and cognitive deficits in young children.
- o **Mercury (Hg):** Bioaccumulated through aquatic food chains as monomethylmercury, this neurotoxin crosses both the blood-brain and placental barriers. It selectively destroys cerebellar Purkinje cells and cerebral cortical neurons, producing sensory constriction, ataxia, convulsions, and severe congenital neurological damage, as observed during the Minamata Bay disaster.

B. Waterborne Microbial Disease Burdens

Worldwide, microbial pathogens remain the leading cause of water-related morbidity and mortality. Fecal contamination of drinking supplies introduces enteric pathogens—including *Vibrio cholerae*, *Salmonella enterica* serovar Typhi, *Shigella dysenteriae*, *Escherichia coli*, Hepatitis A and E viruses, and protozoan cysts (*Cryptosporidium parvum*, *Giardia lamblia*).

These pathogens cause outbreaks of cholera, typhoid fever, bacillary dysentery, and acute gastrointestinal disease. Contaminated water supplies also expose communities to vector-breeding habitats for illnesses like dengue, yellow fever, and malaria, while water-contact parasite cycles drive diseases such as schistosomiasis. In developing regions lacking centralized sewage infrastructure, waterborne diarrheal illnesses account for roughly 1.1 million to 1.5 million deaths among children under five each year.

C. Epidemiological Profiling and Socioeconomic Asymmetries

Empirical field surveys demonstrate that the burdens of water pollution fall disproportionately on socioeconomically vulnerable populations. In the Turag River industrial corridor of Dhaka, Bangladesh, qualitative and quantitative surveys of riverside communities identified that more than 70% of local residents suffered from active skin ulcerations, contact dermatitis, diarrhea, or gastric ulcers.

Dermatological lesions—manifesting as painful boils, rashes, and chemical burns on the extremities—were directly linked to dermal contact with river water containing high concentrations of caustic soda and alkaline textile dyes. Local clinics reported that dermatological treatments were the highest-selling drugs in the area. Maternal health was similarly compromised: local health workers reported rising rates of premature births, anemia, cesarean deliveries, severe pregnancy edema, and stillbirths among women using contaminated river water[cite: 8].

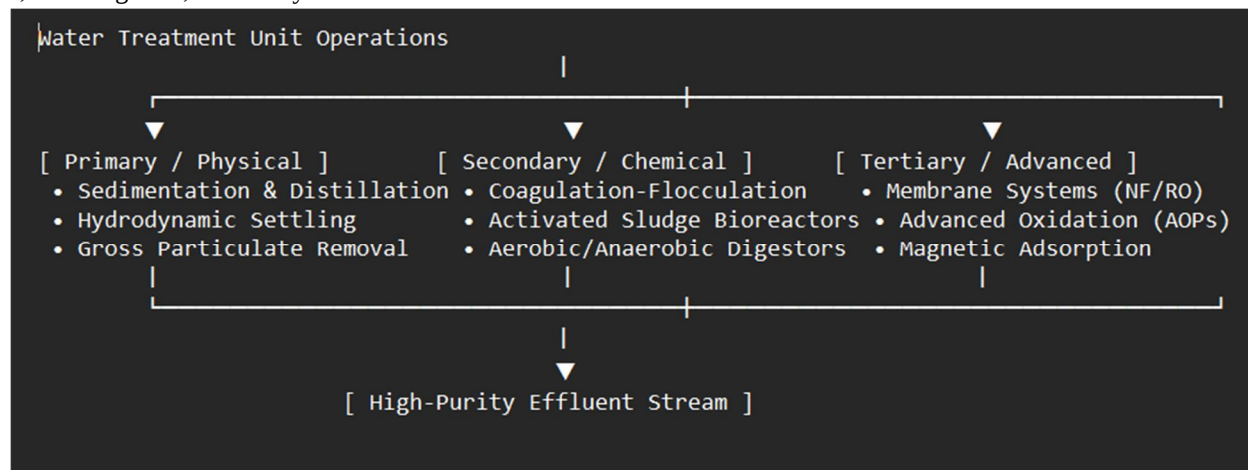
These clinical observations were systematically corroborated by a large-scale econometric and epidemiological study conducted by Wang and Yang using the China Health and Retirement Longitudinal Study (CHARLS) cohort ($N = 14,487$ participants across 51 representative cities):

