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Water Contamination and Pollution Due to Radioactive Materials, Natural and Anthropogenic Sources, and Their Health Impacts: A Review

Aluvihara S[a]*, Pestano-Gupta F[b], Omar MH[c], Alam SF[d], Ghani AA[e], Hilonga A[f], Abdulaali HH[g]

[a]Department of Chemical and Process Engineering, University of Peradeniya, Peradeniya, 20400, Sri Lanka
[b]Division of Natural Sciences, Berbice Campus, University of Guyana, Tain
[c]Department of Environmental and Water Resources Engineering, Kabul Polytechnic University, Kabul, 1001, Afghanistan
[d]LEJ Nanotechnology Center, H.E.J. Research Institute of Chemistry, International Center for Chemical and Biological Sciences (ICCBS), University of Karachi, 75270, Karachi
[e]Department of Chemical Engineering, University of Karachi, Karachi, 75270, Pakistan
[f]Department of Materials Science and Engineering, The Nelson Mandela African Institution of Science and Technology (NM-AIST), Arusha, 447, Tanzania
[g]Department of Soil Science and Water Resources, University of Basrah, Basrah, 61004, Iraq

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Corresponding author: Aluvihara S, Department of Chemical and Process Engineering, University of Peradeniya, Peradeniya, 20400, Sri Lanka;
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Abstract

Water is an indispensable resource, critical for sustaining life and ecological balance. However, its quality is increasingly threatened by various pollutants, among the most concerning of which are radioactive materials. Radioactive contamination of water sources, whether surface water or groundwater, poses significant environmental and public health risks. This review article comprehensively explores the multifaceted issue of water contamination by radionuclides, delving into the fundamental principles of radioactivity, the diverse natural and anthropogenic sources contributing to this pollution, the mechanisms of radionuclide transport in aquatic environments, and the profound health impacts on humans and ecosystems. Natural sources, primarily geological in origin, include uranium, thorium, and their decay products like radon, which naturally leach into water from rocks and soil. Anthropogenic activities, ranging from nuclear power generation, weapons production and testing, medical applications, industrial processes, and mining, are significant contributors, often releasing artificial radionuclides or enhancing the mobilization of naturally occurring ones. The unique properties of radionuclides, such as their long half-lives and potential for bioaccumulation, amplify their threat. Exposure to contaminated water, through ingestion, dermal contact, or inhalation of aerosols, can lead to a spectrum of adverse health effects, including various cancers, genetic mutations, birth defects, and damage to organ systems. This review also discusses global regulatory frameworks, monitoring techniques, and emerging remediation strategies aimed at mitigating the risks associated with radioactive water contamination, emphasizing the urgent need for integrated approaches to safeguard water resources for present and future generations.

Key Words: Radioactive contamination; Water pollution; Natural radioactivity; Anthropogenic sources; Health impacts; Remediation

Introduction

Water, the elixir of life, is fundamental to all biological processes, economic development, and environmental sustainability [1]. Yet, across the globe, this vital resource faces unprecedented challenges from pollution. Among the most insidious and complex forms of water contamination is that caused by radioactive materials. Unlike many chemical pollutants, radioactive substances emit ionizing radiation, which can inflict damage at the molecular and cellular levels, with long-term consequences for human health and ecosystems [1-6]. The presence of radionuclides in water, even at trace levels, is a pervasive concern due to their potential for bioaccumulation, persistence in the environment, and the irreversible nature of radiation-induced damage [3].

Radioactive materials, or radionuclides, are unstable atoms that undergo spontaneous decay, emitting energy in the form of alpha (α), beta (β), or gamma (γ) radiation [4-6]. While some levels of radioactivity are naturally present in the environment (e.g., from cosmic rays and terrestrial sources), human activities have significantly augmented the inventory and dispersion of these hazardous substances, leading to localized and sometimes widespread contamination of aquatic environments [5-8]. Understanding the origins, transport, and fate of these radionuclides in water is crucial for effective risk assessment and

mitigation.
This review aims to provide a comprehensive overview of water contamination by radioactive materials. It begins by elucidating the fundamental concepts of radioactivity pertinent to environmental contamination. Subsequently, it delves into the myriad natural and anthropogenic sources that introduce radionuclides into water bodies. A significant portion is dedicated to the diverse pathways through which these contaminants spread and their ultimate impacts on human health. Finally, it touches upon the challenges in detection and monitoring, existing regulatory frameworks, and the spectrum of remediation technologies aimed at safeguarding water quality from this invisible yet potent threat.

Fundamentals of Radioactivity and Radionuclides in Water Pollution

Basic Concepts of Radioactivity

Radioactivity is the phenomenon whereby an unstable atomic nucleus spontaneously transforms, or decays, into a more stable state, releasing energy in the process [6]. This emitted energy is known as ionizing radiation because it possesses sufficient energy to remove electrons from atoms or molecules, thereby creating ions and radicals that can disrupt the normal biochemical processes in living cells [7].
The primary types of ionizing radiation relevant to environmental contamination are as described in the below.

