UN environment programme

The Weight of Time

Facing a new age of challenges for people and ecosystems

Frontiers 2025

ISBN: 978-92-807-4224-4
Job number: DEW/2706/NA
DOI: https://wedocs.unep.org/20.500.11822/48122

Suggested citation
United Nations Environment Programme (2025). *Frontiers 2025: The Weight of Time – Facing a new age of challenges for people and ecosystems*. Nairobi. https://wedocs.unep.org/20.500.11822/48122

Production: Nairobi
URL: https://www.unep.org/resources/frontiers-2025-weight-time

Cover design: Beverley McDonald

Acknowledgements

The United Nations Environment Programme (UNEP) extends its gratitude to the authors, the reviewers and others for their valuable contributions to the preparation of this report. Authors and reviewers have contributed to the report in their individual capacities. Their affiliations are only mentioned for identification purposes.

Chapter 1. The frozen Pandora's box: Reactivation of microbes in a warming cryosphere

Authors
Andrés Yarzábal, Academic Unit of Health and Wellness, Catholic University of Cuenca, Cuenca, Ecuador
Vanesa Amarelle, Biological Research Institute Clemente Estable, Montevideo, Uruguay

Reviewers
Alexandre M. Anesio, Department of Environmental Science, Aarhus University, Roskilde, Denmark
Ramón Batista Garcia, Research Center for Cell Dynamics, Autonomous University of the State of Morelos, Morelos, Mexico
Tiina Kurvits, Polar and Climate Programme, GRID Arendal, Arendal, Norway
Wasim Sajjad, Northwest Institute of Eco-environment and Resources, Chinese Academy of Sciences, Lanzhou, China
Tina Schoolmeester, Polar and Climate Programme, GRID Arendal, Arendal, Norway
Weicai Wang, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing, China

Chapter 2. Clearing the path: Barrier removal for river restoration

Author
Mellisa Foley, San Francisco Estuary Institute, Richmond, California, United States of America

Reviewers
Chengzhi Ding, Yunnan Provincial Key Laboratory of International Rivers and Transboundary Eco-security, Yunnan University, Kunming, China
David Dudgeon, School of Biological Sciences, The University of Hong Kong, Hong Kong, China
Pao Fernández Garrido, Dam Removal Europe, Groningen, the Netherlands
Jose Galizia Tundisi, International Institute of Ecology, São Carlos Sao Paulo, Brazil
Jingrui Sun, Key Laboratory of International Rivers and Transboundary Eco-security, Yunnan University, Kunming, China

Chapter 3. Demographic challenge: Growing old in a changing environment

Authors
Stessa Tzuyuan Chao, Department of Urban Planning, National Cheng Kung University, Taiwan Province of China
Sun Yi, Department of Building and Real Estate, the Hong Kong Polytechnic University, Hong Kong, China

Reviewers
Rosalía Chavez Alvarado, Department of Sciences, Engineering and Technology, University of Quintana Roo, Quintana Roo, México
Mohamad Abdul Halim Chehab, Community Medicine Residency Program, Hamad Medical Corporation, Doha, Qatar
Sabine Henning, Social Development Division, United Nations Economic and Social Commission for Asia and the Pacific, Bangkok, Thailand
Oh Seok Kim, Institute of Future Land, Korea University, Seoul, Republic of Korea
Abdul Malak, Department of Geography and Environment, Jagannath University, Dhaka, Bangladesh
Karoline Schmid, United Nations Department of Economic and Social Affairs-Population Division, New York, United States of America
Joost van Hoof, Faculty Social Work and Education, The Hague University of Applied Sciences, The Hague, The Netherlands

Chapter 4. Forgotten but not gone: Remobilization of legacy pollutants by flood events

Authors
Markus Brinkmann, Toxicology Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
Animesh Kumar Gain, School of Environmental and Conservation Sciences, College of Environmental and Life Sciences, Murdoch University, Australia

Contributing authors
Markus Hecker, School of Environment and Sustainability, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
Henner Hollert, Department of Evolutionary Ecology and Environmental Toxicology, Institute of Ecology, Evolution and Diversity, Goethe University Frankfurt, Frankfurt am Main, Germany
Tim Jardine, Toxicology Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada
Karsten Liber, Toxicology Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

Reviewers
Kenneth Davis, Chemicals and Health Branch, Industry and Economy Division, UNEP
Fatemeh Izaditame, Environmental Soil Chemistry, Plant and Soil Sciences, University of Delaware, Newark, Delaware, United States of America
Delia B. Senoro, School of Civil, Environmental and Geological Engineering, Mapúa University, Manila, the Republic of the Philippines
Yogesh Chandra Sharma, Department of Chemistry, Indian Institute of Technology (BHU) Varanasi, Varanasi, India
Kei Ohno Woodall, Secretariat of the Basel, Rotterdam and Stockholm Conventions, UNEP, Genève, Switzerland

UNEP Reviewers
Dina Abdelhakim, Raymond Brandes, Kenneth Davis, Andrea Hinwood, Jason Jabbour, Maarten Kappelle, Jian Liu, Bavelyne Mibei, Jessica Troni and Ying Wang.

Production Team
Maarten Kappelle (Project supervisor), Pinya Sarasas (chief editor), Allan Lelei (technical support) and UNEP; and Catherine McMullen (science editor).

Design and layout
Carlos Reyes, Reyes Work, Sweden (design and layout) and Beverley McDonald, UNEP (cover design).

Communication support
UNEP Communication Division: Anastasia Isyuk and Yahan You (project management); Reagan Sirengo (Design); Keishamaza Rukikaire (News and Media); Amina Said (Web); Michael Logan (Writing)

Special thanks are also extended to:
Isabelle Gärtner-Roer, World Glacier Monitoring Service (WGMS), Zurich, Switzerland; Tamiru Abiye, University of the Witwatersrand, Johannesburg, South Africa; Ignatius Gutsa, University of Zimbabwe, Harare, Zimbabwe; Raya Muttarak, University of Vienna, Austria; Steven J. Cooke, Carleton University, Ottawa, Canada; Stefan Zerbe, Free University of Bozen-Bolzano, Italy; Karl-Erich Lindenschmidt, Global Institute for Water Security, University of Saskatchewan, Saskatoon, Canada; Holger Schüttrumpf, Institute for Hydraulic Engineering and Water Resources Management, RWTH Aachen University, Aachen, Germany; Selma Hedges, Samuel Opiyo, Jane Muriithi, Ekaterina Poleshchuk, Charles Sebukeera, Maureen Tanyai, Atila Uras, Edoardo Zandri and staff in the Early Warning and Assessment Division of UNEP.

The 2025 edition of the Frontiers report is supported by the Environment Fund.

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Foreword

UNEP is mandated to keep the environment under review, which means keeping an eye on environmental changes and issues that may wash up on our shores. The Frontiers Report is a key part of this effort, uniting scientists and specialists from across the world to delve into key emerging issues of environmental concern and recommend policies and courses of action. The 2025 edition of this report addresses four issues that need greater attention from policymakers.

The first issue is the threat posed by reactivated microbes in a warming cryosphere. Frozen in ice sheets, glaciers and permafrost are bacteria, fungi and viruses. While most are dead, some are dormant and some are active. As global temperatures hit record highs, these microorganisms will become more active in many ecosystems. Even if melt can be slowed down by mitigating greenhouse gas emissions, we must assess and prepare for possible threats from potential pathogens. Also crucial is documenting and preserving cryospheric microorganisms, which can shed light on the history of climate and evolution, help in finding therapies for diseases and develop innovative biotechnologies.

The second issue is the growing need to remove barriers, such as dams, to rehabilitate river ecosystems – a process increasingly initiated by local communities, Indigenous Peoples, women and youth. Rivers and streams can recover remarkably once barriers are gone, but other stressors such as land-use, pollution and climate change need to be addressed in parallel. Understanding the restoration outcomes of barrier removal is necessary not only to guide future removals but also to inform decisions about existing and future barriers.

The third issue is the risk to ageing populations from environmental degradation. It is estimated that the global share of people over 65 years old will rise from 10 per cent in 2024 to 16 per cent by 2050. Most of these people will live in cities – where they will be exposed to extreme heat and air pollution, and experience more frequent disasters. Older people are already more at risk. Effective adaptation strategies will need to evolve to protect these older populations.

The final issue is the danger posed by legacy pollutants released as extreme rainfall and floods wash away sediments and debris. The Pakistan floods of 2010, flooding in the Niger Delta in 2012 and Hurricane Harvey off the coast of Texas in 2017 are all examples when floodwaters stirred up sediments, releasing heavy metals and persistent organic pollutants. Evaluating sediments to understand hazards, rethinking flood protection to lean on Nature-based Solutions, and investments in natural remediation of contaminated sediments are all options to deal with this problem.

All these emerging issues require careful attention and proactive action. I call on policymakers to read this issue of the biennial Frontiers Report and take forward its findings to protect people, nature and economies from threats that will only grow with each passing year

Inger Andersen
Executive Director
United Nations Environment Programme

Introduction

For over two decades, the United Nations Environment Programme (UNEP) has sought to identify and draw attention to emerging issues of environmental concern. Together with the international scientific community, UNEP is on the frontline of assessing emerging threats and ensuring that potential disruptions to planetary health and innovative solutions to environmental challenges are kept high on the international radar.

The Frontiers Reports are important contributions for delivering scientific insight on emerging issues of concern to policy-makers with the intention of fostering actionable and timely responses. Some issues may be local or relatively small-scale issues today but have potential to become issues of regional or global concern if not addressed early. This latest iteration of the Frontiers report offers an insight into four emerging issues identified through surveys with stakeholders in recent years.

UNEP's Foresight Trajectory

During the development of the latest edition of the Frontiers report, UNEP also embarked on a new Foresight Trajectory initiative. It advances the work on emerging issues, by expanding our collective capacity to anticipate the future, embed futures thinking in the culture of the organization, and, crucially, deliver a proactive and continuous reading on potential disruptions and untapped opportunities to enable better decisions, preparedness and anticipatory action. Launched in 2024, UNEP undertook an 18-month strategic foresight process culminated in eight critical shifts (emerging phenomena) and 18 signals of change which are presented in an inaugural Global Foresight Report – Navigating New Horizons[1]. These signals of change are a small subset of the 280 signals identified in the broader Foresight Trajectory process. Likewise, the emerging issues addressed in this Frontiers report edition are relevant to many identified among the 280 signals. The connections between the topics discussed in this publication and those signals presented in the Global Foresight Report are summarized at the beginning of each chapter.

This collective intelligence process draws on a range of tools and methods to identify signals of change and emerging issues. Building on UNEP's history of emerging issues and early warning, the foresight process responds to the need to enhance the use of scientific evidence in environmental decision-making and strengthens the backbone of UNEP's efforts to anticipate change and provide forward-facing insights for a range of publications, assessments and strategic priorities and hence the backbone to the Frontievrs Series of Reports.

[1] United Nations Environment Programme (2024). Navigating New Horizons: A global foresight report on planetary health and human wellbeing. Nairobi. https://wedocs.unep.org/20.500.11822/45890.

> **"Microorganisms, such as fungi, algae, and protists, have been reactivated from ancient ice dated to 50,000 years old."**

The Global Foresight Report and Process identified a potential disruption emerging on the horizon from ancient and uncharacterized microorganisms released from thawing permafrost, with implications for modern ecosystems and human health. This chapter examines the remobilization of long-dormant microbial communities confined in the rapidly warming cryosphere and potential environmental risks. The chapter also underlines their ecological and biotechnological values and the urgent need to preserve the unique microbial diversity.

Illustrations: Carlos Reyes, 2024. Created with the assistance of generative tools.

01 The frozen Pandora's box

Reactivation of microbes in a warming cryosphere

Authors

Andrés Yarzábal (Academic Unit of Health and Wellness, Catholic University of Cuenca, Cuenca, Ecuador)

Vanesa Amarelle (Biological Research Institute Clemente Estable, Montevideo, Uruguay)

1.1 Life below zero

With humanity's release of greenhouse gas emissions over the last 250 years, our planet is warming at an unprecedented rate. In the last 50 years, the global average surface temperature has increased faster than any previous 50-year period during the last 2,000 years.[1]

Among terrestrial and aquatic ecosystems, the cryosphere is one of the most affected by climate change, suffering substantial damage and irreversible losses. The cryosphere refers to regions where water is frozen solid and ground is seasonally frozen: the Arctic region, the Antarctic and Greenland ice sheets, ice shelves and sea ice that extend into the ocean, mountain glaciers on every continent, permafrost, seasonally frozen ground, and other ice and snow-covered features.

Together these frozen regions occupy approximately 52 per cent of the Earth's land surface and 5 per cent of its ocean area and are a critical component of the global climate system.[2,3] Within the cryosphere, seasonally frozen landscapes are familiar to anyone who experiences cold winters. But permafrost and glaciers stand out for their roles in complex Earth systems: permafrost is a great sink of organic carbon which remains sequestered in this frozen ground, while glaciers and snowpack are essential water sources for billions of people.[4-7]

Although it can be an extreme environment, even the coldest parts of the cryosphere are the habitat for an enormous number of microorganisms, including bacteria, microscopic fungi, protists, single-celled archaea and viruses.[8] They are not evenly distributed, as microbial density ranges from sparse in clear glacial ice to abundant in permafrost soils.[9]

Many of these microbes are ancient, having remained confined in the cryosphere for millennia. That is why frozen habitats are considered paleo archives. Due to the prevailing harsh environmental conditions, most frozen microbes are dead. However, some are metabolically active and multiply

Many of these microbes are ancient, having remained confined in the cryosphere for millennia. That is why frozen habitats are considered paleo archives.

The cryosphere occupies

52%
of the Earth's land surface[3]

5%
of the global ocean area[3]

2°C

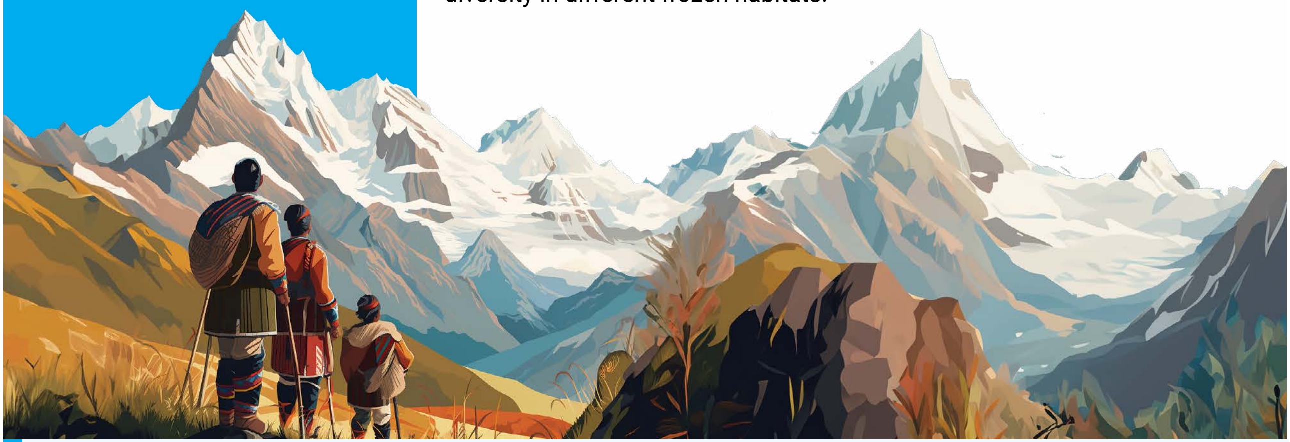
The cryosphere is ground zero for climate change. The impacts of 2°C warming include long-term and irreversible sea-level rise; substantial losses of mountain glaciers, ice sheets and sea ice; and extensive permafrost thaw. Sustained warming at 2°C above pre-industrial levels is too high to prevent cryosphere loss.