- **Dose-Response Relationships:** Industrial water pollution intensity was significantly positively associated with physical and mental health deterioration. For each incremental rise in industrial water pollution intensity, self-reported poor physical health increased significantly (Adjusted Odds Ratio = 1.014, 95% CI: 1.006–1.022), while mental depression scores (assessed via the 7-item CES-D scale) deteriorated by 0.047 points ($p < 0.01$).
- **Contaminant-Specific Pathology:** Elevated concentrations of chemical oxygen demand (COD) and ammonia-nitrogen (NH_3-N) were associated with worse physical and mental health. Heavy metals (*Pb*, *As*, *Hg*) showed stronger links to mental health scores, reflecting the progressive, chronic neurotoxicity associated with low-dose elemental accumulation.
- **Socioeconomic Disparities:** The health impacts of water pollution were heavily stratified by household income. While high-income individuals exhibited lower overall susceptibility to ambient pollution fluctuations, low-income respondents experienced significantly greater physical degradation (OR = 1.012, $p < 0.05$) and sharper declines in mental health (coefficient = 0.045, $p < 0.01$). Affluent individuals could afford defensive adaptations—such as purchasing bottled water, installing domestic filtration systems, or moving away from industrial drainages.

In contrast, low-income households remained reliant on shallow, contaminated wells and degraded surface waters, creating an environmental justice divide where those with the fewest resources bear the highest toxicological burden.

VI. WASTEWATER TREATMENT TECHNOLOGIES: MECHANISMS, EFFICIENCIES, AND LIMITATIONS

Treating contaminated wastewater requires combining physical, chemical, and biological unit processes to remove suspended solids, nutrients, toxic organics, and heavy metals.



A. Physical Separation Technologies

Physical unit operations rely on mechanical forces and phase differences without altering the chemical composition of contaminants:

- **Sedimentation (Clarification):** Settles dense suspended solids and mineral silts under gravity. Although effective as a preliminary step, conventional sedimentation cannot remove colloidal particles, dissolved mineral salts, or soluble organic compounds.
- **Distillation:** Evaporates water into steam, leaving non-volatile minerals, metals, and biological agents behind before condensing the vapor into pure distillate. However, distillation cannot remove volatile organic compounds (VOCs) with boiling points below 100°C and requires high thermal energy inputs, limiting its use to specialized applications.
- **Membrane Separation:** Membrane processes apply hydrostatic pressure across selective, semipermeable barriers:
 1. *Microfiltration (MF)* and *Ultrafiltration (UF)* separate suspended particles and macromolecules (0.1–0.01 μm).
 2. *Nanofiltration (NF)* and *Reverse Osmosis (RO)* filter out multivalent ions, low-molecular-weight trace organics, and monovalent dissolved salts.

While membranes provide treated water of high purity without adding chemical coagulants, their broad-scale use is constrained by high power consumption, membrane fouling, pore scaling, and the challenge of managing concentrated reject brine streams.

B. Chemical Treatment Technologies

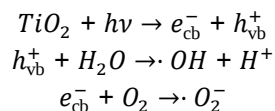
Chemical processes transform, neutralize, or precipitate hazardous dissolved constituents:

- **Coagulation and Flocculation:** Adding multivalent metal salts (aluminum sulfate, polyaluminum chloride, ferric chloride) hydrolyzes coagulants into positively charged complexes. These complexes neutralize the negative zeta potentials of suspended colloidal impurities, destabilizing their dispersion. Subsequent gentle mixing (flocculation) encourages these destabilized particles to aggregate into larger flocs that settle rapidly. While cost-effective for clarifying turbid, highly colored waters, this process generates chemical sludge that requires specialized dewatering and disposal.
- **Ion Exchange:** Relies on solid synthetic resin matrices with active electrostatic sites. Cation-exchange resins swap non-toxic ions (Na^+ , H^+) for polyvalent heavy metals (Ca^{2+} , Mg^{2+} , Cd^{2+} , Pb^{2+} , Ra^{2+}), while anion-exchange resins remove NO_3^- , F^- , and AsO_4^{3-} . Resin fouling by organic matter and the need for frequent chemical regeneration limit broad applicability.
- **Adsorption:** Adsorption on porous substrates is an effective method for binding toxic dyes, heavy metals, and persistent organics. Activated carbon derived from agricultural waste provides large internal surface areas for contaminant capture. Modern developments include magnetic nanocomposite adsorbents—such as iron oxide nanoparticles functionalized with polymers (chitosan, polyaniline)—which achieve rapid, high-capacity binding of metals and dyes and can be separated from the water stream using external magnetic fields.