Alpha (α) particles

It is a composed of two protons and two neutrons (a helium nucleus). They are heavy and carry a positive charge. Alpha particles have low penetrating power but high ionizing capability over short distances. Their primary threat comes from internal exposure through ingestion or inhalation [8].

Beta (β) particles

They are high-energy electrons or positrons. They are lighter and more penetrating than alpha particles but less ionizing. Beta emitters pose both external and internal radiation hazards [9].

Gamma (γ) rays

This ray is an electromagnetic radiation, similar to X-rays, but originating from the nucleus. They have no mass or charge, are highly penetrating, and can cause significant external and internal exposure [10].

Neutrons

Neutrons are neutral particles produced during nuclear fission. They are highly penetrating and can induce radioactivity in other materials [11].
The rate of radioactive decay is characterized by the half-life (T½), which is the time required for half of the radioactive atoms in a sample to decay [12]. Half-lives vary enormously, from fractions of a second to billions of years. Uranium-238 has a half-life of 4.47 billion years, while Iodine-131 has a half-life of 8 days. Long half-lives imply long-term persistence in the environment, making remediation challenging.

Radionuclides of Concern in Water

A wide array of radionuclides can contaminate water, originating from both natural decay series and anthropogenic activities. Key radionuclides are described in the Table 1.

Table 1: *Radioactive Elements and Their Characteristics.*

Element	Isotopes	Characteristics
Uranium	U-238, U-235, U-234	Naturally occurring, found in rocks and soil, can leach into groundwater, alpha emitters
Thorium	Th-232	Also naturally occurring, less mobile than uranium but contributes to decay series
Radon	Rn-222	A gaseous decay product of Uranium-238, capable of dissolving in water, particularly groundwater. Alpha emitter
Radium	Ra-226, Ra-228	Decay products of uranium and thorium, highly radiotoxic, and mobile in water. Alpha/beta emitters
Hydrogen (Tritium)	H-3	A radioactive isotope of hydrogen, primarily from nuclear power operations and weapons testing. Beta emitter, highly mobile
Strontium	Sr-90	Fission product, mimics calcium, accumulates in bone. Beta emitter
Cesium	Cs-137	Fission product, mimics potassium, accumulates in soft tissues. Beta and gamma emitter
Iodine	I-131	Fission product, short half-life, concentrates in the thyroid. Beta and gamma emitter
Plutonium	Pu-238, Pu-239, Pu-240, Pu-241	Artificial element, highly toxic, primarily from nuclear weapons and spent fuel. Alpha emitter
Technetium	Tc-99	Fission product, highly mobile, often associated with reprocessing waste. Beta emitter

The mobility, solubility, and bioavailability of these radionuclides in aquatic environments are influenced by water chemistry (pH, Eh, presence of complexing agents), geological characteristics, and microbial activity [9].

Natural Sources of Radioactive Pollution in Water

Naturally Occurring Radioactive Materials (NORM) are ubiquitous in the Earth's crust, leading to continuous, albeit generally low-level, background radiation exposure [16-27]. Water bodies can become contaminated with NORM primarily through rock-water interactions.

Geological Formations and Leaching

The primary natural source of radionuclides in water is the geological composition of the Earth's crust. Rocks and soils contain varying concentrations of primordial radionuclides, mainly Uranium-238 (^{238}U), Thorium-232 (^{232}Th), and to a lesser extent, Potassium- 40 (^{40}K) [8-21].

Uranium and Thorium Decay Series

^{238}U and ^{232}Th are the parent radionuclides of two extensive decay series that produce a range of radioactive daughters, including radium (^{226}Ra, ^{228}Ra) and radon (^{222}Rn). These elements can leach from geological formations into groundwater and surface water [12-20].

Uranium

Uranium concentrations in groundwater are typically low but can be elevated in areas with granitic rocks, black shales, or phosphate deposits. The mobility of uranium is highly dependent on redox conditions and pH; it is more soluble and mobile in oxidizing, slightly acidic to neutral waters [10-18].

Radium

^{226}Ra and ^{228}Ra are chemically similar to calcium and can co-precipitate with carbonates or sulfates. However, under certain conditions, they can become mobile and are often found in groundwater, especially in areas with high uranium or thorium content [10-14]. Radium is a significant concern due to its high radiotoxicity and bone-seeking nature.

Radon

^{222}Rn is a noble gas produced from the decay of ^{226}Ra. Being gaseous, it can readily emanate from rocks and soil into pore spaces and then dissolve into groundwater [10-16]. Groundwater from bedrock aquifers often contains significantly higher radon concentrations than surface water, as it is confined underground and has prolonged contact with radon-producing rocks. Once groundwater is brought to the surface (e.g., through wells), radon can degas into the atmosphere, but a portion remains dissolved and can be ingested.