Source: The State of the Cryosphere Report 2023 – Two Degrees is Too High[51]

slowly.[10-12] Finally, many others are dormant but still viable, meaning that they survive in a state of very low metabolic activity but can multiply at normal rates again when conditions allow.[13,14]

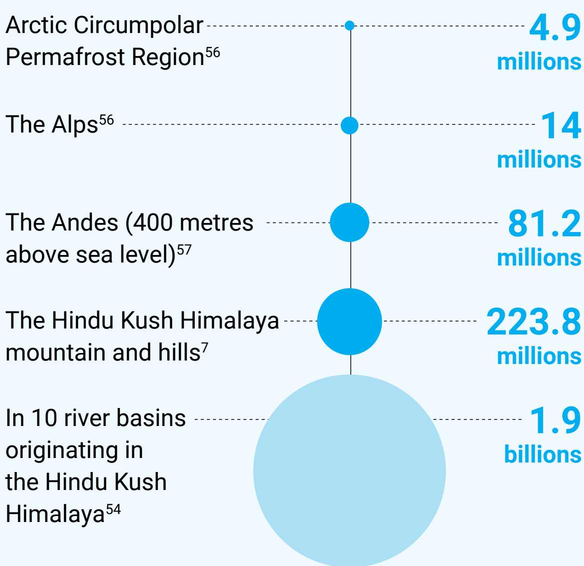
Under controlled laboratory settings and with relative ease, researchers have induced the reactivation of microorganisms from a dormant state after thousands of years.[15-24] Eukaryotic microorganisms, such as fungi, algae, and protists, have been reactivated from ancient ice dated to 50,000 years old.[25-33] Even viruses preserved in permafrost for up to 48,500 years have infected hosts and multiplied when reactivated in laboratory facilities.[34-37]

Bacteria are, by far, the most studied microorganisms in frozen habitats. They are found throughout the cryosphere, from polar ice to permafrost, in mountain glaciers at several kilometres of altitude and in deep subglacial ecosystems several kilometres below sea level in Antarctica.[8,9,38,39] Many of these bacteria form an encasement that make them more resilient – able to endure heat, cold, and desiccation, among many other stressful conditions. Bacteria are not only abundant in frozen ecosystems but also highly diverse. Although less abundant than bacteria, yeasts, a group of unicellular fungi, also exhibit remarkable diversity in different frozen habitats.[40,41]



People and the cryosphere

While some cryospheric landscapes are inhabitable, hundreds of millions of people live within this region. A 2010 estimate indicated that globally, around 670 million people, including Indigenous populations, lived in high mountain regions in all continents except Antarctica, that feature glaciers, snow cover and permafrost.[52] These populations are projected to reach between 736 – 844 million by 2050 in addition to billions living in the river basins downstream.[7,52-54]



What is the cryosphere?

The cryosphere encompasses "components of the Earth system at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground".[58] Cryospheric components exist in approximately 100 countries and at all latitudes.[59] The cryosphere supports unique habitats and plays a critical role in the Earth's climate through the global exchange of energy, water and carbon.[3,52]

Glaciers

A glacier is a perennial mass of ice, and possibly firn and snow, originating on the land surface by the accumulation and compaction of snow showing evidence of past or present flow.[58] Land ice masses of continental size (>50,000 km^2) are referred to as ice sheet.

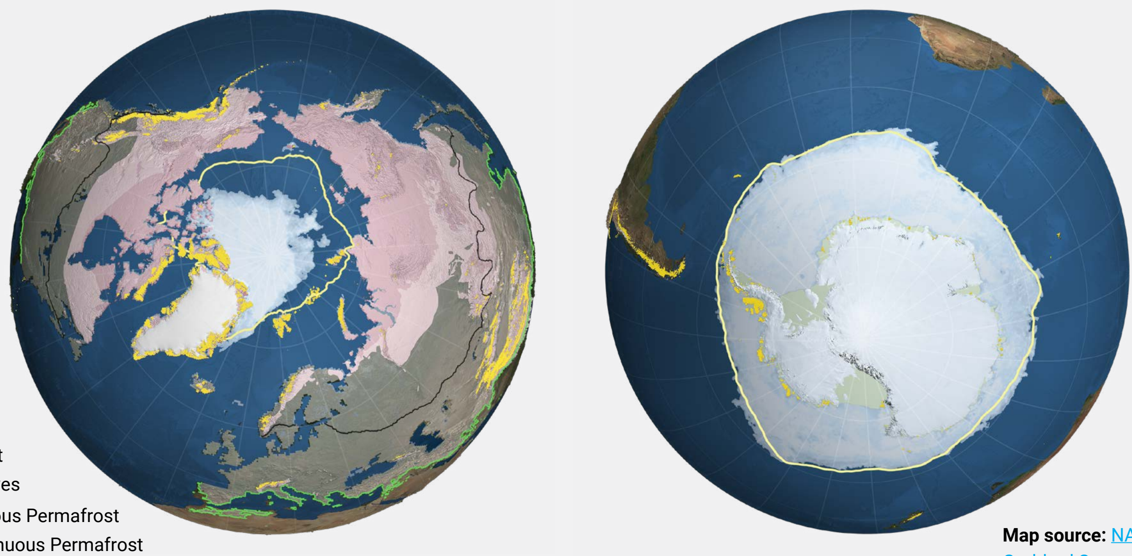
Ice Sheets and Ice Shelves

An ice sheet is an ice body originating on land that covers an area of continental size, generally defined as covering more than 50,000 km^2.[58] The Greenland and Antarctic ice sheets are the only two ice sheets existing in the modern world. Ice shelves are the floating extensions of ice sheets and glaciers into the surrounding ocean.[60] Nearly all ice shelves are in Antarctica.[58]

Glaciers and ice caps cover around 0.5 per cent of global land surface.[3]

Greenland ice sheet occupies about 1.2 per cent of global land surface.[3]

Antarctic ice sheet encompasses 12.295 million km^2, or about 8.3 per cent of global land surface.[3]



Map source: NASA/ Goddard Space Flight Center Scientific Visualization Studio

Permafrost accounts for 9 – 12 per cent of global land area.[3,61] **Seasonally frozen ground** covers about 33% of global land area.[3]

Arctic sea ice occupies between 1.7 per cent of global ocean area in September and 3.9 per cent in March.[3]

Antarctic sea ice occupies between 0.8 per cent of global ocean area in March, and 5.2 per cent in September.[3]

Permafrost

Permafrost is ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least two consecutive years. Note that permafrost is defined via temperature rather than ice content and, in some instances, may be ice-free.[58]

When near-surface soil layers freeze more than 15 days in a year and thaw annually, it is categorized as seasonally frozen ground.[62] It may or may not overlie permafrost.[3]

Sea ice

Sea ice is ice found at the sea surface that has originated from the freezing of seawater. Sea ice occurs in the Arctic Ocean, the Southern Ocean and their adjacent seas.[58]

Snow

Snow is water vapour frozen into the form of ice crystals and falling in light, white flakes. Snowfall is important for the formation of glacier ice and icesheet.

The cryosphere is changing

Cryospheric environments are undergoing significant changes. Many of the consequences of climate change for the cryosphere are expected to be irreversible on time scales of decades or centuries, including the melting of mountain and polar glaciers, depletion of ice sheets and pervasive permafrost thaw.[1,52] Changes in the cryosphere components have cascading effects on regions beyond the cryosphere and adjacent areas.

Sea ice trend

Artic sea ice extent is shrinking. The Arctic Ocean will likely become free of sea ice during the seasonal minimum for the first time before 2050.[63]

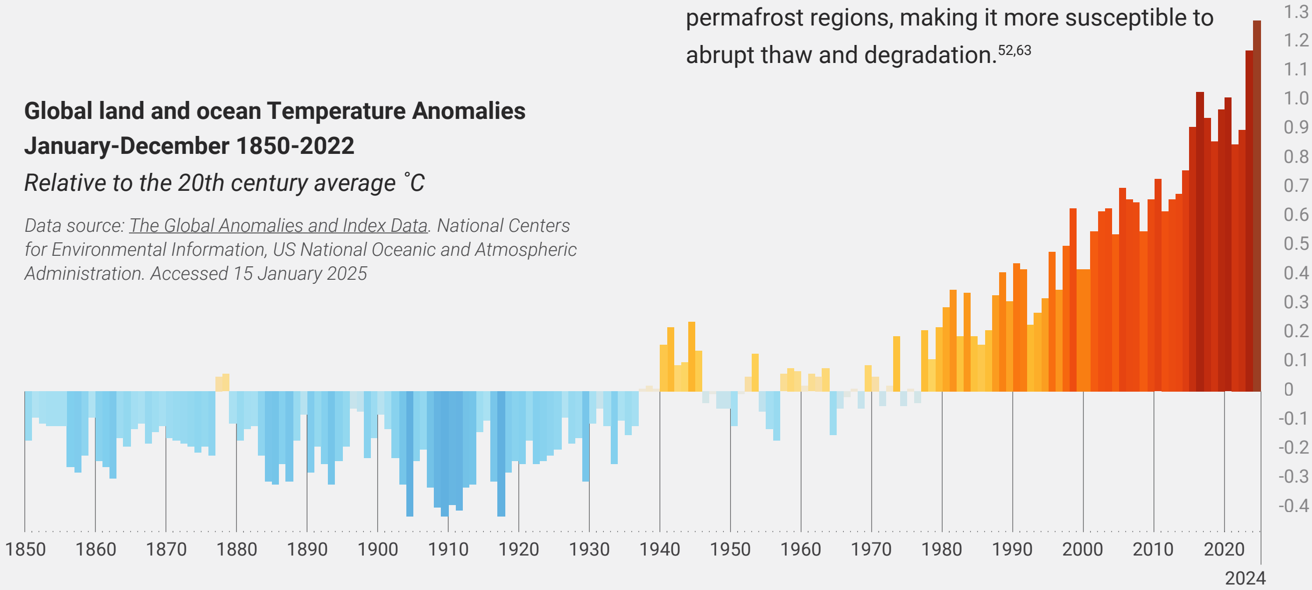
Permafrost trend

Permafrost temperatures have continued to rise to record high levels since the 1980s throughout the permafrost regions, making it more susceptible to abrupt thaw and degradation.[52,63]

Global land and ocean Temperature Anomalies January-December 1850-2022

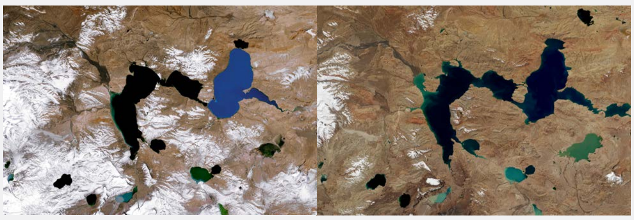
Relative to the 20th century average ˚C

Data source: The Global Anomalies and Index Data. National Centers for Environmental Information, US National Oceanic and Atmospheric Administration. Accessed 15 January 2025



Glacier trend

Glaciers worldwide continue to recede. The extent of glacier mass loss during the decade 2010-2019 exceeded the losses of any previous decade since the beginning of the observational record.[63] In the scenario where greenhouse gas emissions continue to increase unmitigatedly (RCP8.5), regions with mostly smaller glaciers, e.g., Central Europe, Caucasus, North Asia, Scandinavia, tropical Andes, Mexico, eastern Africa and Indonesia, are likely to lose more than 80 per cent of their current ice mass by the end of the century, while many glaciers are likely to disappear regardless of future emissions.[52]



1987 **2021**

Images: Lakes of the Tanggula Mountains—a small range in the central part of the Tibetan Plateau—offer a view of changes caused, in part, by retreating glaciers. The left image was acquired in October 1987; the right image shows the same area in October 2021. The two largest lakes—Chibzhang Co and Dorsoidong Co—have grown larger over time as the mountain glaciers have thinned and shrunk.
Credit: NASA Earth Observatory images by Joshua Stevens, using Landsat data from the U.S. Geological Survey.

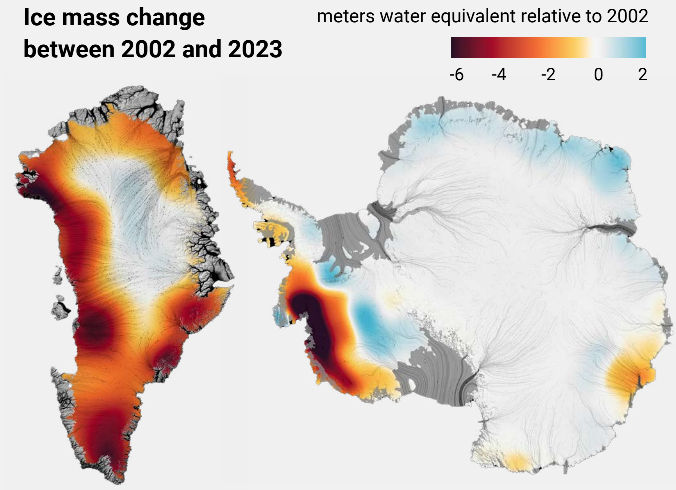
Snow trend

The warming trends in recent decades track declining snow cover in all regions especially at low elevations.[52]

Ice sheet trend

These two ice sheets are very likely to continue losing mass rapidly throughout the 21st century and beyond.[52]

Ice mass change between 2002 and 2023



Greenland
Average mass loss:
269 Gigatons/year

Antarctica
Average mass loss:
142 Gigatons/year

Source:
NASA and JPL/Caltech

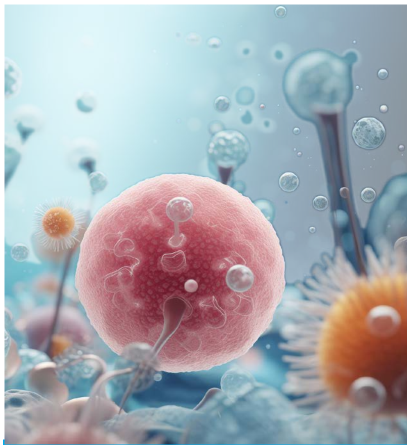
“Cryosphere warming will reactivate and remobilize modern and ancient microorganisms”

Conceptual image of microorganisms suspended in water, recently released after the melting of ancient ice.
Credit: Carlos Reyes, 2024. Created with the assistance of generative tools.

1.2
Thawing cryosphere and reactivated microorganisms

Between 1994 and 2017, 28 trillion tonnes of ice vanished from the Earth's cryosphere and, compared to the 1990s, the overall rate of ice loss increased by 57 per cent over those 24 years.[64] Projections to 2100 suggest that the number of the world's glaciers will be halved, even if temperature increase could be limited to +1.5°C.[65] Glaciers are no longer shrinking – they are disappearing.[63] Similarly, recent estimates suggest that 24 to 69 per cent of the planet's near-surface permafrost will thaw by 2100.[52,66]

Cryosphere warming will reactivate and remobilize modern and ancient microorganisms to new terrestrial and aquatic environments. Once there, specific populations of re-emerging microorganisms might thrive, profoundly modifying the structure and function of the existing microbial communities and surrounding ecosystems.[67-69] A 2022 estimate suggests that 2.9 x 10^{22} microbes will be discharged annually into downstream ecosystems in the Northern Hemisphere for the next 80 years due to glacier melting.[70,71] On the other hand, some cryospheric microorganisms will not survive the thaw, resulting in a loss of both microbial diversity and the potentially valuable information contained within their genomes.