C. Advanced Oxidation Processes (AOPs) and Photocatalysis

For recalcitrant organic contaminants that resist biological degradation, Advanced Oxidation Processes (AOPs) generate non-selective hydroxyl radicals ($\cdot OH$) with a high oxidation potential ($E^0 = 2.80$ V):

- Photocatalytic Degradation: Semiconductor materials—most notably titanium dioxide (TiO_2)—absorb photons of energy equal to or greater than their electronic bandgap, exciting electrons from the valence band to the conduction band and generating electron-hole pairs (e^- / h^+):



These reactive oxygen species mineralize complex organic contaminants (herbicides, antibiotics, textile azo dyes) into harmless end products (CO_2 , H_2O , and mineral acids)[cite: 14, 20].

- Solar-Assisted Systems: Pilot-scale testing demonstrates that solar photocatalysis coupling TiO_2 with sodium persulfate ($TiO_2/Na_2S_2O_8$) removes toxic insecticide residues (chlorantraniliprole, imidacloprid, thiamethoxam, and pirimicarb) and their transformation products from agricultural wastewater. Reclaimed agricultural runoff treated through solar AOPs has been successfully reused for crop irrigation without pesticide accumulation in soils or food plants. The primary industrial bottleneck remains the recovery and reuse of sub-micron catalyst particles from treated effluents.

D. Biological Treatment Technologies

Biological processes harness heterotrophic and autotrophic microbial communities to oxidize and assimilate organic matter and nutrients:

- Activated Sludge Processes: Wastewater passes through aerated biological basins where suspended bacterial flocs consume dissolved organic matter. The biomass oxidizes organic carbon into CO_2 and water while stabilizing organic nitrogen. Secondary clarifiers settle this microbial sludge, recycling a portion back into the aeration tank and routing the remainder to digestion.
- Coupled Algal-Bacterial Systems: Integrated photo-bioreactors leverage symbiotic gas exchanges between microalgae and aerobic bacteria. Microalgae generate dissolved oxygen through photosynthesis, which heterotrophic bacteria use to oxidize organic waste. In return, the bacteria release CO_2 , which fuels algal growth without requiring mechanical aeration, while harvesting the excess algal biomass provides a feedstock for biofuels, fertilizers, and animal feeds[cite: 14].
- Metagenomic Biomonitoring: Assessing biological wastewater performance has historically relied on culturing indicator bacteria (e.g., *E. coli*), a method that can yield false negatives when bacteria enter viable-but-non-culturable (VBNC) states and overlooks over 99% of unculturable environmental microbes.

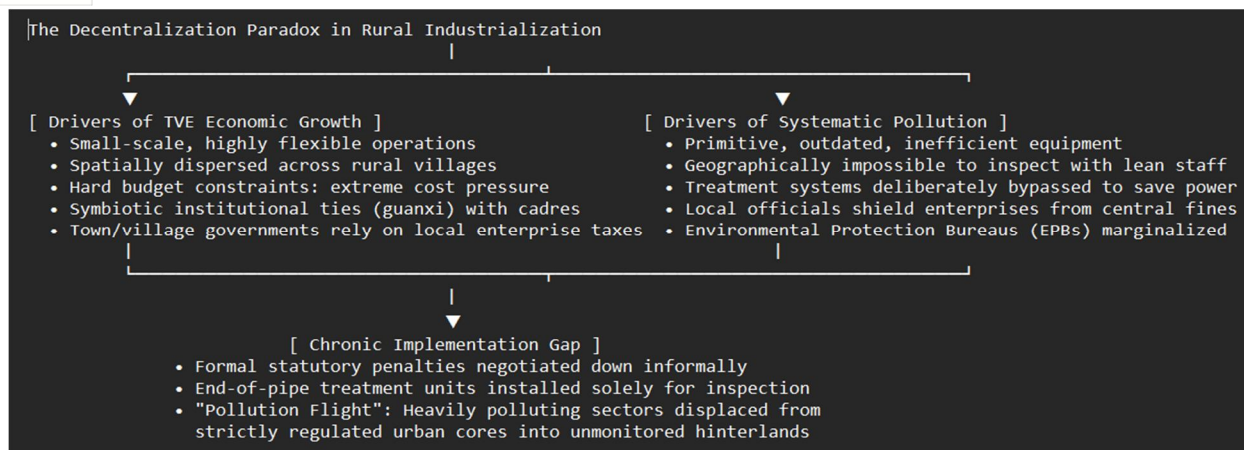
Modern high-throughput metagenomics uses 16S rRNA gene amplicon sequencing, rarefaction curves, alpha diversity metrics (Chao1, Shannon indices), and beta-diversity dissimilarity matrices to characterize environmental microbiomes. Metagenomic profiling maps the distribution of microbial taxa across pollution gradients, identifying functional metabolic pathways and monitoring the spread of antibiotic resistance genes (ARGs) within urbanized catchments.

