# Ecotoxicology and water pollution - fish disease

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**Abstract:** This article traces the evolution of water toxicology into water eco-toxicology, demonstrating how early enthusiasm for protecting aquatic environments laid the foundation for the contemporary multidimensional field. The interchangeability of terms, such as "water toxicology" and "eco-toxicology," is explored, with a focus on key concepts and the contributions of notable researchers. Despite limitations in comprehensive coverage, the article highlights the ongoing relevance of water toxicology challenges and future directions in water eco-toxicology research. Keywords: Water Toxicology, Eco-Toxicology, Environmental Protection, Interchangeability of Terms, Notable Researchers, Evolution, Aquatic Environments, Key Concepts, Challenges, Future Directions.

## 1 Introduction

The theme of ecotoxicology and water pollution remains relevant and crucial in the context of contemporary environmental challenges. With the increase in anthropogenic activities on the planet, the source of water pollution intensifies with various toxic substances such as heavy metals, chemical compounds, pesticides, and other anthropogenic residues. These pollutants can have a negative impact on aquatic ecosystems and living organisms, including fish, which serve as sensitive indicators of the state of aquatic environments.

The primary challenges in this field involve not only identifying various pollutants in water but also assessing their impact on the health of aquatic organisms, including fish. Ecotoxicological studies contribute to understanding the mechanisms of pollutants' effects on biological systems and provide a foundation for developing strategies to manage water resources.

Furthermore, considering climate change and the increased stress on water systems, issues related to ecotoxicology and water pollution take on new dimensions. For instance, changes in temperature regimes and water levels can influence the migration of pollutants and their impact on aquatic ecosystems. Such changes require a deeper understanding of the interactions of factors affecting water systems and their effects on the health of aquatic organisms.

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Thus, research in the field of ecotoxicology and water pollution remains pertinent and holds significant importance for ensuring sustainable management of water resources and the preservation of biodiversity in aquatic ecosystems.

Since the 1970s, the term "Ecotoxicology" has been introduced in literature. Initially defined as a scientific discipline studying the "effects of chemical and physical agents on living organisms, especially on populations and communities in specific ecosystems, including the pathways of these agents' transport and their interaction with the environment" [Truhaut, 1977]. Subsequently, various definitions of ecotoxicology have been proposed, but they all converge on it being a scientific field examining the interaction of potentially toxic substances, polluting the environment, with the abiotic components of ecosystems and their inhabitants. These interactions are analyzed at both the individual and biological community levels. It is crucial to note that ecotoxicology does not address medical issues. In the context of the hydrosphere, aquatic ecotoxicology encompasses a developed branch of aquatic toxicology, intersecting with the interests of sanitary hydrobiology, general ecology, and geochemistry.

In brief, the scope of aquatic ecotoxicology covers the following aspects. It represents a branch of ecology focusing on the occurrence of potentially toxic substances in ecosystems. As part of general toxicology, aquatic ecotoxicology deals with studying the toxic effects on aquatic organisms. It also serves as a section of aquatic toxicology dedicated to nature conservation aspects in the context of water pollution with toxic substances.

## 2 Materials and Methods

In its research, ecotoxicology draws upon the experience of classical toxicology and ecology, providing opportunities for both autecological and synecological approaches. The autecological approach analyzes the fate of an organism and its interaction with the environment against the backdrop of exposure to toxic substances. Meanwhile, the synecological approach examines the impact of environmental pollution on populations and communities.

However, experience indicates that currently predicting the development of ecological processes under chemical exposure, based on changes in individual specimens of a species, is characterized by a low level of reliability. While specific changes may explain more general phenomena, they can only provide relatively accurate predictions of the development of processes in more complex biosystems in rare cases.

Explaining the fundamental principles and patterns of the pollutant effect aims to deepen the understanding of ways to address specific challenges in the field of protecting the aquatic environment from pollution. The term "environment" is often associated with the immediate surroundings where humans live and work. However, for an ecologist, the "environment" encompasses the habitat of any living being, and pollution is considered not only from the perspective of assessing the threat to human health but also considering potential indirect consequences for individual species, biocenoses, and the overall life on Earth, including the existence and development of humans as a species. This comprehensive approach requires the study of the impact of toxic substances on organisms of various systematic positions, often significantly differing from each other in structure and lifestyle.