"While we should remain vigilant for viable pathogens, another facet of the warming cryosphere raises concerns: virulence-related and antibiotic-resistance genes moving between microbes"

Many of these newly released microorganisms will interact with present-day microbial communities and with multicellular organisms. Research suggests that some reactivated microbes could be pathogens, able to infect plants and animals including humans.[37,72-76] The possibility of widespread outbreaks is unlikely, but scientists are honing their abilities to assess the threat presented by the release of these ancient pathogens from their frozen state.[77-83]

For instance, coliform bacteria from Canadian Arctic ice samples of up to 2,000 years of age were isolated in a research facility in the 1990s.[84] In 2015, researchers reactivated strains of *Bacillus anthracis* from three separate layers of sediments deposited since 1300s in Siberia's far northeast Yakutia region.[75]

In July 2016, an Anthrax outbreak in the northwestern Yamal region of the Russian Federation's killed over 2,000 reindeer herds and led to the hospitalization of 90 people from herder communities.[85] Researchers theorized that the abnormally high temperatures in that summer and the permafrost thaw contributed to the reactivation of *B. anthracis* in soil reservoirs, among other factors.[85,86]

The possibility of pathogen reactivation and release from frozen environments is not restricted to bacteria. Fungi, either filamentous or unicellular (yeasts), have also been isolated from cryospheric habitats including some with known pathogenic potential.[73,74,87] Also, research published in early 2023 reports a controlled experiment reactivating 13 new viruses isolated from seven different Siberian permafrost samples and successfully infecting *Acanthamoeba* hosts.[34] The experiment was designed to demonstrate that viruses can reactivate from a frozen state and infect a pervasive protozoan commonly found in soil, air, and water samples worldwide.

While we should remain vigilant for viable pathogens, another facet of the warming cryosphere raises concerns: virulence-related and antibiotic-resistance genes moving between microbes.[88] The transfer of genetic material from one cell to another, called horizontal gene transfer, only exists in the microbial world, where it occurs frequently and indiscriminately among species in natural ecosystems.[89] Acquisition of virulence-related genes by bacteria can give rise to strains with enhanced powers as a pathogen that are more efficient in causing disease. Researchers recently detected thousands of virulence factors in microorganisms collected from 21 Tibetan glaciers.[90]

"Information stored in ancient DNA and RNA could help us gain insight into the extreme virulence of some contemporary pathogens"

Many antibiotic-resistance genes have also been detected in cryospheric environments.[91-96] Their presence is unrelated to and is not affected by human influences since antibiotic-resistance genes have been discovered in pristine frozen areas and in ancient ice-core samples.[93,94,97] Antibiotic-resistance genes can also move by horizontal gene transfer from one bacterium to unrelated bacterial cells, even between different species, conferring resistance to specific antibiotics.

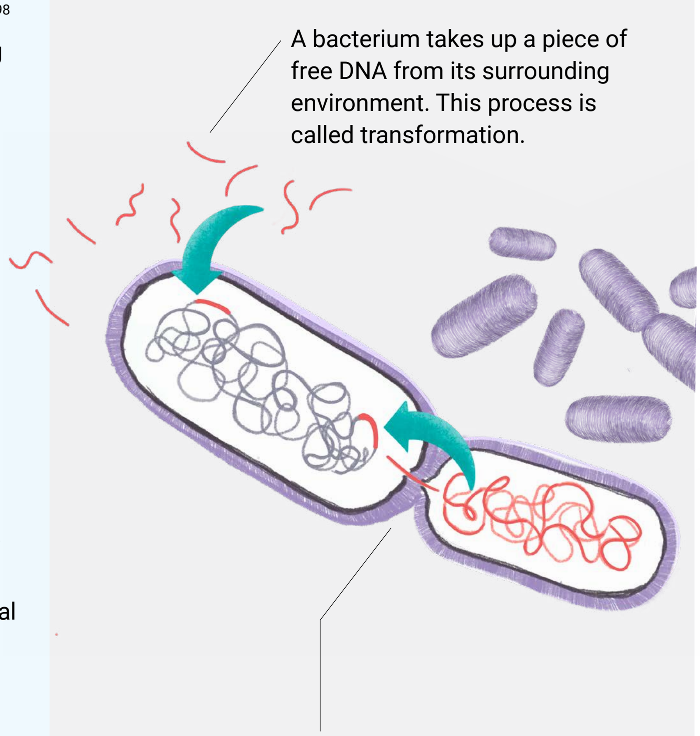
Some microbial genes and more complex genetic elements have remained stored for thousands[93,98] and even millions of years[99,100] in frozen environments. Scientific evidence suggests that horizontal gene transfer could have accelerated microbial evolution in the past and could be currently driving evolution in the terrestrial and aquatic ecosystems that receive an influx of glacial meltwaters.[101,102] This process of constant mixing between modern and newly released but ancient microorganisms, including their respective genomes, is called genome recycling[103] and can lead to the emergence of new strains of microbes with a higher virulence potential.

Unfrozen antimicrobial resistance genes

Another significant aspect of the changes happening in cryospheric microbial communities is the emergence of antimicrobial resistance genes. Antimicrobial resistance occurs naturally and have ancient origins.[98] Myriads of antimicrobial resistance genes, conferring resistance against modern-day antibiotics, such as chloramphenicol, beta-lactams, streptomycin and tetracycline, have been detected in cryospheric ecosystems.[91-96,104]

These antimicrobial resistance genes, which are generally part of mobile genetic elements, can be transferred from one bacterium to their offspring, but also to unrelated neighbor cells, or even between different microbial species. The latter mechanism, called horizontal gene transfer, occurs frequently in natural ecosystems. This is why antimicrobial resistance genes are considered biotic contaminants and represent a genuine ecological problem.[105] Like the microbes to which they belong, these antimicrobial resistance genes—some of which can be part of mobile genetic elements—have remained in frozen environments for thousands[97,98] and even millions of years[99]. Both antimicrobial resistance genes and mobile genetic elements of ancient origins can be acquired by contemporary bacteria by horizontal gene transfer, making them resistant to specific antibiotics.[100]

Mobilization of antimicrobial resistance genes

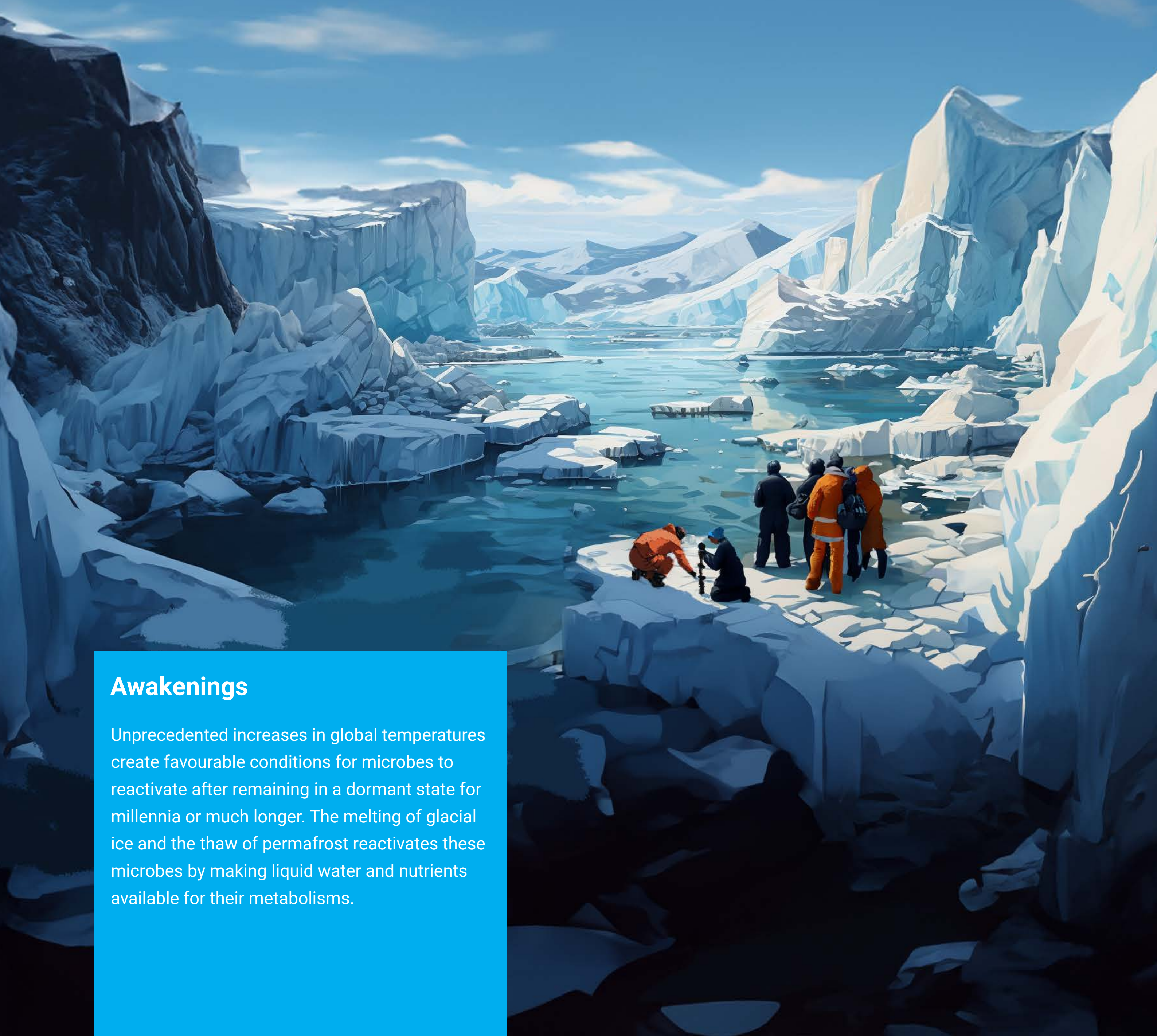


Frozen in time

In the past, glaciers, icesheets and other cryospheric environments were largely ignored as biomes.[106,107] Seemingly too hostile to support any life, cold and icy environments are in fact teeming with diverse and abundant, contemporary and ancient microbial beings. The conditions that limit active multiplication of many microbial species are the same ones that guarantee their preservation for a very long time.

These unique microbes have evolved an array of adaptation strategies to overcome life-endangering extremes including freezing temperatures, limited availability of liquid water and nutrients, and high UV irradiation.[38,108]

At subzero temperatures, these cold-adapted microbes can stay active and multiply very slowly, whereas others remain viable in a dormant state for extended periods, with an extremely low metabolism.[82] Microbial communities in the cryosphere play important roles in the Earth's biogeochemical cycling of carbon, nitrogen, and other elements.[106]



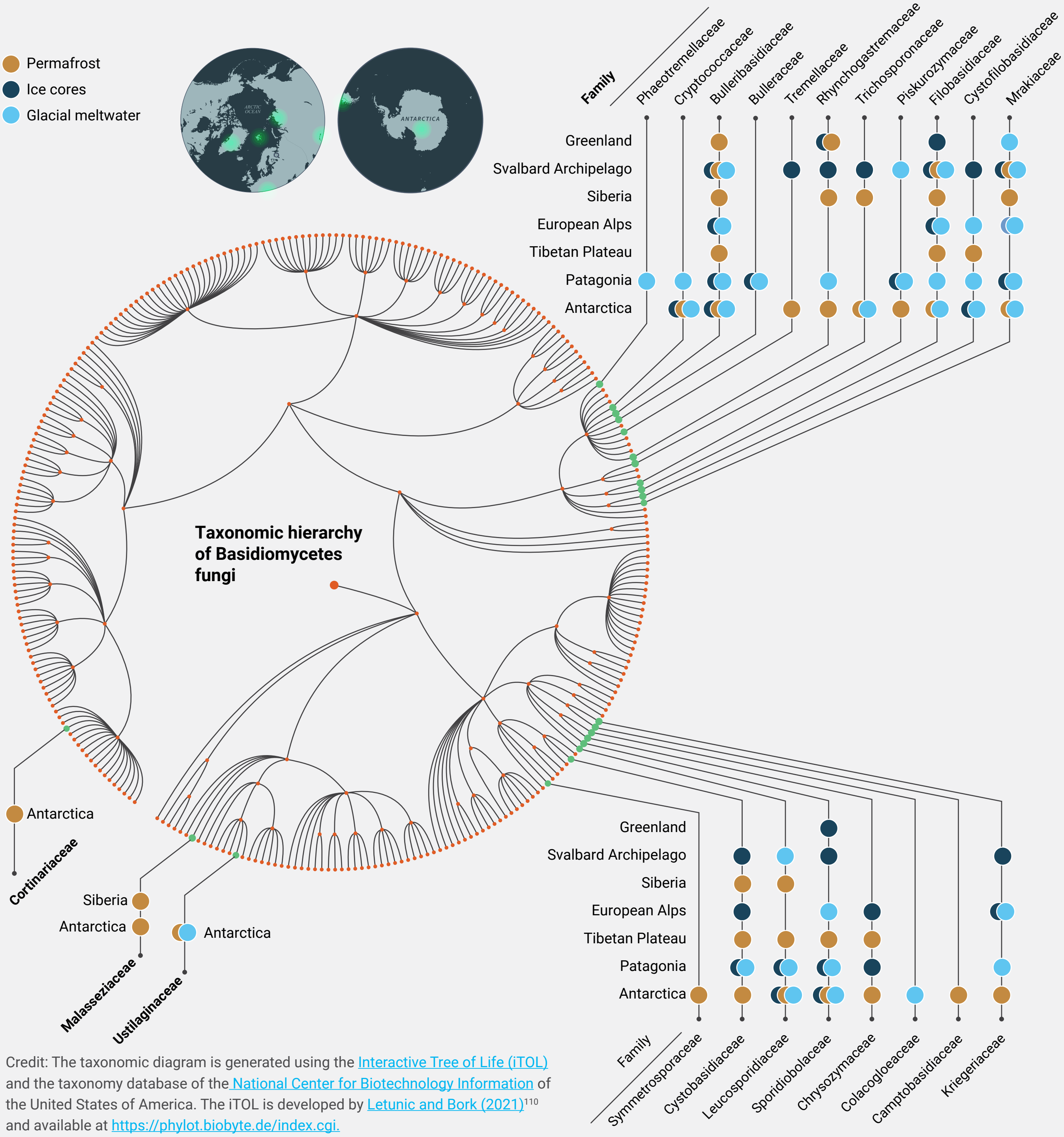
Awakenings

Unprecedented increases in global temperatures create favourable conditions for microbes to reactivate after remaining in a dormant state for millennia or much longer. The melting of glacial ice and the thaw of permafrost reactivates these microbes by making liquid water and nutrients available for their metabolisms.

Samples of frozen microbes

Decades of research and discoveries revealed the abundance, diversity and distribution of microbial communities across different cryospheric environments. Systematic reviews of this research describe a range of cold-loving microorganisms – bacteria, archaea, viruses, and fungi – found in samples from ice cores, meltwater, lake water, seawater, snow, soil and permafrost.

Here, we focus on the Basidiomycota Phylum of fungi to provide a snapshot of the diverse taxa throughout the cryosphere. The cyclic diagram presents the taxonomic hierarchy of Basidiomycetes fungi, including yeasts, down to the Family level. It highlights specific fungi Families found in ice cores, glacial meltwater and permafrost based on the detailed compilations by Buzzini et al. 2017, Sannino et al. 2017, da Silva *et al.* 2019 and de Menezes et al. 2019.[40,41,87,109] This visualization represents a tiny example of the microbial diversity present in frozen environments rather than providing an exhaustive list of all discovered species.