VII. ENVIRONMENTAL GOVERNANCE, POLICY FRAMEWORKS, AND THE "IMPLEMENTATION GAP"

Tackling water pollution requires translating scientific principles into enforceable legal and regulatory policies. Across many emerging economies, however, a gap persists between environmental statutes and their practical enforcement.

A. The Decentralization Paradox: China's Township and Village Enterprises (TVEs)

China's experience with Township and Village Enterprises (TVEs) illustrates how industrial growth models can undermine environmental regulation. Following 1978 economic reforms, rural TVEs became engines of growth, employing over 135 million workers and generating over 30% of national GDP. However, this rapid growth created widespread environmental damage: TVEs discharged over 10 billion tons of untreated industrial wastewater annually, driving contamination across rural watersheds.

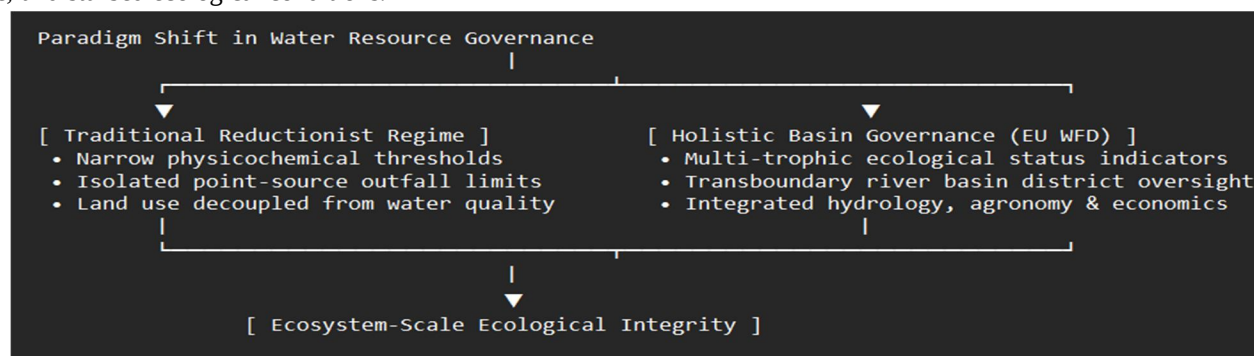


This persistent "implementation gap" is rooted in the structural incentives of local governance:

- **Hard Budget Constraints and Cost Externalization:** Unlike state-owned enterprises, TVEs operated with limited capital and little access to formal bank loans. Facing tight budgets and competitive pressures, rural plant operators had strong incentives to cut costs by discharging untreated effluents and refusing to operate wastewater treatment systems.
- **Spatial Dispersion vs. Regulatory Capacity:** Over 21 million small rural enterprises were dispersed across 43,000 towns and 730,000 villages. China's environmental monitoring staff numbered only ~46,000 inspectors, most stationed in urban centers. In Zhejiang Province, an environmental protection staff of 2,000 was responsible for monitoring over one million TVEs—an impossible ratio of 500 enterprises per inspector.
- **Institutional Collusion and Bureaucratic Structure:** Decentralization made township and village governments financially dependent on the taxes and extra-budgetary revenues generated by TVEs, which often provided up to 80% of local public budgets. Village cadres frequently served as enterprise managers or guarantors for corporate loans. In China's governance matrix, local Environmental Protection Bureaus (EPBs) were subordinate to the county and township magistrates who controlled their funding and promotions. Because local officials were evaluated primarily on regional GDP growth rather than environmental metrics, cadres shielded polluting TVEs from enforcement. Pollution levies were routinely negotiated down through informal networks (*guanxi*), and managers were often warned before scheduled inspections so they could temporarily halt polluting processes.
- **Pollution Flight:** Stricter enforcement in major metropolitan centers like Shanghai pushed heavily polluting facilities into surrounding rural areas with lower enforcement capacity. Urban factories also sold outdated, non-compliant equipment to rural TVEs, relocating industrial pollution into unmonitored rural areas.