Changes in biocenoses under the influence of environmental pollution lead to alterations in the habitat of living beings, sometimes even causing ecocide.

These changes affect humans, manifesting in the deterioration of water quality, reduction in the industrial productivity of water bodies, and deterioration of product quality. Food and clean water are vital resources, the essence of which cannot be compared with values associated with other human needs. In the near future, the creation of products capable of fully replacing natural food seems unlikely. Given the Earth's growing population and the increasing volumes of industrial production, issues related to food, clean water, and the atmosphere will only intensify. Therefore, evaluating the biological consequences of environmental pollution should be conducted with consideration for this perspective. Among the research tasks addressing this issue, along with the necessity of preserving the biological norm, attention should be paid to ensuring the economic norm of the state of aquatic biota in conditions of pollution.

## 3 Results

The practice of thematic forums in recent years attests to the ongoing relevance of issues in aquatic toxicology. Over the past decade, nationwide conferences on aquatic ecotoxicology have been held, dedicated to the memory of B.A. Flerov, on the topic of "Anthropogenic Impact on Aquatic Organisms and Ecosystems" (IBW RAS, 2002, 2005, 2008, 2011, 2014), as well as the international conference "Biodiagnostics-13" and symposium "Biodiagnostics-16" (MSU, 2013, 2016).

Discussions at these events focused on the methodology for assessing the ecological consequences of pollution, the concept of ecological regulation, and the characterization of controlled sources of impact. Issues were addressed regarding their influence on the ecological condition of soils, water, and air, as well as the results of biotesting using zoo-, phyto-, and microbiotic, as well as molecular-genetic indication in natural, agricultural, and urban ecosystems.

Questions of the informativeness and reproducibility of biotesting results in various application areas were discussed, along with approaches to integrating data from chemical, toxicological, and ecological studies to form an ecological regulation system [Grigoryev et al., 2014].

The number of potential pollutants in the aquatic environment requiring toxicological studies is increasing, including nanomaterials [Kukla et al., 2014; Tomilina et al., 2014; Ipatova et al., 2016] and pharmaceuticals [Barenboim, Chiganova, 2014]. As biotesting has become a universal tool for assessing environmental quality, more specific questions arise regarding the principles of selection and use of biological and ecological systems in the process of environmental quality regulation, toxicological control, and bioindication, as well as the standardization of methods and measurements. Special attention is given to the creation of a unified database of standardized test cultures necessary for practical toxicity monitoring of environmental objects.

This article provides a retrospective aimed at demonstrating how, from the initial enthusiasm of the first researchers advocating for the protection of the aquatic environment from pollution, a multifaceted scientific and applied field—"aquatic toxicology"—has emerged. This field, in turn, served as the basis for the emergence and development of "aquatic ecotoxicology."

At times, the terms "aquatic toxicology" and "ecotoxicology" are considered interchangeable. Initially, ecotoxicology, as a research area, was delineated by R. Truhaut [Truhaut, 1975]. In the context of the aquatic environment, particular attention is given to aquatic ecotoxicology [Moiseenko, 2009]. However, to briefly define the scope of aquatic ecotoxicology, the following aspects can be highlighted. It is a part of ecology that explores the emergence of potentially toxic substances in ecosystems, a component of general toxicology studying the interactions of aquatic organisms and communities with potentially toxic substances, and, finally, a segment of aquatic toxicology dedicated to nature conservation in the context of water pollution by toxic substances.

Clearly, the limited scope of this article does not allow for a more detailed examination of the successive stages of the issues related to water pollution and the acknowledgment of all researchers who have contributed to shaping the contemporary landscape of Russian aquatic ecotoxicology.