Credit: The taxonomic diagram is generated using the Interactive Tree of Life (iTOL) and the taxonomy database of the National Center for Biotechnology Information of the United States of America. The iTOL is developed by Letunic and Bork (2021)[110] and available at https://phylot.biobyte.de/index.cgi.

Opening the frozen Pandora's box

The discovery of viable microorganisms in glacial ice dates to the early 1900s.[39] However, pioneering studies in the Antarctic in early 1980s led to a renewed interest in the subject. Over the years, scientists have found diverse types of ancient microbes worldwide and successfully reactivated and cultured them in the laboratory. The map highlights selected studies that have uncovered viable ancient microbes from various cryospheric environments worldwide.

Greenland, Denmark

Scientists recovered hundreds of fungal and bacterial isolates from Greenland ice cores that are nearly 140,000 years old.[111] A subsequent study made a similar dviscovery in ice samples of 500 to 157,000 years old, collected in both Greenland and Antarctica.[22]

Tomato mosaic tobamovirus, a plant pathogen, was recovered from 140,000-year-old Greenland glacial ice.[49]

Alaska, United States of America

Diverse species of bacteria isolated from an ancient ice wedge sample from Alaska's permafrost were culturable after 25,000 years.[112]

Ellesmere Island, Canada

2000-year old coliforms were isolated from Canadian Arctic ice.[84]

South America

Diverse species of bacteria and fungi, including yeasts, have been isolated from high-altitude tropical and Patagonian glaciers of the Andes Mountain Range.[41,113,114]

Qinghai-Tibetan Plateau

Scientists have successfully cultured various phyla of bacteria from the Guliya ice cap on the Qinghai-Tibetan plateau, dated to 750,000 years old.[47]

The Himalaya

Numerous studies find that bacterial isolates from glaciers in the Himalaya – such as East Rathong and Chhota Shigri glaciers in India, Siachen and Batura glaciers in Pakistan – were resistant against commonly used antibiotics and heavy metals.[115,116]

Siberia, Russian Federation

Thirteen new virus species dated to be more than 27,000 years old were isolated from ancient Siberian permafrost samples and intestinal remains of a prehistoric wolf and woolly mammoth. Using amoeba cells as a bait, researchers demonstrated that these viruses were capable of infecting other living cells.[34-36]

Evidence of bacterial survival of up to half a million years was found in permafrost samples from northeastern Siberia.[21]

Viable amoebae species of up to 35,000 years old have been isolated from permafrost in the North-East of Siberia.[31,32]

Antarctica

Numerous viable bacteria species were obtained from accreted ice of Lake Vostok, which is a subglacial lake located approximately 4 km deep under the Antarctic Ice Sheet.[15,16,39] Lake Vostok has been completely isolated from any direct exchange with the atmosphere for at least 420,000 years.

Besides bacteria, more complex microorganisms, such as fungi, have also been isolated with relative ease from ancient Antarctic permafrost of more than 50,000 years old.[25]

1.3 Cryospheric microbes and their importance

Frozen environments are extremely challenging habitats for microorganisms: liquid water is scarce, sharp ice crystals might destroy their delicate membranes, and high doses of UV radiation severely damage their genetic material. Despite these constraints, some microbes thrive under these conditions and they are generally referred to as psychrophiles, a Greek term for cold-loving.[117]

"Cryospheric environments are an invaluable source of modern and ancient genetic material, extraordinary well preserved in the cold."

Psychrophiles have evolved different strategies to counteract restrictions imposed by frozen environments. Such strategies include production of antifreeze compounds, synthesis of molecules that increase membrane fluidity, production of compounds that act like sunscreen, and the ability to enter a dormant state.[118-121]

Psychrophiles' ability to thrive at low temperatures is due, in part, to their enzymes being able to function at low temperatures. Cold-active enzymes are extremely interesting and useful from a biotechnological perspective.[119] In fact, many of them have already been used to develop valuable products. The list is extensive and includes enzymes used by large industrial sectors, like those responsible for the production of food, beverages, detergents and high-quality chemicals, among others.[122-125]

For instance, psychrophilic enzymes have been used to produce pharmaceutical compounds, like antihypertensive, antihyperglycemic, antioxidant, and immunoregulatory drugs.[126] Cold-active xylanases, which help process plant cell walls, are used by the bakery industry to improve the quality of bread.[124] Psychrophilic lipases and proteases, which remove organic stains from textiles, are used as component of cold-water active detergents.[125] Also, various psychrophilic enzymes are crucial for diagnosing many diseases.[124]

Other biological compounds produced by psychrophiles are valuable for the development of new antimicrobials[126] and organic polymers[127], or as protectants of organs and tissues for transplantation purposes[128]. Besides the utility of their molecules, whole cells of some psychrophiles can be employed as biofertilizers to improve crop yields in cold regions because they foster seed germination and then promote plant growth and development.[129,130]

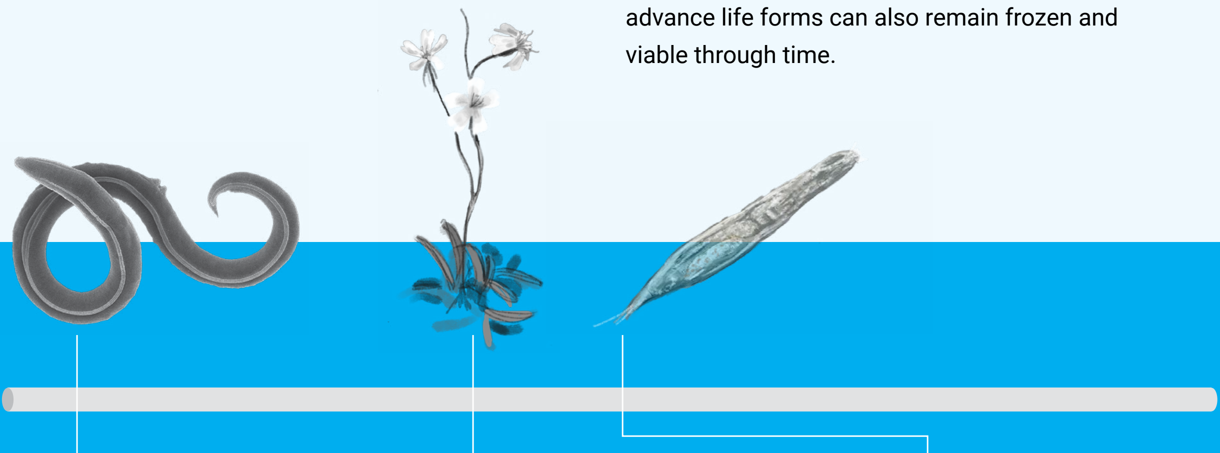
Psychrophilic microbes provide clues about the emergence and evolution of life on Earth.[11,119,133] That, in turn, leads to better understanding of other planetary systems' capacity to sustain life.[134] Since cryospheric environments are analogs of potentially habitable icy worlds, some psychrophiles serve as astrobiological models.[134-136] Only by attaining a deep understanding of microbial life under extreme conditions will space agencies be able to determine where and how to look for extraterrestrial life.[137-138]

Cryospheric environments are an invaluable source of modern and ancient genetic material, extraordinary well preserved in the cold. Besides its paramount importance in comprehending the evolution of many microbial species[139], information stored in ancient DNA and RNA could help us gain insight into the extreme virulence of some contemporary pathogens.[140] Studying ancient antibiotic resistance genes preserved in the cryosphere is essential for appraising how they arose, how they evolved, how they are acquired, and how they disseminate in the environment.[92,94,141-143] This information can then help us to design strategies to fight antibiotic resistance in modern pathogenic microbes.

Our understanding of the microbial world remains limited, especially those microorganisms that thrive in extreme environments. These include examples from volcanic and sulfuric hot springs, dry and hot deserts, deep-sea hydrothermal vents, acid-mine drainages, highly pressurized deep seas, sub-surface caves, and supersaturated salt lakes, as well as cold and high UV-irradiated environments.[144] We must maximize our understanding of these microbes and their adaptations while we still have the opportunity.

Reactivation of complex life-forms

Apart from simple microbial living cells, more advance life forms can also remain frozen and viable through time.



46,000
years old

In 2023 scientists reactivated a female roundworm of novel species that had been found dormant in the Siberian permafrost for 46,000 years.[145] The roundworm also started reproducing asexually.

30,000
years old

Ancient flowering plants were regenerated using tissue from fruits found buried in the undisturbed permafrost dated to the Ice Age.[146]

24,000
years old

Ancient rotifers, microscopic aquatic animals, found in permafrost were revived after 24,000 years of dormancy.[147]

Image credit: Female nematode Panagrolaimus kolymaensis from Shatilovich *et al.* (2023) under CC BY 4.0 DEED / Cropped from original.

1.4
Managing the unavoidable

"By failing to avoid the unmanageable, we now must manage the unavoidable..."

Global cryosphere loss is an ongoing process with potentially irreversible consequences. If greenhouse gas emissions continue unabated, Earth's average temperature will keep rising and, before 2030, will likely exceed the limit of what the Intergovernmental Panel on Climate Change determines as a manageable 1.5°C increase over preindustrial levels.[148] Even if emissions ended today, the cryosphere would take centuries to return to mid 20th century conditions.[63]

While efforts must continue to end emissions, a few approaches to slow the effects of warming on the cryosphere are possible as adaptive management. One approach is to restrict air pollutants that accelerate glacier melting, like black carbon particles. Dark particles that accumulate on glacier surfaces reduce their albedo causing them to absorb more heat, accelerating their melting. Black carbon must be addressed at the source. Primary sources of black carbon include particulates from diesel engines, open-field agricultural burning and wildfires.[7,149,150] Other measures include limiting and refining tourism activities in fragile cryospheric environments.[151-153] Finally, some proposals suggest expanding the use of reflective geotextile sheets over ice surfaces to reduce seasonal melt.[154] However, scaling up the current practice of preserving ski slopes to shielding whole glaciers from the sun and warmth would entail huge expense and negative effects from plastic material degradation.[155]

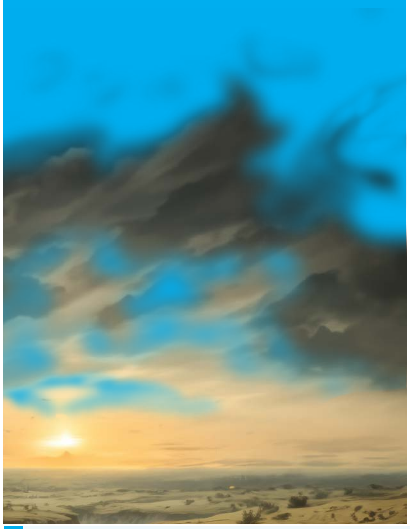
Slowing the thaw of permafrost is even more complex. Experiments on a small scale to rewild permafrost tracts with herds of large grazers like bison, horses and reindeer in the expectation that they harden the snowpack and extend its insulating properties, involve so many interacting systems at various scales that success has been elusive.[156-158] The idea is intriguing. However, many assumptions must be overcome: to work at the required scale, the scheme would involve huge effort, commitment and expense over an extended time frame.[159]

While glacial and permafrost ecosystems continue to disappear, the documentation and preservation of cryospheric microorganisms must continue. Once the less robust microbes die off and the adaptable evolve, it will be difficult if not impossible to trace the origin of epidemiological agents discharged from thawed habitats. Despite the high value in understanding these microbes and their evolution, coordinated efforts to establish dedicated culture collections and biobanks exclusively for psychrophilic microbes and their genetic information are minimal. The conservation of their genetic material is crucial, as they can provide information about the history of climate and evolution, but also reveal unknown metabolic variants, which could help in finding therapies for a variety of diseases and develop highly innovative biotechnologies.

While many questions concerning the potential threat posed by the release of harmful infectious agents from thawing permafrost and other cryospheric habitats remain under intense investigation, and even though international and coordinated actions have not been undertaken yet, there is an increasing concern on this matter. This was clearly established in a recent international workshop organized by the InterAcademy Partnership, the European Academies Science Advisory Council and the US National Academies of Sciences, Engineering, and Medicine.[160] It is thus becoming clear that public health surveillance in the cold regions would need to take into consideration climatic and environmental factors that favour the reactivation of dormant microbial communities.

Rapid melting of glaciers and thawing of permafrost are examples of how the failure to mitigate greenhouse gas emissions over the last three decades is delivering ominous repercussions. By failing to avoid the unmanageable, we now must manage the unavoidable, witnessing the loss of stable ecological systems that our species evolved with and struggling to preserve samples of those systems' diversity and unimaginable value.

"Permafrost soils in the northernmost region store the largest volumes of organic carbon ... readily available for microbial decomposition."



Active microbes and greenhouse gases

The most pertinent consequence of reactivated microbes from cryospheric habitats is the decomposition of organic matter in thawing soil, transforming a carbon sink into a carbon source. Permafrost soils in the northernmost region store the largest volumes of organic carbon in the form of peat layers, readily available for microbial decomposition.[161] Increased microbial activities enhanced by permafrost thaw release vast amounts of carbon dioxide, methane and nitrous oxide, three well-known greenhouse gases, to the atmosphere.[162-164] At the same time, microbes exist that consume these gases. The interactions and composition of these GHG-producing and -consuming microbes, together with changing environmental conditions, play a critical role in determining the permafrost carbon feedback to climate.[165]

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While humans have benefited significantly from these services, nearly all barriers modify water flow and temperature, habitat quality and quantity, downstream sediment transport, and fish movement.

The Global Foresight Report and Process brought to light important signals of rapid and advancing processes of environmental, technological and social change that steadily degrade the resilience of social and ecological systems. At the same time, it identified signals of opportunities offering novel ways to address social and environmental problems. This chapter discusses the emerging opportunities to restore the health and resilience of degraded river ecosystems through the removal of unsafe and obsolete dams and river barriers.

Illustrations: Carlos Reyes, 2024. Created with the assistance of generative tools.

02 Clearing the path

Barrier removal for river restoration

Author
Mellisa Foley (San Francisco Estuary Institute, Richmond, California, United States of America)

2.1 Damming the river

About 62,000 large dams are reported globally.[1]

Many millions of smaller dams and barriers may exist worldwide.[2-4]

People have built barriers – from small weirs to large dams – on rivers for thousands of years and for a myriad of reasons, including water storage and supply, irrigation, flood protection, power for mills, electricity generation, and recreation. While humans have benefited significantly from these services, nearly all barriers modify water flow and temperature, habitat quality and quantity, downstream sediment transport, and fish movement. Inland fisheries that communities depend on as local food sources can be devastated following the construction of a barrier, particularly large dams. These damages to the river spread out to the surrounding riparian ecosystems and further downstream, often all the way to estuaries and coastal areas.

Barriers in river systems

In this report, 'barrier' refers to structures of various sizes, designs and functions placed on streams or rivers forming an obstacle to natural flow, such as those shown below. Other smaller barriers include culverts, sluices, fords and ramps.