B. Holistic Catchment Governance: The EU Water Framework Directive (WFD)

Passed in December 2000, the European Union's Water Framework Directive (2000/60/EC) moved away from piecemeal, chemical-specific discharge limits toward holistic catchment-scale ecological quality. The WFD required all member states to restore surface and groundwater bodies to "good ecological status" by 2015. It defines good ecological quality as having minimal deviation from pristine, undisturbed ecological conditions.

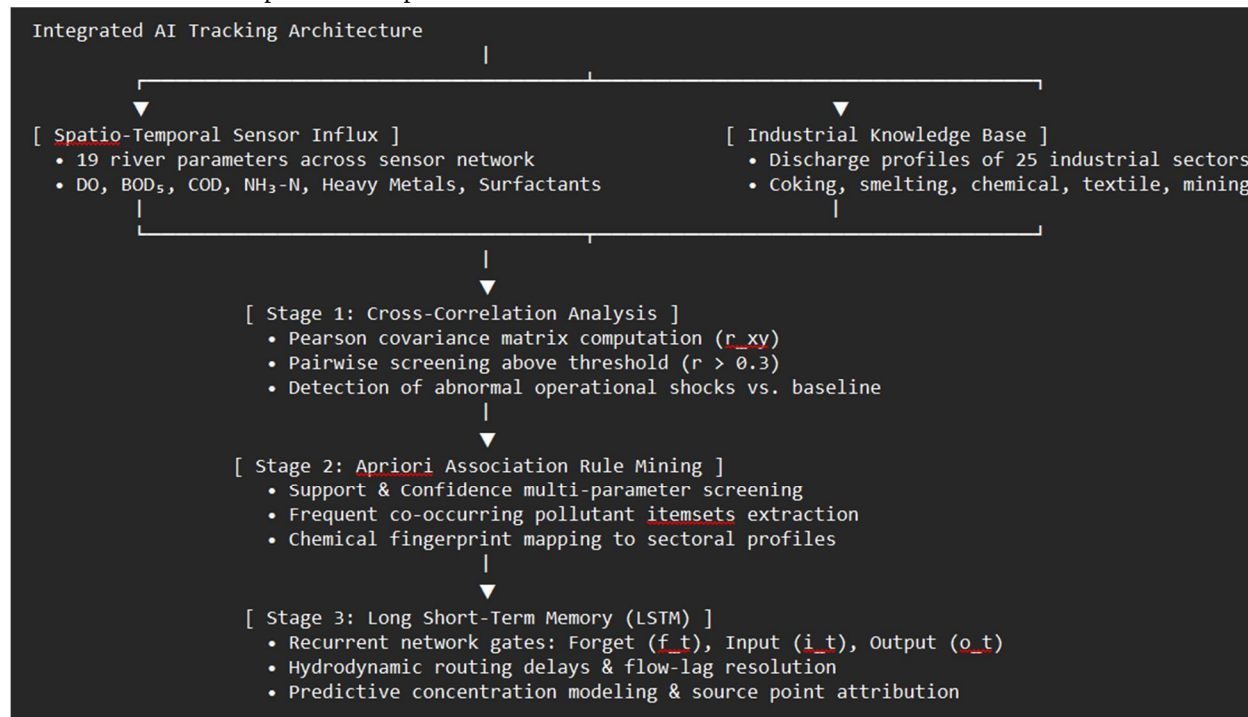


The WFD highlights a critical challenge for intensively farmed landscapes. Standard arable agricultural soils inevitably leach roughly $25 \text{ kg N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$, resulting in baseline stream concentrations of at least $10 \text{ mg NO}_3\text{-N/L}$.

Restoring shallow lakes and lowland rivers to diverse macrophyte and invertebrate communities requires lowering winter nitrate maxima down to $1\text{--}2 \text{ mg NO}_3\text{-N/L}$. Simple mass balance calculations show that achieving this target using wetland buffer strips would require converting up to 80% of current arable agricultural land into permanent riparian buffer zones. This underscores the trade-off between modern agricultural production and river restoration.

C. Innovative Monitoring: Deep Learning and Source Tracking

To overcome the limitations of manual water inspections, recent advances deploy artificial intelligence (AI) and data mining architectures to track industrial point-source polluters across river basins:



- 1) Cross-Correlation Mapping: Calculates the covariance and correlation coefficient (r_{xy}) across monitoring indicators without needing detailed hydraulic flow simulations:

$$r_{xy} = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$

Pairs with $r_{xy} > 0.3$ reflect common industrial sources. For example, strong correlations between BOD₅ and COD_{Mn} ($r = 0.70$) reveal volatile organic industrial effluent releases, whereas correlations between Cd and Pb ($r = 0.96$) capture discharges from battery, smelting, and pigment production facilities.