**Table 1**. A structured overview of the stages of development, key concepts and well-known researchers in the evolution of aquatic toxicology to aquatic ecotoxicology.

| Stage of Development | Key Concepts | Notable Researchers |
|---|---|---|
| **Early Enthusiasm** | Protection of aquatic environment, pioneers in water pollution defense | Pioneering researchers advocating for water quality protection |
| **Formation of Water Toxicology** | Emergence of "water toxicology" as a multidimensional scientific-applied field | Establishment and evolution of "water toxicology" |
| **Rise of Eco-Toxicology** | Development of "eco-toxicology" as a natural progression from water toxicology | Recognition and expansion of eco-toxicology |
| **Interchangeability of Terms** | Occasionally interchangeable use of "water toxicology" and "eco-toxicology" | Acknowledgment of interchangeable terminology |
| **Founding Researchers** | Recognition of R. Truhaut (1975) as a pioneer in defining eco-toxicology | R. Truhaut and other early contributors to eco-toxicological research |
| **Focus on Water Eco-Toxicology** | Special attention to water eco-toxicology concerning aquatic environments | Moiseenko's (2009) contributions to water eco-toxicology |
| **Scope of Water Eco-Toxicology** | Examining potential toxic substances in ecosystems, studying interactions with aquatic organisms, and addressing nature conservation aspects | Research on water eco-toxicology encompassing multiple dimensions |
| **Limitations of the Article** | Constraints on detailing all stages and acknowledging every contributor | Inability to comprehensively cover the development of water eco-toxicology |
| **Future Challenges** | Continued relevance and expansion of water toxicology challenges | Ongoing challenges and future directions in water eco-toxicology research |

Many pollutants have both direct and indirect impacts on the behavior of terrestrial and aquatic organisms. Specifically, fish behavior is significantly affected by various inorganic and organic pollutants, influencing a range of activities such as movement, exploration, avoidance, sociability, aggressiveness, sexual and feeding behaviors (summarized in Table 1). Some studies have also explored the impact of contaminants on behavioral types or personalities, reflecting consistent interindividual variations in behavior. Additionally, pollutants have been shown to affect fish cognitive performance, potentially leading to cascading effects on fitness.

These behavioral changes are often linked to alterations in cholinesterase activity, neurotransmitter levels, or hormone levels. For example, the carbofuran pesticide can disrupt neurofunction and activity in sea bass, while the antidepressant fluoxetine (Prozac) can affect aggression, boldness, and learning in Siamese fighting fish by altering the serotonin system. Other behavioral shifts may be indirectly related to changes in energetic balance, driven by the costs of detoxification and stress responses. For instance, low doses of pesticides have been associated with decreased activity in goldfish, likely due to increased detoxication and physiological defense costs.

Interestingly, pollution-induced behavioral changes could potentially lead to positive feedback loops, further increasing exposure to pollution and exacerbating its negative effects on fish fitness. However, existing evidence for this phenomenon is largely indirect. Spatial behaviors, such as activity, exploration, and avoidance, are particularly impacted by pollution, influencing traits essential for gathering information about the environment. Social interactions are also often disrupted, potentially affecting social learning and information acquisition from conspecifics.

Contaminants significantly impact spatial cognitive abilities, including spatial memory and spatial learning, with potential consequences for fish adaptation to new environments. Dispersal and migration are also affected, potentially altering animal exposure to pollution. For example, pesticides and pharmaceuticals can influence downward migration and homing behaviors in salmonid fish, potentially exposing them to higher pollution levels if they cannot return to their clean home river.

Pollution's influence extends to fish boldness, appetite, and foraging patterns, which can affect their susceptibility to dietary contamination. For instance, perch exposed to psychiatric drugs exhibited increased activity and boldness, leading to a higher foraging rate on zooplankton carrying accumulated drugs. Organisms exposed to pollutants often have higher metabolic rates and greater energetic needs, potentially increasing their activity and foraging, and consequently, their exposure to dietary-transmitted pollutants.

In summary, pollution-induced alterations in exploration, sociability, memory, learning, appetite, boldness, and foraging may amplify fish exposure to environmental or dietary contamination, creating positive feedback loops with significant implications for fish fitness. However, the current evidence is largely indirect, necessitating further experimental studies to test these hypotheses.

Human activities serve as a source of numerous organic and inorganic pollutants, such as plastics, pharmaceuticals, pesticides, and metals, exerting negative impacts on terrestrial and aquatic ecosystems. However, the accuracy of predicting their effects on the wild environment is constrained by scientific challenges. While direct impacts of pollutants on animal physiology and mortality have been included in routine ecotoxicological studies, more complex behavioral effects on personality and cognition in animals, especially in wild species and multi-stress conditions, have been less extensively examined. Additionally, the connections between behavioral changes, cognitive indicators, and individual fitness are rarely considered in studying pollutant effects, limiting our ability to predict the cascading long-term influence of human activities on population resilience and evolutionary trajectories.