Dam:
a structure built across a stream or a river to control the flow of water and create a reservoir.[5] When the structure is 15 metres or higher from the lowest point of the foundation to the top, it is considered a large dam.[1]

Weir or low-head dam:
a structure placed in an open channel to raise the water level to the required height and allow water to flow freely over the top. Weirs vary in shape and size but are usually less than 5 metres high.[6]

Barrage:
a structure similar to a weir but installed with adjustable gates to regulate the water level and flow pattern at various times.[7]

Most existing barriers are small – under 3 metres in height – but their effects can be extensive, particularly when multiple barriers are built along a single river course.[2,8] Besides contributing to the declining health of waterways, larger barriers that create extensive reservoirs often displaces Indigenous and marginalized communities.[9,10] In addition to displacement, dam building can further impede Indigenous communities by removing access to rivers they depend on for food, water, culture, ceremony, and well-being.[11,12]

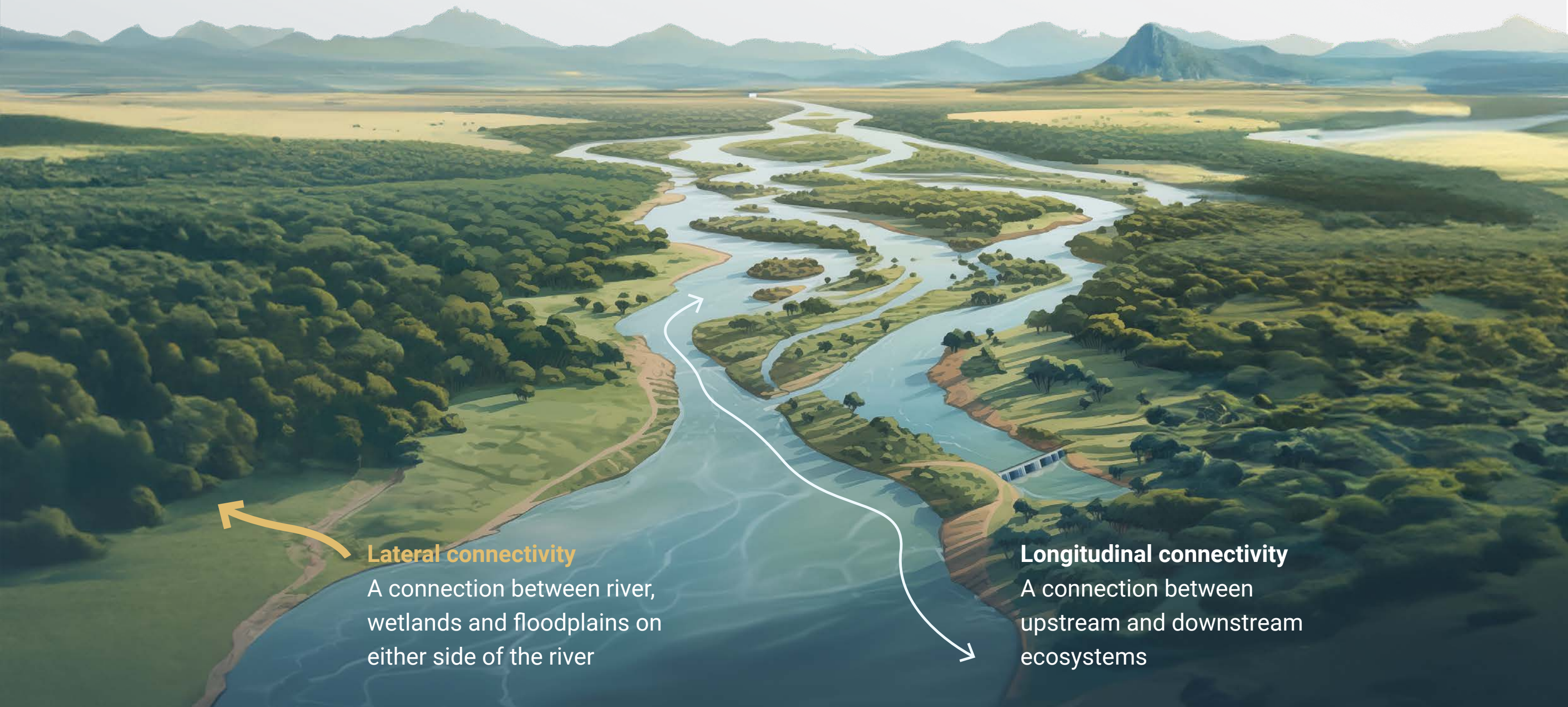
"One of the major drivers of barrier removal is to restore long-distance migration pathways for fish, particularly species that swim from the ocean to spawn in rivers."

Recognition of the ecological and social damages caused by dams has increased over the last 30 years. As more barriers, particularly large dams, reach their operational lifespans and become unsafe[13,14], obsolete[15], or economically unviable[16], removing barriers is an increasingly accepted strategy to restore river health.[17-20] The number of barrier removals worldwide is increasing, particularly in North America and Europe.[21-28] These removals include many dams that are over 10 metres high.[27,29-31] In almost every case, dams considered for removal no longer serve their intended purpose, produce adverse effects on flora and fauna, or cause more problems than they solve. They are legacy installations that continue to obstruct natural processes.[32] With each barrier removal, an opportunity emerges to see how the river responds and whether reconnecting the flow of water, sediment, nutrients, plants, and animals along a river is sufficient to restore these long-altered ecosystems to a healthy condition. As with ecosystem integrity in general, reducing fragmentation and restoring connectivity in river ecosystems benefits aquatic, avian and terrestrial communities and builds resilience to withstand future threats to ecological health.[33]

River connectivity

Free-flowing rivers are vital for the maintenance of aquatic and terrestrial biodiversity and the provision of ecosystem services. Natural river connectivity allows movement and interchange of water, organisms, nutrients and sediments through four dimensions: up and downstream or longitudinally, out over the riverbanks and floodplains or laterally, from the underlying aquifer up to the atmosphere or vertically, and through all the seasons or temporally.[1,34]

Humans have modified natural river connectivity for millennia by building structures along the longitudinal or lateral flow paths. Physical structures of various sizes – such as dams, weirs, and barrages – diminish the natural movement of living and non-living matter, impeding the ecological integrity and health of the river system.



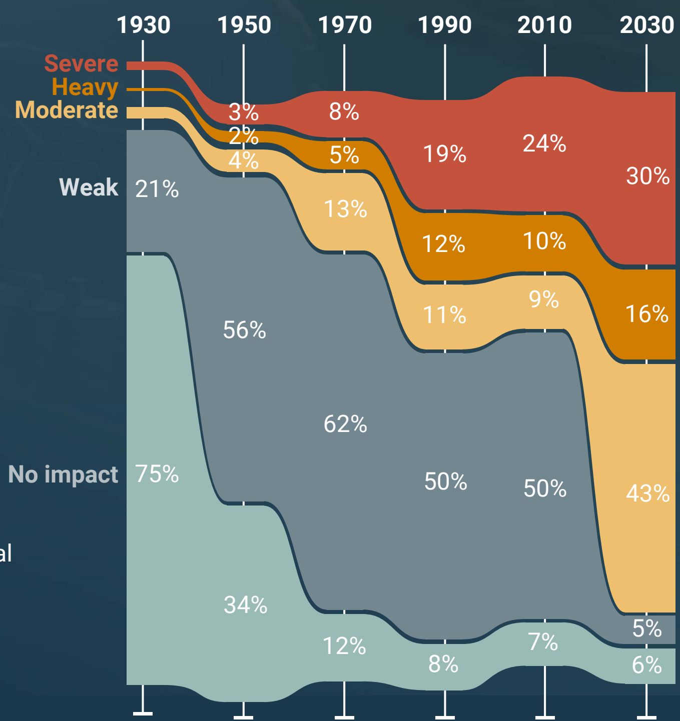
River fragmentation

A global analysis by Grill et al. (2015)[8] assessed the cumulative effects of large dams on river fragmentation at basin and sub-basin scales, accounting for 6,374 existing large dams and 3,377 hydropower dams under construction or proposed.

When a dam is installed in a river, the aquatic habitat is divided not only in length, but also in volume. Using the river volume as the basis for impact analysis, the investigators revealed that by 2030, 89 per cent of global river volume will be moderately to severely impeded by fragmentation – a sharp rise from 43 per cent in 2010.

The analysis by Grill et al. (2015)[8] considered only large dams due to the lack of georeferenced data on smaller dams and barriers. Other researchers estimate that several million barriers may exist worldwide.[2-4] The effects of barriers of all sizes on global river connectivity are likely to be far greater and more severe than the findings of the global river fragmentation analysis suggested.

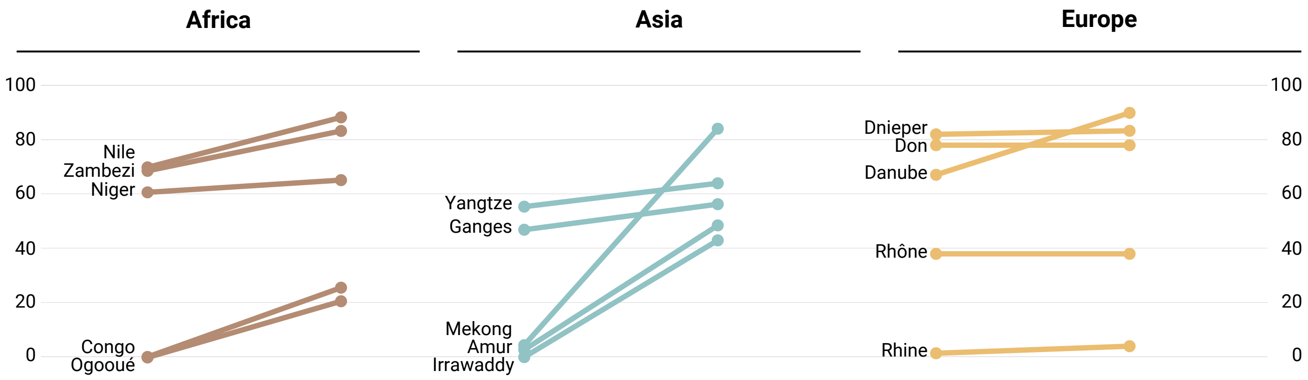
Trends in river fragmentation 1930-2030



Trends in river fragmentation by large dams in selected river basins

The graphs show the levels of river fragmentation in 2010 with projections for 2030, based on an Index developed by Grill et al. (2015).[8] The River Fragmentation Index measures river fragmentation by dams impeding longitudinal connectivity in a basin.

The Index of an unfragmented river network is 0 in a basin with no dams. Introducing a dam and each subsequent barrier on the same river network raises the Index, with the maximum value being 100. The Index for 2030 is calculated based on the assumption that all dams planned or under construction at the time of the analysis are completed by 2030.



Niger: Dams along the Niger River system have decreased water and sediment flows, so less sediment reaches the delta and shoreline. Extensive petroleum extraction activities that cause land subsidence and pollution threaten the deltaic ecosystems of the Niger, impairing their resilience as sea level rises.[35-37]

Zambezi: Dams on the Zambezi provide hydropower and control flow for irrigation and flood prevention. As climate changes, prolonged droughts broken by torrential rains force erratic flow releases, straining dam design and capacity. More dams are planned, disrupting the delivery of adequate sediments to wetlands of floodplains and deltaic ecosystems that support iconic wildlife and their habitats.[38-40]

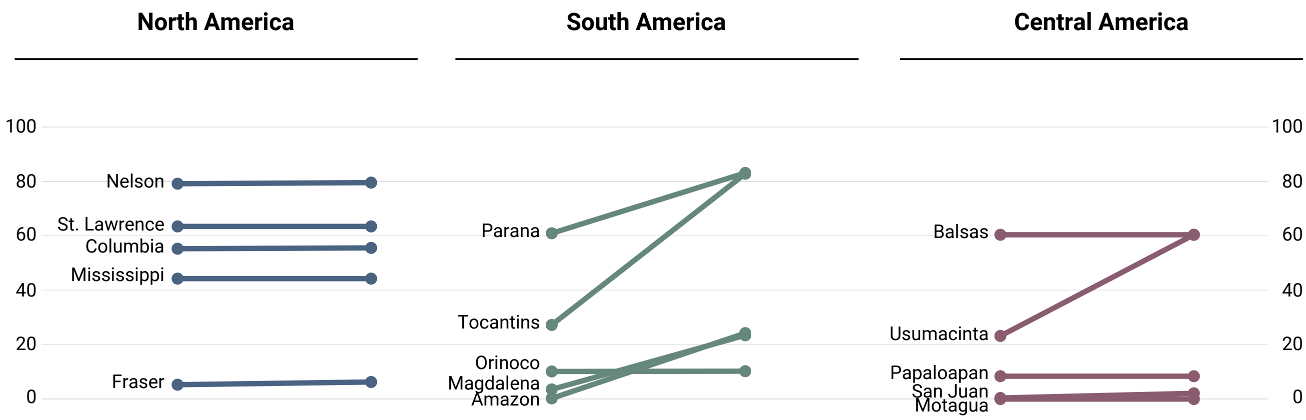
Mekong: Upstream dams reduce sediment supply downstream, resulting in riverbank erosion and loss of riverbank gardens.[41] A study of Mekong sediment loads reports a 74 per cent decline in supply to the Mekong Delta between 2012 and 2015. Sediment starvation and rising sea levels are significant factors in the shrinking of the Vietnamese Mekong Delta.[41,42]

Yangtze: At least 50,000 dams of various sizes exist in the Yangtze River Basin, profoundly altering the hydrology, morphology and ecology of downstream river systems.[43,44] The operation of the Three Gorges Dam has caused a 77 per cent reduction in annual sediment supply, resulting in riverbed deformation and morphologic changes in the Yangtze Delta.[43,45-47]

Danube: Nearly all countries in the Danube basin depend on hydropower. The proposed construction of more than 1,300 primarily small hydroelectric dams on tributaries across the Balkans raises concerns for the survival of endemic freshwater fish and mollusc species in the Balkan Peninsula.[48]

Rhine: Twenty-one dams exist in the upper section of the Rhine to regulate discharge and produce hydropower.[49] Below that, the river is channelized and embanked but free-flowing to facilitate transport. The Rhine's fragmentation Index is low, as much of the river network remains connected along its length. However, lateral connectivity to its floodplain is hampered by embankments for flood control and enhanced navigation, nearly eliminating characteristic habitats and species that depend on regular flooding.[51,52]

Source:
The river-specific messages draw from the findings of cited studies highlighting the impacts of barriers on both longitudinal and lateral connectivity of the rivers, while the data forming the graphs originate from the analysis by Grill et al. (2015)[8] focusing on longitudinal connectivity.



Mississippi: Many dams and levees have been built in the Mississippi River basin since the 1800s for flood management and river-level control to enable shipping. Recent research attributes Mississippi Delta shrinkage to sediment retention by dams (20 per cent) and levees (40 per cent) and to subsidence caused by oil and gas extraction (40 per cent).[53,54]

Fraser: A significant salmon habitat, the Fraser River is free of dams along its main stem, but several exist on its tributaries.[55] However, the Lower Fraser River does contain more than 1,200 smaller instream barriers, such as floodgates and culverts, that can obstruct fish access to upstream ecosystems.[56]

Paraná River: The demand for hydropower in South America is rising. The Paraná River has 389 operational plants, 8 under construction, and 577 planned. Dams on the Paraná obstruct the migration of long-distance species, hindering their survival. These structures also enable invasive fish species that prey on native fish species, further threatening native species' ability to adapt to changing conditions.[58,59]

Amazon: At least 351 more dams are planned for the Amazon River. Projections suggest that the dams proposed for the upper basin will reduce downstream sediments by 54 per cent, phosphorous by 51 per cent, and nitrogen by 23 per cent. These substantial declines in sediment and nutrient inputs will alter channel geomorphology and suppress floodplain fertility and aquatic productivity.[60,61]

Central America has 187 dams in operation, 34 under construction, and 205 planned. Hydropower dams and diversions of river flows have affected 25 per cent of the region's 622 freshwater fish species and 45 per cent of species classified as threatened with extinction by the IUCN Red List of Threatened Species.[57]

2.2
Removing barriers to healthy rivers

"Removing several barriers along a continuous stretch of the same river can have notable positive effects on river health."