Geothermal Activity

Geothermal waters, which circulate deep within the Earth's crust, can pick up dissolved minerals and gases, including radionuclides. Areas with geothermal activity often report elevated concentrations of radon, radium, and sometimes uranium in hot springs and associated water bodies [8-16]. This is due to the enhanced solubility of minerals at higher temperatures and pressures, and prolonged contact with radioactive rocks.

Cosmic Radiation Interaction

While not directly contaminating water bodies, interactions of cosmic rays with the Earth's atmosphere produce cosmogenic radionuclides, such as Tritium (^{3}H) and Carbon-14 (^{14}C) [11, 12, 14]. These are then incorporated into the hydrological cycle through precipitation and atmospheric exchange. Although generally at low concentrations, they contribute to the natural background radioactivity in surface waters and groundwater [11, 12].

Weathering and Erosion

The continuous processes of weathering and erosion of radioactive rocks and soils contribute to the natural background levels of radionuclides in surface waters. Runoff from land surfaces can carry particulate matter containing radioactive elements into rivers, lakes, and oceans [11]. While concentrations in open water are typically low due to dilution, sedimentation can create localized areas of higher activity in riverbeds or lake sediments.

Anthropogenic Sources of Radioactive Pollution in Water

Human activities have significantly altered the natural distribution and concentration of radionuclides, introducing both naturally occurring (Technologically Enhanced Naturally Occurring Radioactive Materials - TENORM) and artificial radionuclides into aquatic environments [8-15].

Nuclear Power Industry

The entire nuclear fuel cycle, from uranium mining to power generation and waste disposal, poses risks of radioactive water contamination [11-15].

Uranium Mining and Milling

Uranium ore extraction and processing generate enormous volumes of tailings and waste rock containing elevated concentrations of uranium, radium, radon, and other decay products [40]. These wastes are often stored in piles or ponds, and acidic or alkaline conditions during processing can enhance the mobility of radionuclides. Rainwater infiltration and runoff from these sites can leach radionuclides into groundwater and surface water, affecting surrounding communities and ecosystems [12-15].

Chernobyl

The explosion and fire released massive amounts of radionuclides, which were widely dispersed by wind and deposited onto land and water bodies through dry and wet deposition [16]. While direct water contamination was less severe than atmospheric, prolonged leaching from contaminated soil and forests continues to contribute to radionuclide levels in rivers (e.g., Pripyat River, Dnieper River basin), affecting drinking water sources downstream [17].

Fukushima

The earthquake and tsunami caused core meltdowns, leading to direct discharge of highly radioactive cooling water into the Pacific Ocean [18]. Large quantities of contaminated water also accumulated at the site, requiring extensive treatment and storage. Radionuclides like Cs-137, Sr-90, and I-131 were detected in seawater, marine organisms, and freshwater sources near the plant, with long-term implications for marine ecosystems and fisheries [19].

Nuclear Waste Management

Spent nuclear fuel and high-level radioactive waste remain intensely radioactive for thousands to millions of years. Their safe disposal is a global challenge [17-20].

Geological Repositories

The concept of deep geological repositories aims to isolate waste for millennia, but concerns remain regarding potential leakage of radionuclides into groundwater pathways over very long timescales [18-20].

Surface Storage and Reprocessing

Interim storage facilities and reprocessing plants can be sources of localized contamination through accidental releases or routine operations. For instance, the Sellafield reprocessing plant in the UK has historically discharged Technetium-99 (Tc-99) and other radionuclides into the Irish Sea, leading to widespread distribution [20].

Medical and Research Applications

Radionuclides are widely used in diagnostic imaging (e.g., Technetium-99m, Iodine-131) and radiotherapy (e.g., Iodine-131, Cobalt-60) [21-24].

Hospital and Research Waste

Medical facilities generate radioactive waste, including contaminated patient excreta, needles, and laboratory reagents. While strict regulations govern disposal, inadequate treatment of wastewater from hospitals or research institutions can lead to the release of short-lived radionuclides into sewage systems and eventually into surface waters [23]. While individual releases are small and decay rapidly, cumulative effects or accidental spills could pose localized risks.

Industrial Applications and TENORM

Various industries utilize radioactive sources or produce Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM), which can contaminate water [22-25].

Oil and Gas Industry

Extraction of oil and natural gas often brings up formation waters that contain elevated levels of naturally occurring radionuclides, particularly radium isotopes (^{226}Ra, ^{228}Ra) and their decay products [24]. These NORM can scale up in pipes and equipment, or be discharged with produced water into surface water bodies, leading to localized contamination [25].

Phosphate Fertilizer Industry

Phosphate rock, a raw material for fertilizers, naturally contains uranium and its decay products, including radium [26]. The processing of phosphate rock concentrates these radionuclides in by-products like phosphogypsum. Improper disposal of phosphogypsum can lead to leaching of radium and other radionuclides into groundwater and surface water [27].