In this context, we analyze existing literature on fish to investigate the behavioral effects of pollutants under multi-stress conditions. Fish are widely used for behavioral and cognitive analyses and serve as focal subjects in ecotoxicology studies. Here, we synthesize (non-exhaustively) available data on the behavioral impact of pollutants on wild fish. While ecologically relevant pollution levels were employed in most previous studies, they evaluated only the consequences of pollution within a single stress framework. However, pollution effects are often modulated by the concurrent influence of other natural or anthropogenic stressors in the wild, leading to synergistic interactions and/or intensified impacts on fish fitness. Nevertheless, empirical data on the influence of multi-stress on fish behavior remains scarce. Furthermore, strong correlations between different traits are often observed, but most studies measure behavioral traits in isolation, and the impact of pollutants on the syndrome structure remains unclear.

**Table 2.** A structured overview of the stages of development, key concepts and well-known researchers in the evolution of aquatic toxicology to aquatic ecotoxicology.

| Year | Event/Discovery | Researcher(s) | Significance/Impact |
|---|---|---|---|
| **1960s** | Initial studies on water pollution | Enthusiast researchers | Ignition of interest in pollution issues |
| **1975** | Establishment of ecotoxicology as a field | R. Truhaut | Defining a new research direction |
| **2009** | Emphasis on water ecotoxicology | Moiseenko and colleagues | Integration of nature conservation aspects into water toxicology |
| **2023** | Retrospective article on water ecotoxicology | Article author | Emphasizing the importance of the history and development of this field |

Lastly, most previous studies used domesticated species or representatives from a single population of wild species, limiting consideration of inter-population variability and the evolution of behavioral reactions to pollution. Investigating the impact of pollutants on fish fitness through changes in behavior and cognitive functions in wild populations and their evolutionary consequences thus presents an exciting scientific challenge for the coming decades.

Instead of being one-dimensional, animal personalities often consist of sets of interconnected traits known as behavioral syndromes. These syndromes, such as boldness, exploration activity, and sociability in fish, are essential for fitness and evolutionary trajectories. For instance, three-spined sticklebacks with bold and aggressive traits are more likely to evade predator attacks, leading to higher fitness compared to other trait combinations. Behavioral syndromes also play a crucial role in information use and learning. It is important to consider these syndromes as they can help predict the impact of stressors on fish's physical form and cognition.

Various mechanisms, such as genetic linkage, correlational selection, resource allocation compromises, genetic or physiological pleiotropy, tightly link physiological traits and personality traits in fish. For example, trout lines selected for low stress reactions exhibit lower cortisol production and higher metabolism, along with being bolder and more aggressive, indicating an interplay between stress reactions and energy-related behaviors in fish.

Since pollutants often induce significant stress reactions and metabolic changes, they can influence the structure of behavioral syndromes, impacting cognitive abilities and responses to environmental signals. Pollution can trigger stress responses, affecting energy status, energy consumption, and metabolism. Thus, pollution may alter energy distribution among traits, creating the potential for divergence in the correlation between physiology and behavior.

On one hand, stressors can have a revealing impact on syndromes, reinforcing trait connections. Conversely, adverse neurophysiological effects of stressors may limit fish's ability to express a full range of behavior, reducing observed phenotypic variations and masking any links between traits apparent under mild or single stressor conditions.

The influence of pollution on syndromes is not yet clear and warrants further investigation. Existing literature suggests that pollutants do influence syndrome structure, affecting physiological and behavioral connections. However, specific effects seem to depend on the nature/dose/duration of stressors.

Additionally, the syndrome structure may be shaped by past natural selection and have significant consequences for evolutionary trajectories. Natural selection may favor specific combinations of physiological, behavioral, and cognitive traits. The impact of pollution on the evolution of behavioral reactions in wild fish populations remains largely unexplored, and further research is essential to refine our ability to predict the evolutionary effects of pollution on behavior.

It is intriguing that the growing body of work in the field of evolutionary ecotoxicology indicates diverse responses of certain fish populations to experimental pollution under conditions of chronic exposure to pollutants. These phenomena suggest potential local adaptation to the influence of pollutants. For instance, killifish (Fundulus heteroclitus) from heavily polluted environments develop genetic and physiological mechanisms for more efficient processing of organic pollutants. However, research on the impact of pollution on behavior shows some variability, and empirical evidence of behavioral local adaptation to pollution through genetic evolution and/or plasticity remains insufficient.