Assessing the success of barrier removal in restoring ecological health to rivers depends on the metrics used to evaluate ecological health and how success is defined. When barriers are removed, river connectivity is restored allowing water, sediment, nutrients, and organisms to move up and downstream. One of the major drivers of barrier removal is to restore long-distance migration pathways for fish, particularly species that swim from the ocean to spawn in rivers. Upon removal of a barrier, the upstream passage opens almost immediately, so fish and other mobile species benefit from access to tens or hundreds of kilometres of formerly unavailable upstream habitats and can rapidly recolonize and repopulate.[14,23,62-68]

However, in some cases, the abundance of aquatic plants and animals may initially decline before their populations increase.[69-71] When the reservoir drains, conversion from a lake-like ecosystem back to a free-flowing riverine system can drive fundamental shifts in aquatic communities from species that favour lakes and reservoirs to those adapted to flowing waters.[72-74] Biological response may be rapid, but the long-term ecological recovery may not settle at pre-dam conditions.

Biological recovery tends to lag behind sediment redistribution. Once connectivity is restored, the downstream flow of sand, silt and clay resumes. Eventually, the renewed sediment delivery will support the revival of habitats for fish and invertebrates and reverse the legacy of erosion along the river, in riparian areas, and in some cases, coastal beaches.[75-77] However, the initial pulse of released sediment can jeopardize some species, particularly flora and fauna that are sensitive to high amounts of particles in the water column. Larger and older barriers tend to have more sediment stored behind them, so the initial disturbance is often far greater than following the removal of small barriers.[78-81]

On river systems that host multiple small barriers, removing a single barrier often does not alleviate the disruptions to natural processes because the length of reconnection is typically short. Removing upstream barriers while retaining those downstream also tends to result in minor changes to overall river health because the spatial scale of any benefit is limited.[82] However, removing several barriers along a continuous stretch of the same river can have notable positive effects on river health.[82,83]

"Removal of barriers, especially larger ones, is often a contentious process at the intersection of ecological, economic, and cultural concerns."

The success of river restoration following barrier removal depends on a combination of factors unique to each situation. Multiple stressors damage the health of rivers, particularly stressors from surrounding land use changes. Where watersheds have been crucially altered by land use changes such as urbanization or deforestation, dam removal alone may not significantly improve to river health.[73,84,85]

As such, when assessing the potential ecosystem-restoration outcomes of a particular barrier removal, considerations should include the position of the dam and the number of additional dams within the watershed. The goal is to open as much river habitat along as many extended stretches of unimpeded flow as possible. The size of the barrier is also a crucial factor, with the understanding that removing a single small barrier will have less effect than removing a large one. Another important concern is the amount and type of sediment stored behind the barrier that will be moving through the system following dam removal. Sometimes pollutants are trapped in reservoir sediment and will require alternative sediment-removal strategies.[73,86,87] Finally, the prevalent conditions and expected improvement in ecosystem health of the surrounding habitats should be considered in assessing possible outcomes.[88,89]

Freeing the river

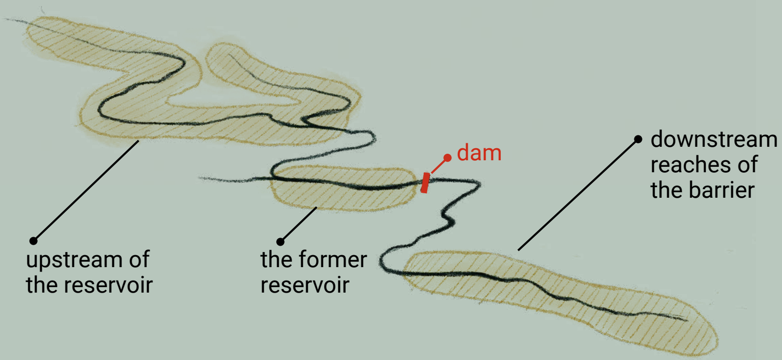
Rehabilitating river ecosystems has increasingly become a key motivation for barrier removal. When a barrier is removed, natural river connectivity re-establishes, allowing upstream movement of organisms and nutrients and downstream sediment delivery along the river and shorelines.

Rivers and streams often recover remarkably once barriers are gone. However, barrier removal may not achieve anticipated ecosystem rehabilitation unless broader stressors are addressed. The presence of other barriers in the same watershed, land use, pollution and climate change are among the factors limiting the trajectory of both physical and ecological recovery.[73]

Ecological responses

The local context for each barrier is unique. Therefore, the natural responses to barrier removal are individually distinct and largely dependent on interactions among physical and biological components of the watershed.[74]

Ecological responses to barrier removal differ among three distinct zones: upstream of the reservoir, the former reservoir, and downstream reaches of the barrier.



Upstream of the reservoir

The upstream passage of organisms drives ecological recovery and restoration above the former impoundment. As river connectivity returns, the restored ability of organisms to move into upstream tributaries, recolonize, and repopulate will increase species richness and life-history diversity, especially for migratory fish populations.[73]

There is also a risk that the re-established connectivity could allow non-native or invasive aquatic species to disperse into new upstream habitats.

The former reservoir

The former reservoir segment undergoes the most substantial physical, biological, and ecological changes.

As the reservoir drains, a new river channel forms within the bed of the former reservoir and erodes years of accumulated sediment.

Conversion of impounded waters to free-flowing rivers shifts fish-community assemblages from those favouring slow currents to species better adapted to swift currents.

Pioneer vegetation species, including non-native species, can quickly colonize newly exposed sediment and stabilize riverbanks.[74]

Complementary restoration efforts, such as planting and seeding, accelerate vegetation recovery and reduce colonization by non-native species.[90]

Once riparian vegetation returns, terrestrial species follow, re-establishing ecological interactions across terrestrial and aquatic boundaries.[73,90]

Downstream of the barrier

The re-established natural flow of water, sediment, organic matter and nutrients drives changes in the river systems downstream of the barrier.

Sediment pulses moving and depositing material downstream during and after barrier removal are the main drivers of initially decreased abundance of fish and benthic organisms.[72]

Adverse effects downstream of the removal are relatively short-lived. Over time the river can largely recover from perturbances caused by the barrier removal process and resume its natural functions.[73]

Redeposition of reservoir sediments can build downstream channel beds and reconnect the river with surrounding floodplain habitats.[72,76]

Sediments

Sediment is a critical concern in barrier removal. Removing a large dam exposes sediment accumulated over decades to erosion and downstream transport.

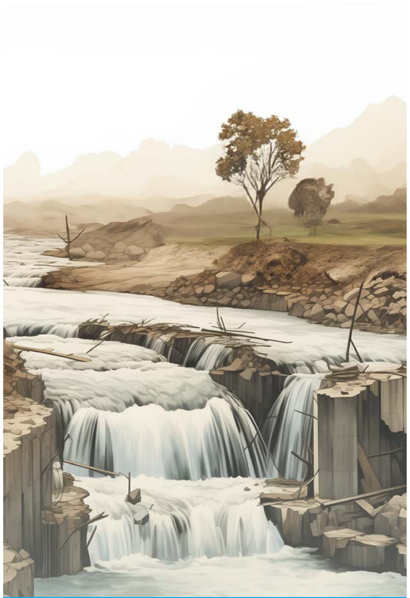
The strategic removal of multiple, smaller barriers in the same watershed can deliver large amounts of sediment at the watershed scale with overall effects similar to those of larger dam removals.[85]

Contaminated sediments

Sediments behind barriers may contain accumulated pollutants. The release of such contaminants can be a critical concern for local communities, especially downstream.

Dredging contaminated sediment before barrier removal can dramatically increase project costs because responsible handling requires a cautious dredging process and a location where contaminants can be contained, as well as transport to the dump site.[91]

2.3
Momentum gained for river restoration



"While river restoration is often the platform used to start barrier removal discussions, safety and economics tend to be the main determinants of whether to remove a barrier."

Barrier removal is practiced widely in North America and Europe, and most of the removed structures have been small and old barriers.[21,24,27] In the European Union, river barriers were recognized as a significant anthropogenic pressure under the Water Framework Directive of 2000, when data analysis showed that at least 20 per cent of the European Union's surface waterbodies were affected.[92] More recent analysis suggests there is one dam for every kilometre of river in Europe, contributing to the poor ecological status of their rivers.[2] Barrier removal is gathering momentum as a means to achieve the ecological goals of the Water Framework Directive, and estimates indicate that about 5,000 dams had been demolished by 2018.[93] In addition, in July 2023 the European Parliament passed the new Nature Restoration Law with one target intended to free at least 25,000 kilometres of rivers from barriers by 2030.[94]

Removal of barriers, especially larger ones, is often a contentious process at the intersection of ecological, economic, and cultural concerns.[85,95-97] Differing perspectives on barrier removal can produce lengthy administrative processes or fail to reach a decision at all.[98] Although many old barriers no longer fulfil their original purposes, they may serve as historical landmarks or tourist destinations. Furthermore, the impoundments above barriers can provide recreational activities such as fishing and boating. High property values dependent on proximity to shorelines may create considerable resistance to barrier removal.

The difficult conversations about barrier removal are increasingly initiated and facilitated by local communities and Indigenous groups – often led by women and supported by youth activism – to create space for dialogue around concerns, communicate information about the benefits and risks of the barrier removal process, and build support for barrier removal and river restoration.[99,100] Stakeholder engagement and collaboration incorporate broader perspectives and local knowledge, promoting public acceptance of project implementation and restoration outcomes.[96,101]

While river restoration is often the platform used to start barrier removal discussions, safety and economics tend to be the main determinants of whether to remove a barrier. In 36 European countries, estimates conclude that of the nearly 1.2 million existing instream barriers, 68 per cent are under 2 metres in height with a significant portion that are unused and unmaintained.[2] With the risk of their collapse and subsequent unanticipated flooding of downstream areas, they can compromise public safety. In the United States of America, the number of barrier failures per year since 2010 has increased from 10 to over 25, primarily due to ageing infrastructure.[102] As climate change causes more extreme weather events worldwide, ageing barriers will contend with conditions they were not designed to withstand.[103-106] Removal of severely compromised barriers is an adaptation that would improve river health, eliminate maintenance costs, and avoid potential disasters.

Prioritizing removals based on the potential for risk reduction and other benefits will facilitate decision making.[107] Scientists are developing tools to help river managers evaluate the risks of existing barriers and the likely ecosystem effects and broader benefits of barrier removal.[108-112] More comprehensive tools are also in development that could assess the trade-offs of barrier removal, combining social, economic, and ecological criteria.[113,114] Many of these tools support the formation of prioritized lists of barriers for removal that will maximize safety, river restoration, and economic benefits. Recognition of the restoration economy also contributes to the economic evaluation of removing obsolete infrastructure, particularly where removal results in long-term employment related to environmental restoration.[115]

Dam removal can be an expensive endeavour, depending on barrier height, drainage area, sediment management protocols, alleviation of adverse effects, and post-removal activities, among other key factors.[116] While removing old, small and obsolete barriers is often less expensive than repairing them[13], funding for barrier removals remains a challenge. In most cases, advancing a barrier-removal project requires multiple funding sources, including from public and private sources. Funding sources and availability may be tied to the reason for barrier removal, such as species restoration or safety. In the United States of America, for example, the Federal Government's 2021 Bipartisan Infrastructure Legislation allocated US$800 million to barrier removal to restore river ecosystems.[117] In the European Union, a private fund called the Open Rivers Programme was created in October of 2021 to support small river-barrier removals in greater Europe with €42.5 million.[118]

Leading the path: Role of Indigenous communities in restoring the Klamath River

Restoration or rehabilitation of ecosystems destroyed by obsolete barriers has become the focus of local, regional and national efforts in many parts of the world.[4,19,119] One of the world's largest dam removal projects is near completion, with ecosystem restoration phases still underway, in the United States of America, along the Klamath River in Northern California and Southern Oregon.[120,121] Led by Indigenous communities, particularly the Yurok and Karuk Tribes[122] and encompassing government agencies, land and dam owners, and environmental groups, stakeholders spent decades negotiating the removal of a series of obsolete dams and rehabilitating natural ecosystems. That restoration may establish a framework for future large barrier removals and successful ecosystem restoration.[123]

As each reservoir drains and sediments move downstream, revegetation crews clear out invasive species along the slopes and then disperse seeds from native species collected over previous years from surrounding landscapes.[124] These crews must work quickly to establish native vegetation to pre-empt colonization by invasive species. Nearly 100 species of native grasses, flowering plants, shrubs and trees are designated for specific sites and aspects along newly exposed surfaces that emerge as the reservoirs empty. The revegetation plan calls for planting approximately 17 billion seeds and 300,000 tree saplings and shrub plugs collected or cultivated as an initial phase of the dam removal process and ecosystem restoration objectives.[124]

The Klamath River Renewal Project is a case study in progress. The dams were built to provide hydropower to the region, but that value diminished over their 100-year life spans and cost-benefit analyses concluded that removal made better business sense than necessary upgrades.[120]

All of the four dams have been removed, with the last reservoir emptied in October 2024.[124] Transport of residual sediments from the reservoirs, restocking fish populations, and rewilding the river and surrounding landscapes will continue over decades, as researchers and practitioners scrutinize every decision and every outcome.[125] The successes and setbacks encountered over those decades will add to the knowledge being gained about barrier removal processes, community and Tribal engagement, and ecosystem restoration to inform future barrier removal projects worldwide.[123] At the same time, the area will become a recreational destination for sport fishing and other activities – including citizen scientists monitoring progress on rehabilitation along 400 kilometres of the Klamath River.[121] Most importantly, the local Indigenous communities will lead the restoration efforts designed to enhance and restore the traditional ecosystem benefits provided by the river and the surrounding watershed.[122]

2.4
Informing future removals and guiding existing operations

Barrier removals represent rare opportunities to study how river ecosystems recover from prolonged alterations and whether desirable ecological, economic, and social benefits can be collectively achieved while aligning with long-term conservation goals. While the scientific community has learned much about river response to barrier removal over the last 40 years[72,89], many gaps remain in our ability to anticipate how rivers will respond and understand why the responses vary widely. To fill these gaps, practitioners must develop coordinated, long-term monitoring studies before and after dam removal that integrate biological, chemical, and physical responses[127-129] and share the knowledge and experience gained to minimize the learning curve for others.[73]

"Preserving freshwater resources and their aquatic ecosystems, which provide profoundly essential ecosystem services to all species, must be a prime focus of ecosystem-restoration initiatives."

We also need to know how many barriers exist on the landscape, their locations, and their intended functions. Most current databases include only barriers over 10 metres tall, ignoring the vast majority of those that are small, obsolete and compromising river health.[2,8,130-133] New technologies are now available to locate those small barriers more efficiently than traditional walkover surveys, including remote sensing and machine learning.[134,135]

Understanding the restoration outcomes of barrier removal is necessary not only to guide future removals but also to inform decisions about future barrier building and the continued operation of existing barriers.[89,136] In much of Africa, Asia and South America, where barrier building far outpaces removal, hydropower dams are seen as a green option to provide energy that supports the needs of growing populations.[137] This infrastructure can be carefully designed and placed on the landscape in ways and locations that minimize disturbances to river health.[136,139] Many dams across the globe are not candidates for removal, yet there are ways to modify structures and operations that foster as much connectivity in the river basin as possible.[139,140] Where feasible, developing a portfolio of renewable energy options, including wind and solar, as alternatives to building new dams should be considered particularly in the context of a changing climate that could reduce the effectiveness of hydropower dams at some point in their service life.[4,141] Climate change will increasingly influence these discussions as demands for freshwater storage and low-carbon energy sources build.