- 2) Apriori Association Rule Mining: Uses the Apriori algorithm to identify frequent pollutant itemsets across monitoring networks based on support and confidence metrics:

$$\text{Support}(X, Y) = P(XY) = \frac{\text{count}(XY)}{N}$$

$$\text{Confidence}(X \rightarrow Y) = P(Y|X) = \frac{P(XY)}{P(X)}$$

Frequent multi-pollutant itemsets are matched against an industrial emission database covering 25 manufacturing sectors, pinpointing the facilities responsible for observed pollution patterns.

- 3) Long Short-Term Memory (LSTM) Networks: Water pollutants travel downstream with variable hydrological transport times, creating time-lagged relationships between point discharges and downstream sensor readings. Standard feedforward neural networks cannot resolve these long temporal dependencies.

An LSTM network uses specialized internal gating cells—comprising a forget gate (f_t), input gate (i_t), and output gate (o_t)—to regulate information flow across time:

$$\begin{aligned} f_t &= \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \\ i_t &= \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \\ \tilde{c}_t &= \tanh(W_c \cdot [h_{t-1}, x_t] + b_c) \\ c_t &= f_t \cdot c_{t-1} + i_t \cdot \tilde{c}_t \\ o_t &= \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \\ h_t &= o_t \cdot \tanh(c_t) \end{aligned}$$

Applied across the river basins of Shandong Province, China, this cross-correlation–Apriori–LSTM framework achieved prediction accuracies of 0.95 to 1.00 in tracing downstream water quality changes back to upstream industrial sources (petrochemicals, metal smelting, coking). These algorithmic frameworks provide environmental regulators with objective, real-time tools to identify illicit discharges and address historic monitoring deficits[cite: 15].

VIII. INTEGRATED MITIGATION AND REMEDIATION STRATEGIES

Addressing global water pollution requires coordinated interventions spanning on-farm practices, engineering solutions, nature-based infrastructure, and community participation.

A. On-Farm and Watershed Management

Agricultural pollution control requires integrating soil conservation with source-reduction techniques:

- **Balancing Erosion Control with Leaching Prevention:** To prevent conservation tillage from accelerating nitrate leaching into aquifers, farmers should set realistic yield goals, conduct soil and manure nutrient testing, and adjust fertilizer applications for organic carryover from cover crops and residues.
- **Water-Saving Irrigation:** Conventional flood irrigation wastes water, promotes soil salinization, and accelerates agrochemical runoff. Advanced irrigation strategies—such as deficit irrigation (DI) and partial root-zone drying (PRD)—alternate wetting and drying across root zones. PRD triggers hormonal stress responses (such as root-derived abscisic acid) that induce stomatal closure, reducing transpiration and improving water-use efficiency without lowering crop yields or washing nitrates into groundwater[cite: 4].
- **Precision Agrochemical Application:** Replacing broadcast fertilizer spreading with subsurface injection reduces volatile ammonia emissions and dissolved nutrient runoff. Implementing Integrated Pest Management (IPM)—using biological predators, pest traps, and crop rotations—reduces reliance on persistent synthetic biocides.

B. Nature-Based Solutions and Green Infrastructure

Nature-based systems utilize natural processes to filter and buffer runoff across landscapes:

- **Riparian Buffer Strips and Constructed Wetlands:** Vegetated riparian buffer strips along farm edges and river corridors intercept sediment, promote microbial denitrification, and trap particulate phosphorus. Multi-stage constructed wetlands slow stormwater runoff, allowing suspended solids to settle while wetland plants and root biofilms absorb nutrients and break down organic pollutants.
- **Urban Green Infrastructure:** Expanding urban green infrastructure helps reduce stormwater surges. Replacing impermeable concrete with permeable pavements, bioswales, retention ponds, and green roofs increases rainfall infiltration and recharges local aquifers. This reduces peak urban storm runoff and prevents combined sewer overflows (CSOs) from discharging untreated municipal sewage into adjacent waterways.