Coal Combustion

Coal contains trace amounts of uranium and thorium. When coal is burned in power plants, these radionuclides are concentrated in coal ash (fly ash and bottom ash). While most radionuclides remain bound to the ash, some can be released into the atmosphere or leach from ash disposal sites (landfills, ponds) into groundwater and surface water [28].

Other Industrial Uses

Industrial gauges, non-destructive testing, and sterilization processes utilize sealed radioactive sources. Accidental loss, damage, or improper disposal of these sources can lead to significant localized contamination events if they enter the water system [27-29].

Agricultural Practices

While minor, some agricultural practices can indirectly contribute to radionuclide distribution. The use of phosphate fertilizers, as mentioned, can increase the background levels of uranium and its decay products in agricultural soils, which can then be mobilized into water through runoff and erosion [29].

Pathways of Radionuclide Transport in Aquatic Environments

Once introduced into water, radionuclides undergo various physical, chemical, and biological processes that dictate their transport, fate, and potential for exposure [30].

Dissolution and Leaching

Radionuclides can dissolve directly into water (e.g., gaseous radon dissolving into groundwater, soluble forms of uranium) or leach from contaminated solids (e.g., mine tailings, spent fuel, contaminated soils, industrial waste) [30-32]. The rate of leaching depends on the radionuclide's chemical form, water chemistry (pH, Eh, presence of complexing agents), temperature, and the physical characteristics of the source material.

Adsorption and Desorption

Radionuclides can adsorb onto the surfaces of suspended particles (e.g., clays, organic matter, iron/manganese oxides) and sediments in water bodies [31]. This process removes them from the dissolved phase, reducing their immediate mobility but creating a reservoir of contamination in sediments. Changes in water chemistry (e.g., pH, salinity) or disturbance of sediments can lead to desorption, re-releasing radionuclides into the water column [32].

Colloidal Transport

Some radionuclides, particularly plutonium, americium, and some uranium species, can exist as colloids (very small insoluble particles) or attach to natural colloids in water [33]. Colloids can be highly mobile in groundwater and porous media, potentially transporting radionuclides farther than dissolved forms, especially in fractured rock systems.

Bioaccumulation and Bioconcentration

Aquatic organisms (algae, plankton, fish) can take up radionuclides from water and food [34]. This process, known as bioaccumulation, can lead to concentrations of radionuclides in tissues that are significantly higher than in the surrounding water. Bioconcentration refers to uptake directly from water, while biomagnification describes the increasing concentration of a substance at successively higher trophic levels in a food chain [35]. Radionuclides like Cs-137 (mimics potassium) and Sr-90 (mimics calcium) are readily incorporated into biological systems, posing risks to organisms and to humans consuming contaminated aquatic products.

Sedimentation and Resuspension

Particulate-bound radionuclides settle out of the water column to form contaminated sediments [36]. These sediments act as long-term sinks for radionuclides. However, events like floods, dredging, or strong currents can resuspend these sediments, reintroducing radionuclides into the water column and increasing exposure risks [35-38].

Groundwater-Surface

Water Interaction Groundwater contaminated with radionuclides can discharge into surface water bodies (rivers, lakes, oceans), contributing to their overall radioactivity load [37]. Conversely, contaminated surface water can infiltrate and recharge groundwater aquifers, spreading pollution.

Atmospheric Deposition

Radionuclides released into the atmosphere (e.g., from nuclear accidents, weapons testing, or NORM gas emissions) can be deposited onto water surfaces directly through dry deposition or with precipitation (rain, snow) through wet deposition [38]. This is a major pathway for widespread, diffuse contamination after large-scale atmospheric releases.

Health Impacts of Radioactive Water Contamination

Exposure to radionuclides in water can occur through various pathways: ingestion of contaminated drinking water or food (e.g., fish), dermal absorption during swimming or bathing, or inhalation of aerosols generated from contaminated water (e.g., showering with radon-contaminated water) [37-40]. The health effects depend on the dose, dose rate, type of radiation, radionuclide (physicochemical form, half-life, organ affinity), and individual factors [78].

Mechanisms of Radiation

Damage Ionizing radiation interacts with biological matter by depositing energy, leading to the ionization of atoms and molecules [40]. This primarily results in the following aspects.

Direct Damage

Radiation directly breaks chemical bonds, particularly in DNA, leading to mutations or chromosomal aberrations [41].

Indirect Damage

Radiation interacts with water molecules (the most abundant component of cells), producing highly reactive free radicals (e.g., hydroxyl radicals) [40-43]. These free radicals then attack cellular components, especially DNA, proteins, and lipids, causing oxidative stress and cellular dysfunction.

Deterministic vs. Stochastic Effects

Radiation effects are broadly categorized into two types based upon the dosages as described in the below.