Preserving freshwater resources and their aquatic ecosystems, which provide profoundly essential ecosystem services to all species, must be a prime focus of ecosystem-restoration initiatives.[142] The goal of re-establishing free flow in rivers and rehabilitating their ecosystems complements the United Nations Decade on Ecosystem Restoration objectives and its guiding principles.[143-145] The ten principles underpinning ecosystem-restoration initiatives emphasize the need for a range of activities and practices that address the direct and indirect drivers of ecosystem degradation and fragmentation. These options should promote natural recovery and ecological connectivity over the long term, while engaging stakeholder groups and communities of practice throughout the process. As river restoration efforts intensify in this and decades to come, barrier removal serves as an emerging tool to reverse fragmentation and restore natural processes in river ecosystems for greater resilience at the watershed scale.

Rivers are the lifeblood of many communities, and they bear a significant burden as humans continue to extract the benefits provided by these precious resources.[146] Barrier removal is one restoration strategy that can dramatically and immediately affect river health. Returning rivers to their free-flowing state restores water and sediment delivery, revives habitats, and reconnects habitats, animals, and plants across the landscape.

UN Decade of Ecosystem Restoration 2021-2030

To generate momentum and scale up efforts to prevent, halt and reverse the degradation of ecosystems worldwide, the United Nations General Assembly declared 2021–2030 as the United Nations Decade on Ecosystem Restoration.[143] Ecosystem restoration refers to "the process of halting and reversing degradation, resulting in improved ecosystem services and recovered biodiversity. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice".[145] In support of restoration activities across the globe, the UN Decade of Ecosystem Restoration underscores a set of ten principles for ecosystem restoration to achieve maximum net gain for biodiversity, ecosystem health and integrity, and human health and well-being.[144] Click on the link for a detailed description of the principles.

- Ecosystem restoration contributes to the UN Sustainable Development Goals and the goals of the Rio Conventions
- Ecosystem restoration promotes inclusive and participatory governance, social fairness and equity from the start and throughout the process and outcomes
- Ecosystem restoration includes a continuum of restorative activities
- Ecosystem restoration aims to achieve the highest level of recovery for biodiversity, ecosystem health and integrity, and human well-being
- Ecosystem restoration addresses the direct and indirect causes of ecosystem degradation
- Ecosystem restoration incorporates all types of knowledge and promotes their exchange and integration throughout the process
- Ecosystem restoration is based on well-defined short-, medium- and long-term ecological, cultural and socio-economic objectives and goals
- Ecosystem restoration is tailored to the local ecological, cultural and socio-economic contexts, while considering the larger landscape or seascape
- Ecosystem restoration includes monitoring, evaluation and adaptive management throughout and beyond the lifetime of the project or programme
- Ecosystem restoration is enabled by policies and measures that promote its long-term progress, fostering replication and scaling-up

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The Global Foresight Report and Process identified the potential impacts of the various megatrends and signals of change on vulnerable populations, including youth, women and indigenous populations. This chapter explores the potential impact of future disruptions on an often-overlooked group – the older population and how global environmental changes could influence the ways in which this population is supported through adaptation and mitigations transitions.

Photo collage: Carlos Reyes, 2024. Created with the assistance of generative tools.

03 Demographic challenge

Growing old in a changing environment

Authors

Stessa Tzuyuan Chao (Department of Urban Planning, National Cheng Kung University, Taiwan Province of China)
Sun Yi (Department of Building and Real Estate, the Hong Kong Polytechnic University, Hong Kong, China)

65+

Defining old age

Different societies categorize 'older persons' according to varying age thresholds and social policies. The measures and indicators used by the United Nations and associated researchers define older persons as those aged 60 or 65 years and over.[20] In this chapter, older persons refer to those aged 65 years and above unless specified otherwise.

Photo: iStock

3.1 Demographic transitions and ageing populations

Over the past two centuries, the global population has been experiencing demographic transitions.[1,2] With improved sanitation, public health, and better nutrition reaching most countries, life expectancy has been increasing worldwide as more people in every age group live longer. At the same time, birth rates have been declining in most regions, driven by improved access to family planning, education and empowerment of women.[3] These demographic trends lead to population ageing, with fewer dependents under the age of 15, a greater proportion of people in their prime, and more individuals living into old age. On the global scale, this transition is to persist at varying rates across regions.[4,5] Projections indicate that the share of the global population aged 65 years and older will rise from 10 per cent in 2024 to 16 per cent by 2050, with the number of those aged 80 and older nearly tripling (UNDESA 2024), and with most concentrating in low- and middle-income countries.[4,6,7]

Along with the ageing trend, the world is also becoming increasingly urbanized. Approximately 57 per cent of the world's population currently lives in cities, but by 2050, it is expected to rise to 68 per cent.[8,9] This increase in urbanization is particularly evident in developing regions.[10,11] With 58 per cent of people aged 60 and older residing in cities in 2015, the proportions of older urban residents are growing steadily.[12] Many older people seek urban living to access better healthcare facilities, vital social activities, and dependable public transit, among other benefits. A rising number of cities will therefore soon face the new reality of increasingly ageing urban dwellers.[13]

Maintaining good health and vitality is crucial at any age and minimizing risk factors for diseases become even more critical as we age. In addition to the genetic, physiological, behavioural and social influences, environmental conditions plays a crucial role, especially in cities that bring together a high concentration of a variety of environmental health risks.[14-18] Exposure to environmental stressors and pollutants in old age, combined with the effects of lifetime exposure, may promote the development and progression of a wide range of age-related non-communicable diseases, accelerating ageing processes, and other health issues.[16,19]

Older people are especially susceptible to environmental risks caused by climate change. Climate-related disasters exert substantial pressure on people's physical and mental well-being. Chronic health conditions and general frailties make the physical hazards from extreme weather events more challenging or even life-threatening, given the reduced mobility experienced by many older persons.[19,21,22] When Hurricane Katrina struck New Orleans in 2005, 75 per cent of those who died were over 60, despite that age group amounting to only 16 per cent of the affected population.[21,23]

"Nearly a quarter of the global disease burden is attributable to unhealthy environmental factors that are modifiable and manageable through proven measures and existing policies."

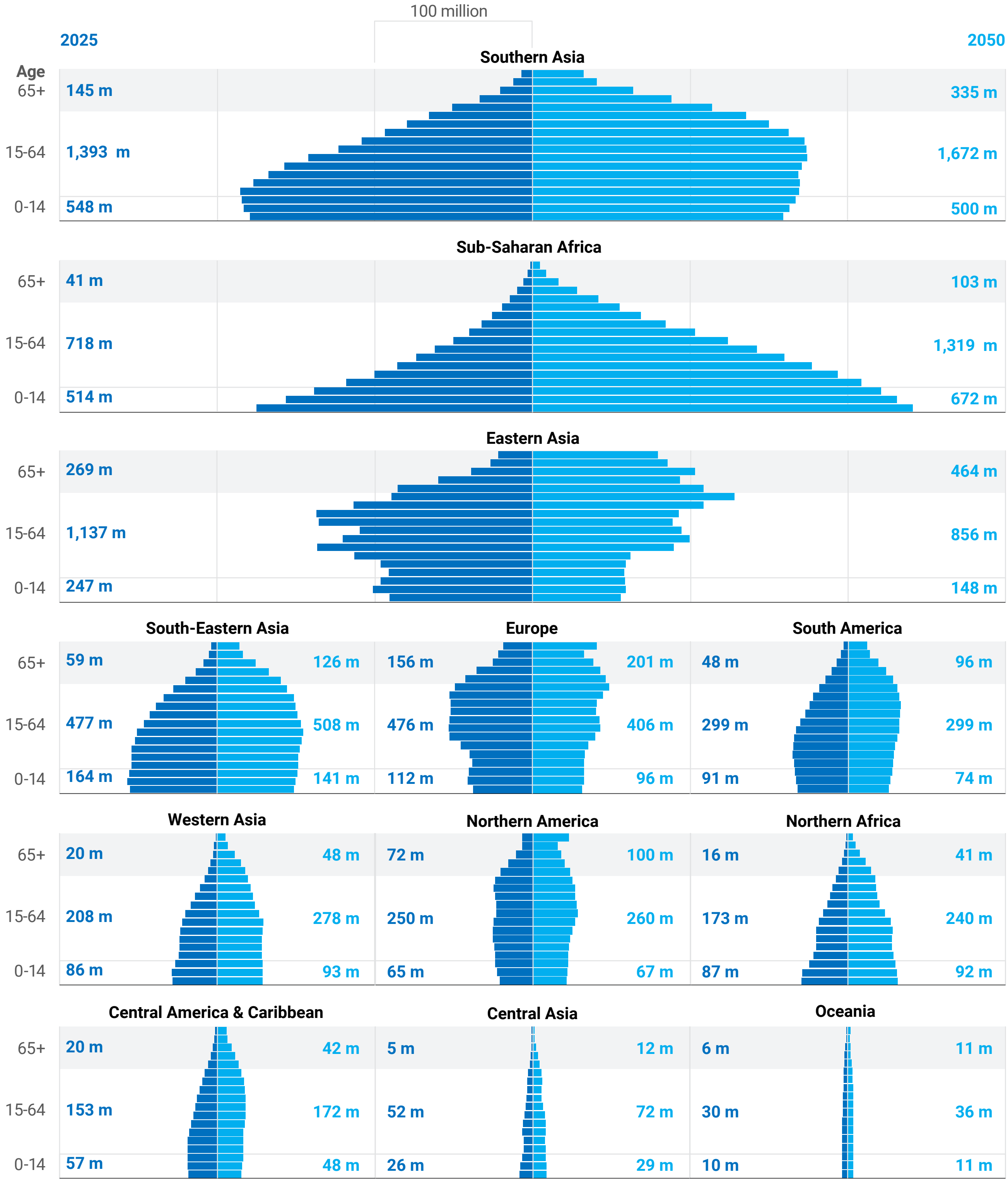
The consequences of environmental and climate threats for ageing populations will vary across regions. Still, a commonality is that older people, as a group, are at risk from these consequences due to their increasing physical and psychological limitations.[24-26] They are more likely to experience "…mobility, cognitive, sensory, social, and economic limitations that can impede their adaptability and ability to function during disasters".[27] The expected increase in threats from pollution, heat, storms, and other phenomena brings a significant challenge to fostering climate adaptation and building resilience in an ageing society.

Photo: iStock

Accelerating population ageing

This series of population pyramids represent the size, age and sex composition of projected subregional population in 2025 and 2050. The accelerating shifts towards the older age groups are clearly apparent in many subregions.

The regional groupings are based on the geographic regions defined under the Standard Country or Area Codes for Statistical Use (known as M49) of the United Nations Statistics Division and used by the reporting on SDG indicators. To ensure the graph readability, the population data of Central America and the Caribbean are combined and presented in one graph.



Note: The population data of 2050 is based on the medium scenario projection.

Data source: World Population Prospects 2024, Population Division, Department of Economic and Social Affairs of the United Nations.[6]

3.2
Environmental risks for ageing populations

Nearly a quarter of the global disease burden is attributable to unhealthy environmental factors that are modifiable and manageable through proven measures and existing policies.[28-30] Exposure to polluted air and water, chemicals and food contaminants contribute to early and rapid health decline and increased vulnerability to further illnesses in older adults.[15,31-33] A large body of research documents the role of urban air pollutants – even at concentrations below current air quality standards – in increasing the late-life onset and progression of respiratory, cardiovascular, metabolic and neurological diseases and of mortality among older populations.[15,34-43]

"In the event of extreme conditions such as storms, floods and wildfires, older people suffer disproportionately..."

Older people are especially vulnerable to weather changes. Extreme heat can be deadly for older populations given their reduced ability to regulate body temperature.[44-46] Their vulnerability can be tracked as a pattern, where older people experience high rates of illness and death during extreme heat and cold events among various age groups.[47-60] An analysis of mortality due to extreme temperatures in 326 cities across Latin America from 2002 to 2015 estimated that 7.6 per cent of deaths in older populations were associated with extreme cold and, to a lesser extent, heat.[55] A study of heatwave-related mortality in China from 1979 to 2020 indicated that people over 75 accounted for 55 per cent of all heat-related deaths.[50] Vulnerability to heat also increases among those living in social isolation and in overcrowded urban areas.[61-63]

With climate change, we can expect more intense and more frequent heatwaves.[64,65] According to projections of heat stress on humans, combining air temperature with relative humidity, the exposure to dangerous heat levels will likely double for people living in the tropics and reach 3 to 10 times for some living in the mid-latitudes.[66] A study of future exposure to extreme heat events in the Republic of Korea suggests that, by 2060, older people in its cities will be four times more exposed to extreme heat than today.[67]

In the event of extreme conditions such as storms, floods and wildfires, older people suffer disproportionately from an increased risk of injury and mortality, especially those with chronic health conditions[57,68,69], those living in low-income and deprived communities[7,70,71], and those living in areas with high levels of multi-hazard risk such as low-lying coastal zone and floodplains[72]. Economic, social and cultural factors, including age discrimination, play a role in compounding older people's vulnerability to environmental threats. Research shows that about 1.8 billion people globally reside in areas prone to high flood risk, with 89 per cent of them living in low- and middle-income countries.[73]

Pre-existing health conditions and the weakened physical strength of many older people, sometimes coupled with a diminished capacity to assess the situation, can increase their dependency on help from younger family members and others.[21,70] Older people living in socially deprived neighbourhoods often lack social networks for support and resources, making them more susceptible to environmental hazards.[70,71] Climate-related disasters can significantly increase the social burden on older people – particularly older women – given their traditional caregiving and domestic responsibilities in many parts of the world.[74-76] The needs of older people and their responsibilities and extra burdens are often overlooked in disaster preparedness planning and, consequently, during the response.

Growing old in a changing environment

An unhealthy environment affects people of all ages. Older populations are more likely to suffer from medical conditions and age-related health issues that make them particularly sensitive to environmental hazards. Ageing bodies have a reduced capacity to compensate for the adverse effects of environmental stressors and a weakened immune response to protect against infections and diseases.[77,78] Limited mobility and poor cognitive functioning also puts some older people at greater risk during extreme weather events.