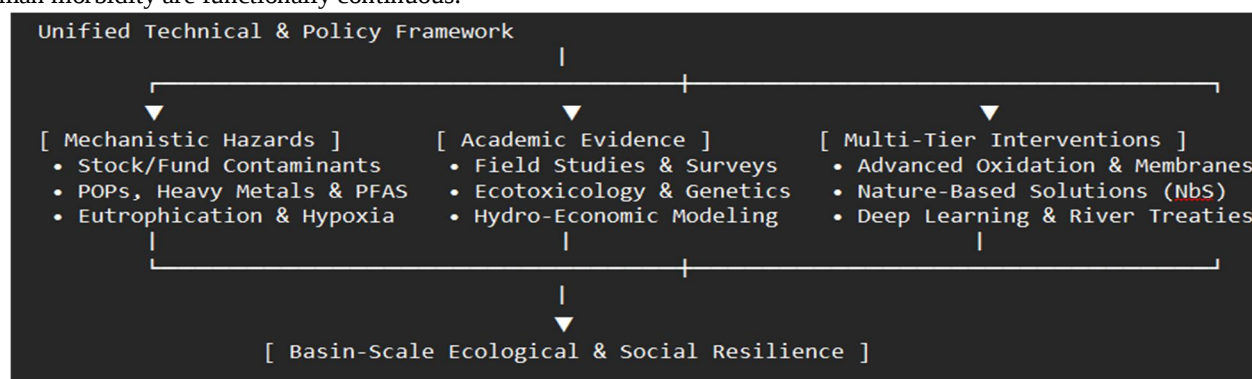
C. Regulatory Enforcement, Economic Instruments, and Education

Policy measures provide the institutional framework needed to sustain technical interventions:

- The Polluter-Pays Principle: Environmental levies must be set higher than the marginal operating costs of wastewater treatment facilities to eliminate the incentive for operators to bypass treatment systems. Making corporate officers legally and financially accountable strengthens compliance.
- Comprehensive Water Quality Standards: Regulatory frameworks must expand beyond basic physical parameters (pH, DO, BOD) to include enforceable limits for persistent organic pollutants, trace heavy metals, and emerging contaminants[cite: 17].
- Targeting Environmental Disparities: Given that low-income households bear a disproportionate burden of waterborne disease, public investments should prioritize drinking water treatment, deep tube-well installations, and basic sanitation across underserved rural and peri-urban areas.
- Community-Based Environmental Education: Formal environmental education helps build local stewardship. Educational initiatives should train agricultural producers in responsible agrochemical management, instruct urban communities in waste minimization and plastic recycling, and support community-based monitoring programs.

IX. SYNTHESIS AND GLOBAL PERSPECTIVES

The evidence synthesized across these 20 foundational investigations demonstrates that freshwater pollution is an interconnected systemic crisis. The pathways linking upstream industrial, urban, and agricultural land use to downstream ecological degradation and human morbidity are functionally continuous.



The fundamental driver of this persistent crisis remains the disconnect between economic growth strategies and ecological constraints. In rural industrial economies, such as China's TVE boom, the institutional structures that fueled rapid local development—decentralized fiscal incentives, small-scale industrial operations, and close ties between local officials and enterprise managers—directly fostered widespread water degradation.

Similarly, globalized agricultural trade often externalizes environmental burdens, driving high nitrogen use and water pollution across major agricultural river basins in Asia and Latin America to support international supply chains[cite: 12].

Solving these systemic challenges requires moving beyond narrow, end-of-pipe technical fixes[cite: 5]. While advanced engineering solutions (reverse osmosis, solar photocatalysis, magnetic nanocomposites) and digital tracing tools (cross-correlation, Apriori mining, LSTM neural networks) are vital components of modern pollution management, they must be supported by broader institutional reforms:

- 1) Catchment-Scale Ecological Regulation: Water policy must move away from single-substance laboratory standards toward holistic, basin-scale frameworks aligned with the EU Water Framework Directive. Environmental protection agencies must operate with independent horizontal authority, backed by pollution levies that reflect true ecological and public health remediation costs.
- 2) Transforming Agricultural Policy: Non-point source pollution control requires integrating soil conservation with input-side nutrient management[cite: 10]. Combining realistic crop yield targets, soil nutrient testing, water-saving irrigation (such as PRD), and riparian wetland buffer strips helps mitigate both surface runoff and groundwater leaching.
- 3) Addressing Socioeconomic Vulnerability: Because industrial pollution disproportionately impacts lower-income communities, environmental protection must be treated as an essential component of public health and social equity. Expanding centralized drinking water infrastructure and prioritizing remediation in vulnerable communities are critical steps toward reducing environmental injustice[cite: 16].