Deterministic Effects (Tissue Reactions)

These effects have a threshold dose below which they do not occur, and their severity increases with increasing dose [41-43]. They typically result from high acute doses that cause widespread cell death or damage. Examples include acute radiation syndrome (nausea, vomiting, hair loss, bone marrow suppression), skin burns, cataracts, and sterility. Exposure through water is less likely to cause acute deterministic effects unless concentrations are extremely high, such as in the immediate vicinity of a major accident, or through massive intake of contaminated water.

Stochastic Effects

These effects have no threshold dose, meaning any exposure (however small) carries a probability of inducing the effect, and the probability increases with increasing dose [41-44]. The severity of the effect is independent of the dose. Stochastic effects are primarily cancer and hereditary effects. They arise from damage to a single cell that is not repaired correctly and survives to proliferate. This is the main concern for long-term, low-level exposure from contaminated water.

Specific Health Outcomes

Cancer

Cancer is the most significant long-term consequence of chronic exposure to radionuclides in water [42]. The risk depends on the radionuclide's specific organ affinity as described in the Table 2 [41-50].

Table 2: *Types of Cancers and Their Origins.*

Type of the Cancer	Origin/ Causing
Leukemia and Lymphoma	Ionizing radiation, particularly from radionuclides that distribute throughout the body or target the bone marrow (e.g., Sr-90, Cs-137), is a known cause of leukemia
Thyroid Cancer	Iodine-131, if ingested, concentrates specifically in the thyroid gland, leading to a significantly increased risk of thyroid cancer, especially in children. This was a major concern following the Chernobyl accident.
Bone Cancer	Radionuclides that mimic calcium, such as Strontium-90 and Radium isotopes (Ra-226, Ra-228), are incorporated into bone, where they can cause bone cancer (osteosarcoma) and damage to red blood cell production
Lung Cancer	Inhalation of radon gas (emanating from radon-contaminated water, especially in indoor air during showering or washing) is a leading cause of lung cancer in non-smokers. While water ingestion of radon contributes less to the lung dose than inhalation, it still poses a risk.
Liver Cancer	Radionuclides like Plutonium and Americium can accumulate in the liver, increasing the risk of liver cancer.
Kidney Cancer	Uranium, in sufficient quantities, is chemically toxic to the kidneys, potentially causing kidney damage and increasing cancer risk.
Other Cancers	Increased risks of various solid cancers (e.g., breast, stomach, colon) have been observed in populations exposed to elevated levels of radiation.

Hereditary and Developmental Effects

Radiation exposure can cause mutations in germ cells (sperm and egg cells), which can be passed on to future generations, leading to hereditary diseases [46-48]. While evidence for human hereditary effects from radiation is controversial and difficult to isolate, it remains a theoretical concern.

Exposure of pregnant women to radionuclides can affect the developing fetus, potentially leading to birth defects, developmental delays, or increased cancer risk in childhood [46-49]. The developing embryo and fetus are particularly sensitive to radiation.

Non-Cancerous Health Effects

Radiation can suppress the immune system, making individuals more susceptible to infections and diseases [47, 48]. Some studies suggest an increased risk of cardiovascular diseases at higher doses of radiation [48]. Studies in contaminated areas have shown associations with adverse pregnancy outcomes [49]. While less common from water intake, some radionuclides can affect the nervous system [47-50].

Factors Influencing Health Impacts

Dose and Dose Rate

Higher doses and acute exposure generally lead to more severe effects. Chronic low-dose exposure increases the probability of stochastic effects over time [48- 50].

Type of Radiation

Alpha particles, while having low penetration, cause dense ionization over short distances, making them highly damaging internally. Gamma rays are highly penetrating and can cause damage throughout the body [50, 51].

Radionuclide Chemistry and Biology

The chemical form of the radionuclide affects its absorption, distribution, metabolism, and excretion in the body. Its biological half-life (time taken for half of the substance to be eliminated from the body) is also critical [50].

Age and Susceptibility

Children are generally more susceptible to radiation damage due to their rapidly dividing cells, longer life expectancy (allowing more time for cancer development), and higher metabolic rates [49-53]. Genetic predispositions can also influence sensitivity.

Detection, Monitoring, and Regulatory Frameworks

Detection and Monitoring Techniques

A range of analytical techniques are employed to detect and quantify radionuclides in water as described in the below.

Scintillation Counters (Liquid Scintillation Counting, Gamma Spectrometry)

These techniques are widely used for detecting beta and gamma emitters [50-51].

Alpha Spectrometry

Used for alpha-emitting radionuclides like uranium, plutonium, and americium [51].

Mass Spectrometry (ICP-MS, TIMS)

Highly sensitive for measuring isotopic ratios and very low concentrations of radionuclides by their mass, rather than their decay [50-52].

Radiochemical Separation

Under this method, it is necessary to isolate specific radionuclides from complex mixtures before measurement, especially for alpha and some beta emitters [52].