Consider the example of brown bullhead (Ameiurus nebulosus) from a polluted river, which exhibited increased aggressiveness compared to fish from an unpolluted environment. However, in this case, it is challenging to distinguish between the genetic and plastic components of the observed behavioral diversity in the F0 generation, limiting the ability to predict the consequences of pollution for future generations. In another case, guppies (Poecilia reticulata) from Trinidadian rivers contaminated with polycyclic aromatic hydrocarbons showed reduced exploratory activity compared to fish from uncontaminated rivers after several generations in common holding conditions, indicating genetic differences in behavior between populations. However, other studies with the same model species suggest a lack of evidence for adaptive plasticity, especially in unpolluted environments.

Furthermore, the distinction between the evolutionary effects of pollutants and other environmental stressors remains complex, likely due to the fact that numerous stressors can exert conflicting selective pressures. Adaptation to one stressor, for example, may interfere with adaptation to another, complicating the prediction of the consequences of pollutant exposure in different environments.

The difficulty in distinguishing the effects of pollutants from other stressors is also associated with the fact that some stressors may have conflicting impacts. For instance, tolerance to pesticides in some amphibians and crustaceans is associated with increased susceptibility to diseases. Populations of European flounder (Platichthys flesus) living in polluted rivers demonstrate lower resistance to heat stress, although the mechanisms of these changes are yet to be determined. However, some physiological adaptations to one stressor may confer advantages in the face of additional stressors.

Finally, plasticity, including behavioral plasticity, plays a crucial role in evolutionary responses to anthropogenic conditions. Behavioral changes can either drive evolutionary processes under new conditions (the so-called "behavioral drive") or, conversely, limit evolutionary changes if behavioral plasticity is sufficient to mitigate the consequences of pollution. Plastic behavioral responses to pollution may differently impact genetic selection depending on environmental conditions, requiring further research to understand their role in the adaptive landscape. However, new pollutants such as pesticides, pharmaceuticals, plastics, and nanoparticles represent novel chemical agents that fish have not encountered in their evolutionary history.

Therefore, the evolution of behavioral responses to pollution may introduce its own complexities into the adaptive landscape.

Thus, pollution-induced behavioral changes may potentially generate inadequate effects and evolutionary traps, although this hypothesis remains to be tested.

In conclusion, ecotoxicology and water pollution have a significant impact on the health of fish and the overall ecosystem of aquatic environments. Research shows that water pollution with various toxic substances, such as heavy metals, pesticides, and petroleum products, can lead to the development of various diseases in fish.

Factors such as changes in the chemical composition of water, temperature fluctuations, and the loss of natural habitats are associated with the increased spread of diseases among fish. This not only threatens fish populations but also the aquatic habitats as a whole.

It is important to note that the effects of water pollution on fish health have long-term consequences and can create a chain reaction in the aquatic ecosystem. Managing and reducing water pollution become extremely important for maintaining biodiversity and ensuring the sustainability of aquatic ecosystems.

## 3 Conclusion

In conclusion, the existing literature emphasizes the need to consider pollution and its associated behavioral, cognitive, and fitness effects in a multi-stress context to better understand the complex responses of wild fish to pollution and their potential feedback cycles. Additionally, pollutants and multiple stressors may influence the link between physiology and behavior, altering the structure of the syndrome, leading to disparities between behavioral and personality disorders. Future work should now aim to identify the evolutionary forces contributing to such behavioral variability in the face of increasing pollution and their impact on the evolutionary trajectories of wild populations. Through this research, we hope to encourage future studies that bridge the gap between ecotoxicology, behavioral ecology, and evolutionary ecology to better predict the impact of pollutants on evolutionary processes and population resilience in anthropogenically altered ecosystems.

Fish diseases caused by ecotoxicological factors serve as indicators of problems in the water environment. Developing strategies to reduce pollution and support the health of aquatic organisms becomes an integral part of sustainable water resource management. Only through joint efforts of society, the scientific community, and governments can we ensure the preservation and restoration of the health of aquatic ecosystems and prevent further threats to fish and the environment.

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