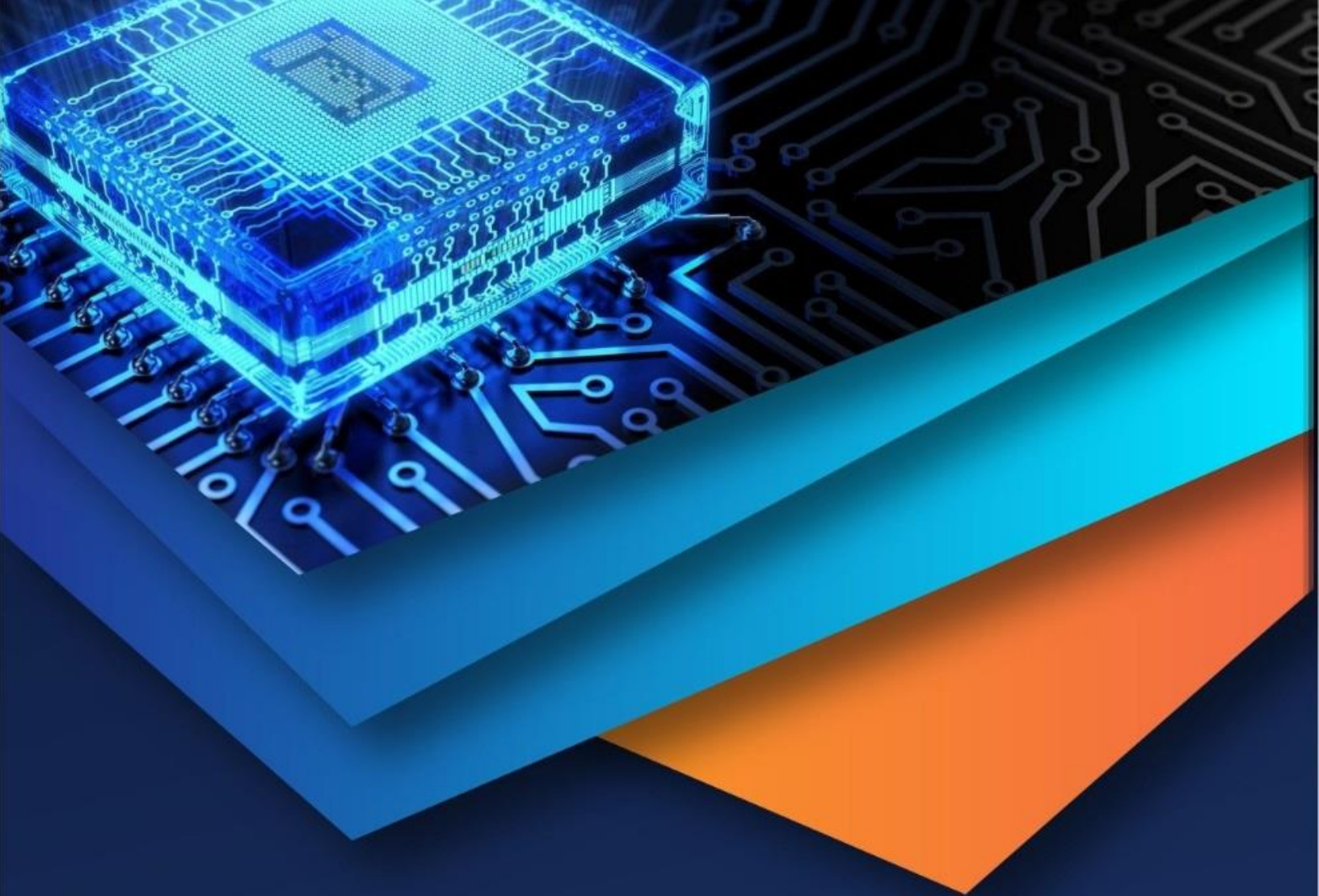
- 4) Transparent Data and Civic Engagement: Effective water resource management depends on open environmental data, metagenomic water quality monitoring, and widespread public education. Educating communities and giving civic organizations a voice in resource decisions helps build lasting local stewardship.

Securing global freshwater resources in the 21st century requires balancing human development with ecological boundaries.

Integrating advanced environmental engineering, predictive machine learning, and catchment-scale ecological policies offers a viable path toward protecting global freshwater security and public health for generations to come.

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