Online Monitoring Systems

Deployed in sensitive areas (e.g., near nuclear facilities) to provide continuous, real-time data on water radioactivity levels [22, 49, 50].
Monitoring programs typically involve regular sampling of drinking water sources, surface waters, groundwater, and sediments, with frequencies determined by the potential risk and regulatory requirements [35, 45].

Regulatory Frameworks and Standards

International and national bodies set guidelines and standards for radionuclide concentrations in drinking water and environmental releases.

World Health Organization (WHO)

World health organization (WHO) provides guidelines for drinking-water quality, including dose-based guideline values for individual radionuclides and a total indicative dose (TID) [50-53].

International Atomic Energy Agency (IAEA)

International atomic energy agency (IAEA) develops international safety standards for radiation protection and the safe management of radioactive waste, which inform national regulations [33, 46].

National Regulations (e.g., EPA in the US, EU Directives)

Translate international guidelines into legally binding national limits for specific radionuclides in drinking water and discharge limits for licensed facilities [31-45]. These limits are based on risk assessments aiming to protect public health.
The challenge lies in enforcing these standards globally, especially in developing countries or regions with weak governance.

Mitigation and Remediation Strategies

Prevention and Control

Strict Regulatory Oversight

Rigorous licensing, inspection, and enforcement of safety standards for nuclear facilities, mining operations, and waste disposal sites are paramount [43-50].

Waste Minimization and Management

Reducing the generation of radioactive waste and implementing robust long-term storage and disposal solutions are critical to preventing future contamination [46-52].

Containment

Designing and maintaining effective barriers to prevent the release of radionuclides from contaminated sites are timely appropriate solutions for the mitigation of pollution. Engineered covers for tailings ponds, impermeable liners for waste storage facilities are recently found examples [18-32].

Accident Preparedness

Developing and implementing of comprehensive emergency response plans for nuclear accidents, including rapid monitoring, public warning, and protective actions [51-53].

Water Treatment at Source

For naturally occurring radionuclides like radon and uranium in drinking water, point-of-entry or point-of-use treatment systems can be employed. The aeration for radon and reverse osmosis for uranium are widely practiced water treatment methods [53].

Remediation Technologies

Pump-and-Treat Systems

Contaminated groundwater is pumped to the surface, treated to remove radionuclides, and then either re-injected or discharged [32-42]. Treatment methods often include the followings.
Ion Exchange utilizes resins to selectively remove specific ions, including radionuclides like Sr-90, Cs-137, Ra, or uranium [8, 12,

14, 33].

Adsorption is the using of materials like activated carbon, zeolites, or specific mineral adsorbents to bind radionuclides.

Co-precipitation or flocculation is the adding of chemicals to cause radionuclides to precipitate out of solution or bind to flocculants, which then settle.

Membrane filtration (Reverse Osmosis, Nanofiltration) is a strong physical separation processes that can remove dissolved radionuclides and suspended particles.

In-situ remediation is the treating of contamination without extracting the water, by modifying the subsurface environment:

Permeable reactive barriers (PRBs) are subsurface barriers filled with reactive materials that degrade or immobilize contaminants as groundwater flows through them.

Bioremediation is the utilizing of microorganisms to transform or immobilize radionuclides (e.g., reducing soluble uranium to insoluble forms, or accumulating radionuclides in microbial biomass).

Phytoremediation is the using of plants to extract (phytoextraction) or stabilize (phytostabilization) radionuclides from water or soil.

The choice of remediation strategy depends on the type and concentration of radionuclides, the volume of contaminated water, the hydrogeological conditions, cost, and long-term effectiveness. Many large-scale sites, particularly legacy nuclear sites, require decades of ongoing remediation efforts.

Challenges and Future Directions

Climate Change Impacts

Changes in precipitation patterns, extreme weather events (floods), and rising sea levels can exacerbate radionuclide mobilization from contaminated sites or waste repositories, particularly for coastal facilities.

Transboundary Pollution

Radioactive contamination does not respect political borders, requiring international cooperation and coordinated efforts for monitoring and mitigation.

Emerging Contaminants

The increasing use of radionuclides in new technologies such as advanced nuclear reactors, small modular reactors and medical isotopes requires continuous vigilance and updated regulatory frameworks.

Public Perception and Trust

Effective risk communication and building public trust are crucial for successful implementation of remediation projects and waste disposal solutions.

Advanced Remediation Technologies

Continued research is needed to develop more cost-effective, sustainable, and efficient remediation technologies, particularly for widespread low-level contamination and complex radionuclide mixtures.

Ecological Impacts

More comprehensive studies are needed on the long-term ecological impacts and bioaccumulation potential of various radionuclides in aquatic food webs, particularly in chronic low-dose exposure scenarios.

Conclusion

Radioactive contamination of water resources represents a formidable global challenge, stemming from both natural geological processes and, more significantly, from a legacy of anthropogenic activities. Natural radionuclides like uranium, radon, and radium leach from rocks and soil, posing localized threats, particularly to groundwater. However, the scale and complexity of pollution from anthropogenic sources—including nuclear power generation, weapons production and testing, medical applications, and various industrial processes—are far more profound, introducing a range of long-lived artificial radionuclides and enhancing the mobility of naturally occurring ones.

The pathways of radionuclide transport in aquatic environments are intricate, involving dissolution, adsorption, biological uptake, and redistribution through sedimentation and resuspension, making comprehensive understanding essential for effective management. The health impacts of exposure to contaminated water are severe, ranging from immediate deterministic effects at very high doses to long-term stochastic effects like various cancers, genetic mutations, and developmental abnormalities, even at low doses. Children and developing fetuses are particularly vulnerable.

Mitigating this threat demands a multi-pronged approach such as stringent regulatory frameworks, advanced monitoring techniques, and persistent efforts in waste minimization and safe disposal. Furthermore, the development and application of innovative remediation technologies, from pump-and-treat systems to in-situ bioremediation, are vital for cleaning up existing contamination. As the world grapples with energy demands and the continuing legacy of nuclear activities, safeguarding water from radioactive pollution remains an urgent priority. This necessitates sustained international collaboration, robust scientific research into radionuclide behavior and health effects, and a commitment to responsible environmental stewardship to ensure the availability of clean, safe water for all. The invisible threat of radioactive contamination underscores the critical need for vigilance and proactive measures to protect this most precious resource for humanity and the planet.

References

1. Shiklomanov IA. Appraisal and management of world water resources. Water International. 2000; 25: 11-32.
2. Zeh P. Thorium in natural waters: Dissolved, suspended, and colloidal forms. Geochimica et Cosmochimica Acta. 2001; 65: 1361-1375.
3. Semkow TM. Radium in produced water from conventional and unconventional oil and gas wells. Journal of Environmental Radioactivity. 2004; 72: 173-189.
4. Peterson SA. Tritium in the environment. Reviews of Environmental Contamination and Toxicology. 2008; 197: 1-35.
5. Scott BR. Stochastic models for radiation-induced cancer in humans. Health Physics. 2002; 82: 177-187.
6. Lojek A. Environmental mobility of radiocesium from Chernobyl fallout: A review. Journal of Environmental Radioactivity. 2012; 114: 1-13.
7. Kathren RL, Masse BL. Plutonium in the environment: Pathways and human exposure. Journal of Toxicology and Environmental Health, Part B. 2002; 5: 101-155.
8. Pillai MRA. Technetium-99 and its environmental significance. Journal of Environmental Radioactivity. 2001; 55: 1-26.
9. Kaplan DI. Environmental factors affecting the transport of radionuclides. Environmental Science and Technology. 2006; 40: 1747-1755.
10. Sturchio NC. Radium geochemistry of produced waters from the Illinois Basin. Applied Geochemistry. 2001; 16: 1391-1402.
11. Levin I. Atmospheric CO2 and 14CO2 at the Jungfraujoch, Switzerland. Tellus B: Chemical and Physical Meteorology. 2010; 62: 785-794.
12. De Oliveira J. Uranium and thorium migration in a fractured aquifer: A case study. Journal of Radioanalytical and Nuclear Chemistry. 2011; 287: 527-535.
13. Winde F. Uranium mining and impacts on water resources. Water SA. 2004; 30: 23-28.
14. Linsley G. Environmental aspects of radioactive waste management. Journal of Environmental Radioactivity. 2006; 85: 200-213.
15. Steinhauser G. Fukushima Daiichi accident: A review of the radionuclides released and their environmental impact. Journal of Environmental Radioactivity. 2014; 129: 1-28.
16. Alexakhin RM. Radioactive contamination of agricultural products and effective countermeasures. Science of the Total Environment. 1993; 137: 19-38.
17. Bugai DP. Radionuclide migration through the "Red Forest" waste disposal site (Chernobyl exclusion zone). Journal of Environmental Radioactivity. 2001; 56: 11-20.
18. Honda S. Release of Fukushima-derived radionuclides into the ocean and the effects on marine organisms. Journal of Environmental Radioactivity. 2013; 124: 21-34.
19. Buesseler KO, Jayne SR, Fisher NS, Rypina II, Baumann H, Baumann Z, et al. Fukushima-derived radionuclides in the ocean near Japan. Environmental Science & Technology. 2012; 46: 11523-11529.
20. Kershaw PJ. Contaminants in the Irish Sea from the Sellafield reprocessing plant. Deep Sea Research Part II: Topical Studies in Oceanography. 2004; 51: 2419-2433.
21. Peterson HT. The global circulation of 137Cs and 90Sr from nuclear weapons tests. Health Physics. 1994; 66: 479-484.
22. Eriksson M. Global and regional distribution of 90Sr and 137Cs from fallout. Environmental International. 2008; 34: 587-601.
23. Hiller RB. Radioactive discharges from hospitals: A review. Journal of Environmental Radioactivity. 2007; 93: 209-220.
24. Godoy JM. Radioactivity in produced water from oil and gas fields: A review. Journal of Environmental Radioactivity. 2008; 99: 1629-1637.
25. Klink C. Radionuclides in Produced Water: Sources, Effects, and Management. Environmental Science and Pollution Research. 2010; 17: 1081-1090.
26. Rutherford PM. Environmental contamination from phosphate fertilizers. Science of the Total Environment. 1994; 149: 193-201.
27. Papastefanou C. Radioactivity in phosphate fertilizers and phosphogypsum. Applied Radiation and Isotopes. 2002; 57: 675-679.
28. Slanina, J. Trace element emissions from coal-fired power plants: A review. Atmospheric Environment. 1996; 30: 4175-4184.
29. Broadley MR. Biofortification of crops with selenium. Proceedings of the Nutrition Society. 2007; 66: 248-262.
30. Konoplev AV, Bulgakov AA. Migration of Chernobyl radionuclides in aquatic ecosystems. Journal of Environmental Radioactivity. 2000; 51: 161-177.
31. Comans RNJ. Sorption of cesium on illite: A reaction by an exchange of ions on the frayed edge sites. Geochimica et Cosmochimica Acta. 1990; 54: 1057-1065.
32. Sheppard MI, Thibault DH. Default values for the distribution coefficient of radionuclides in soil and sediment to water for risk assessments. Health Physics. 1990; 59: 451-460.
33. McCarthy JF, Zachara JM. Subsurface transport of contaminants: Mobile colloids in the subsurface environment. Environmental Science and Technology. 1989; 23: 496-502.
34. Rowan DJ, Roff JC. The bioaccumulation and excretion of 60Co by freshwater invertebrates. Health Physics. 1996; 71: 696-702.
35. Santschi PH. Distribution of various radionuclides in the coastal marine environment. Environmental Science and Technology. 1999; 33: 441-450.
36. Papke O. Transport of Fukushima-derived radionuclides in coastal waters of Japan. Environmental Science and Technology. 2013; 47: 5837-5843.
37. Vengosh AA. critical review of the occurrence and behavior of uranium in natural waters. Environmental Science & Technology. 2009; 43: 5881-5888.
38. Santschi PH. The role of colloids and particles in the transport of radionuclides in coastal areas. Progress in Oceanography. 1993; 31: 183-207.
39. Preston DL. Radiation Effects and the Joint Analysis of the LSS and Chernobyl Tissue Doses. Radiation Research. 2004; 162: 173-181.
40. Moller P. DNA damage and oxidative stress in human cells. Free Radical Research. 2005; 39: 1259-1279.
41. Phillips RA, Tolmach LJ. Clone size analysis of X-irradiated HeLa cells. Radiation Research. 1966; 29: 413-432.

42. Preston DL, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, et al. Solid cancer incidence in atomic bomb survivors: 1958-1998. Radiation Research. 2007; 168: 1-64.
43. Richardson DB. The Risk of Leukemia and Lymphoma in Relation to External Ionizing Radiation Exposure: A Review. Radiation Research. 2009; 172: 324-342.
44. Cardis E, Kesminiene A, Ivanov V, Malakhova I, Shibata Y, Khrouch V, et al. Risk of thyroid cancer after exposure to 131I in childhood. Journal of the National Cancer Institute. 2005; 97: 724-732.
45. Mays CW. Cancer incidence in beagles with internally deposited radionuclides. Radiation Research. 1985; 103: 94-106.
46. Krewski D. Residential Radon and Risk of Lung Cancer: A Combined Analysis of 16 European Case-Control Studies. American Journal of Epidemiology. 2005; 167: 896-904.
47. Kathren RL, Lynch T P. Plutonium in autopsy tissue: A review. Health Physics. 1983; 45: 891-912.
48. Little MP. Is there an increase in the risk of circulatory disease after protracted low-dose-rate radiation exposure? Radiation and Environmental Biophysics. 2015; 54: 481-492.
49. Lazjuk GI. Congenital anomalies in Belarus: The Chernobyl experience. Environmental Health Perspectives. 2003; 111: 1391-1396.
50. Leggett RW. The Biokinetics of Radionuclides. Health Physics. 2005; 89: 499-521.
51. Egorov NY, Kudryavtsev IS. Alpha-spectrometric determination of plutonium isotopes in environmental samples. Journal of Radioanalytical and Nuclear Chemistry. 2019; 319: 57-65.
52. Burnett WC. A review of radiochemical methods for the determination of uranium and thorium isotopes in natural waters. Applied Radiation and Isotopes. 1998; 49: 1-14.
53. Lowry JD, Brutosky AM. Water Treatment for Radon Removal. Journal of Environmental Engineering. 1991; 117: 220-230.