Environmental exposure is a significant modifiable risk factor for health and disease outcomes.[28-30] By addressing modifiable environmental factors – such as ambient air pollution, chemical exposures, urban heat, and climate change – and promoting healthy environments, we can reduce the risk of illnesses and death among older adults, potentially increasing number of years lived without chronic diseases or disabilities.[15,17,28]

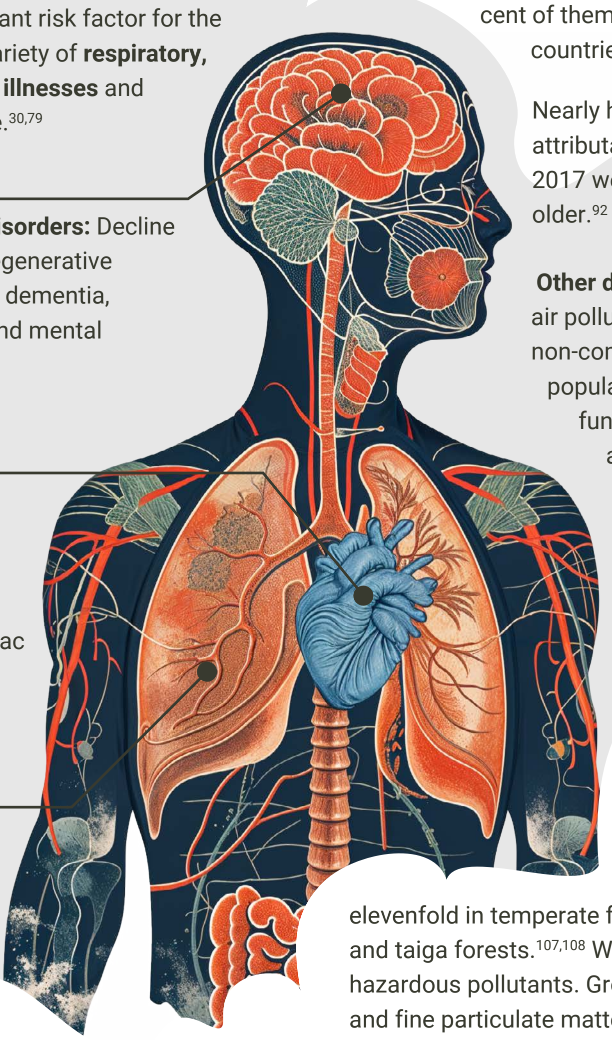
Air pollution

Exposure to air pollutants – such as fine particulate matter, ground-level ozone, nitrogen dioxide and sulphur dioxide – is a significant risk factor for the onset and progression of a variety of **respiratory, cardiovascular and cognitive illnesses** and related deaths in older people.[30,79]

7.3 billion

Number of people worldwide directly exposed to $PM_{2.5}$ levels considered unsafe by WHO. About 80 per cent of them live in low- and middle-income countries.[91]

Nearly half of the 1.24 million deaths attributable to air pollution in India in 2017 were those aged 70 years or older.[92]



Neurological and cognitive disorders: Decline in cognitive function, neurodegenerative diseases, the development of dementia, late-life depression, anxiety and mental health.[36,37,80-84]

Other disorders: : Associations between air pollution and risks of other non-communicable illnesses in older populations – such as arthritis, kidney function impairment and disease, age-related macular degeneration, obesity, diabetes, and endocrine diseases – are under intense investigation.[93-101]

Cardiovascular diseases: : Myocardial infarction, arrhythmias, atrial fibrillation, hypertension, heart disease, congestive heart failure, cardiac arrest and stroke.[35,85-87]

Respiratory diseases: Asthma, bronchiectasis, chronic bronchitis, chronic obstructive pulmonary disease, respiratory infections and lung cancer.[88-90]

Choked by smoke

Wildfires are becoming more frequent, more severe and more extensive under climate change.[105,106] Since 2003, the annual number of extreme wildfire events surged by elevenfold in temperate forests, and sevenfold in the boreal and taiga forests.[107,108] Wildfires release large amounts of hazardous pollutants. Ground-level ozone, carbon monoxide and fine particulate matter are among those of great concern. Wildfires also pose life-threatening challenges to older adults due to limited mobility and disaster preparedness.[109]

Air and noise

Multiple environmental stressors often co-occur and may interact synergistically, generating combined effects on human health.[102] Exposures to both traffic air and noise pollution are significant risk factors for health issues, including myocardial infarction, heart failure, hypertension, diabetes and mental health.[103,104]

10 days

The average number of days per year that global populations were exposed to substantial air pollution from fires burning in natural and agricultural landscapes from 2010 to 2019.[110]

Chemical contamination

Exposure to environmental contaminants—including pesticides[16,111], heavy metals[15,112,113], persistent organic pollutants[15,114], polyaromatic hydrocarbons[15,115], emerging organic chemicals[116-122], and endocrine-disrupting chemicals[15]—plays a significant role in promoting age-related cardiovascular, cerebrovascular and brain function disorders as well as diseases in other organ systems.

The environment matters in the development, transmission and spread of antimicrobial resistance.[123] Biological and chemical pollution from municipal wastewater and solid waste, effluent from hospitals and pharmaceutical manufacturing, and agricultural run-off create favourable conditions for microorganisms to develop resistance and spread in the environment and back to plants and animals including humans.

Extreme temperatures

As we age, our bodies become less effective at regulating internal body temperature. Acute and prolonged exposures to intense heat and cold put a significant strain on the heart, increasing the risk of illnesses and death from common cardiovascular, cerebrovascular and respiratory conditions, such as stroke, myocardial infarction, heart failure, asthma and pneumonia.[124,125]

Adults aged 65 years and older, women, and people living in lower-middle income countries and tropical climates are at high morbidity and mortality risk from exposure to high temperatures and heatwaves.[56]

A review of studies on elderly mortality due to heatwaves in Europe from 2000-2016 suggests that elderly women face greater health risks from heat waves than men.[128]

296,000
deaths

Number of heat-related deaths in people aged 65 years and older in eastern China, northern India, Japan and Europe in 2018.[126]

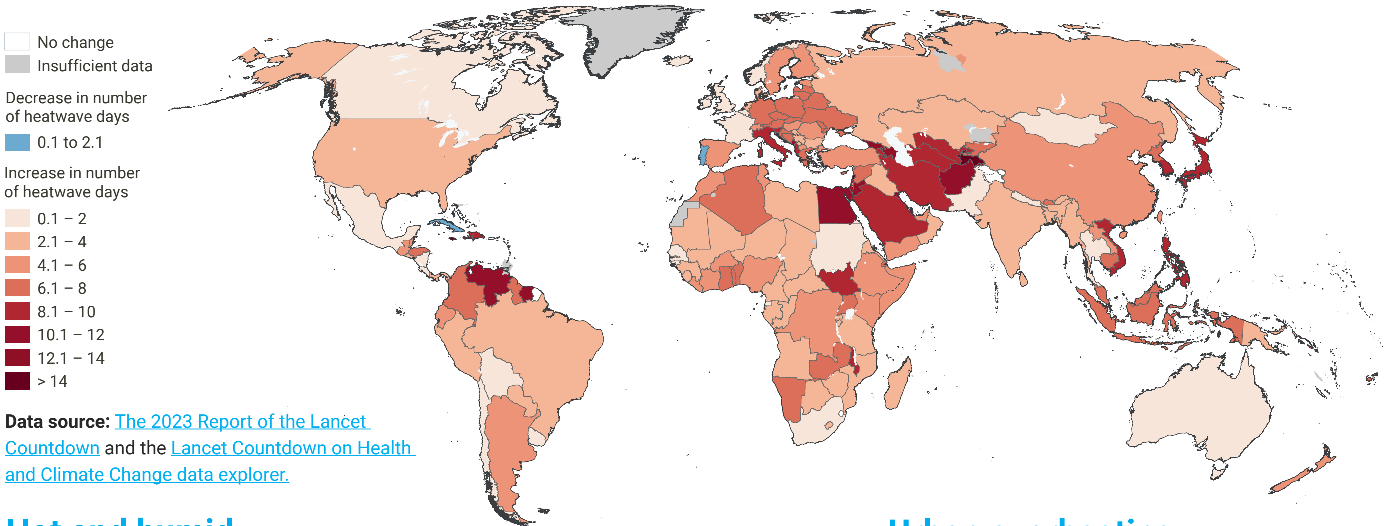
+85%
since 1990s

Increase in annual heat-related deaths of adults aged 65+, driven by both warming trends and fast-growing older populations.[127]

+370%
by 2050

Projected increase in annual heat-related deaths in older populations if global temperatures rise by 2˚C.[127]

Changes in average number of heatwave days per person per year experienced by older adults aged 65 years and older, comparing 1986-2005 and 2013-2022



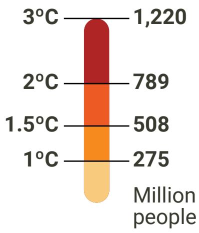
Data source: The 2023 Report of the Lancet Countdown and the Lancet Countdown on Health and Climate Change data explorer.

Hot and humid

Projections indicate that heatwaves will become more intense, frequent and persistent in nearly all regions.[64] As heatwaves intensify, scientists warn us of the amplified danger when extreme heat and humidity combine.[129-131] Higher humidity tends to limit the human body's ability to cool itself through the evaporation of sweat.

The low-lying tropical regions of India and Pakistan, the Persian Gulf, the Arabian Gulf, the Red Sea, and eastern China are already experiencing humid heatwaves.[64]

Estimated number of people to be exposed to humid heatwaves[132]



Urban overheating

Urban centres usually experience higher temperatures than surrounding rural areas because buildings, pavement, and other artificial surfaces trap, retain and re-radiate heat. This urban heat island effect and heat waves interact synergistically, exposing urban residents to greater heat and amplifying health risks.[133-136]

Drought and dust

Agricultural and ecological droughts are intensifying in almost all regions under the influence of climate change.[65] Drought causes various health-related concerns, such as water- and vector-borne diseases, cardiovascular, respiratory and kidney disorders, malnutrition and food insecurity, and mortality.[137]

Drought contributes to poor air quality by mobilizing dust and fine particulate matter and increasing ground-level ozone pollution.[137-141] Drought is also a significant driver of dust storms and wildfires, causing greater morbidity and mortality risks in vulnerable populations.

Female and adults 65+

Population groups at significant risk of cardiovascular, respiratory and all-cause mortality due to exposure to particulate matter from dust storm events worldwide, according to a meta-analysis of 28 published studies.[142]

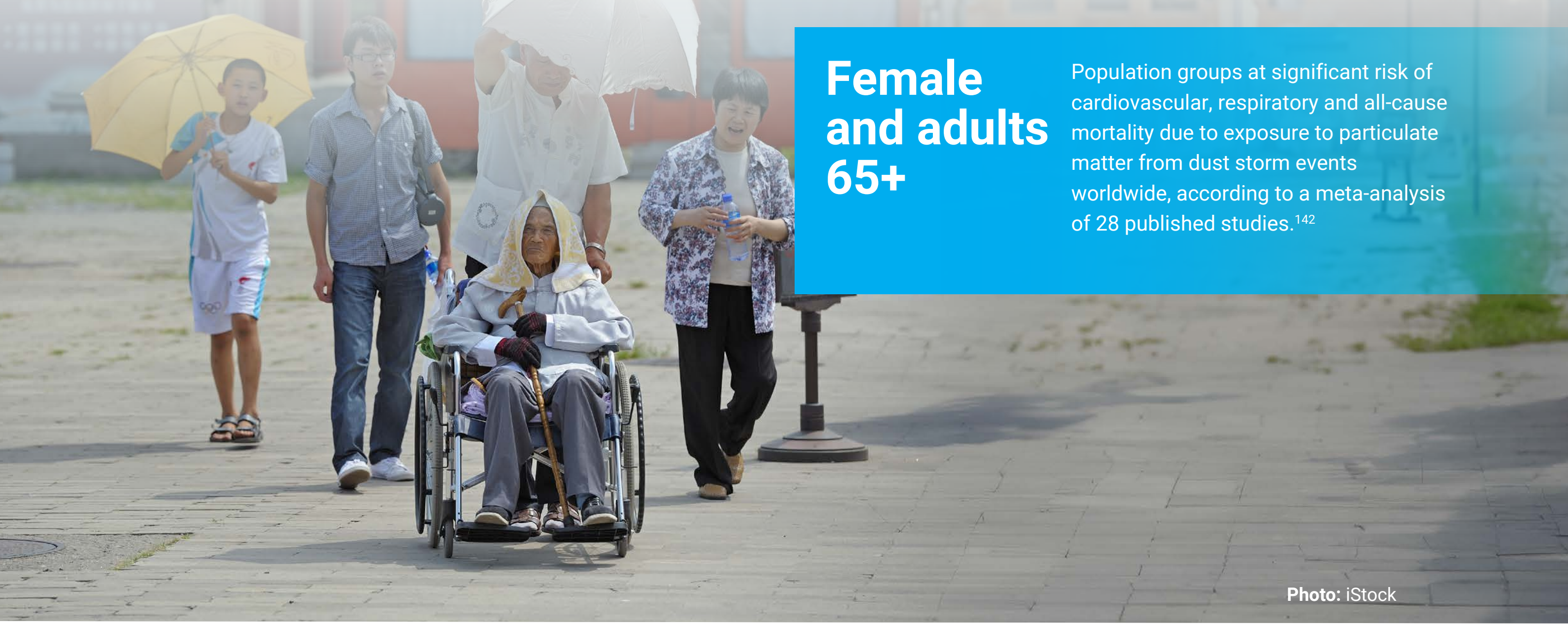


Photo: iStock

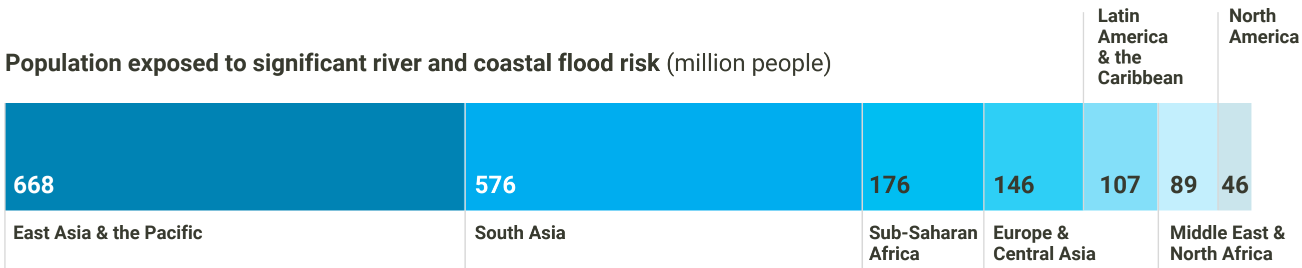
River and coastal flooding

About 1.81 billion people, or nearly one in four of the world's population, are exposed to a significant level of river and coastal flood risk and most of them are in South and East Asia.[73]

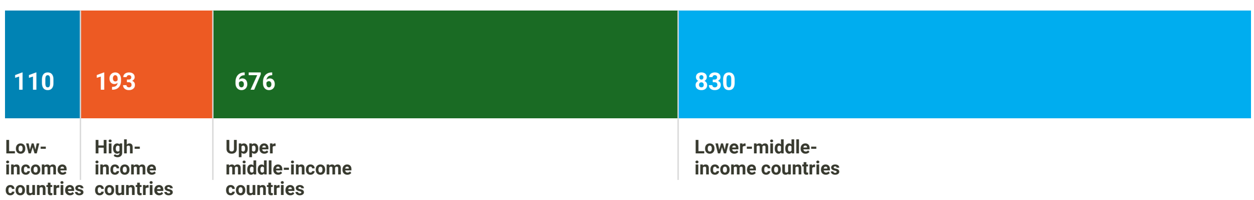
Coastal cities and communities are increasingly exposed to more frequent and more intense storms, rising sea level and coastal flooding. In many regions, coastal cities are a preferred retirement destination for older people, adversely putting themselves at greater risk of environmental hazards.[68]

Low-lying coastal areas of less than 2 metres above mean sea level—most at risk to accelerated sea level rise—are home to 267 million people.[144] The majority of the coastal lowland areas are in the tropics with an estimated population of 191 million. Of which, 157 million are in tropical Asia.[144]

Population exposed to significant river and coastal flood risk (million people)



Flood-exposed population by income group (million people)



Source: Rentschler, Salhab and Jafino (2022)[73]

Photo: © iStock

3.3 Inclusive resilience for the ageing population

A healthy environment enables people to develop, maintain, and improve their physical, mental, and social well-being, with the goal of achieving active, independent and healthy ageing as they get older.[145] Transforming cities to be age-friendly, free of pollution, resilient to environmental hazards and more environmentally sustainable is a priority for global public health and urban planning agendas.[11,18,146-148] Policies and approaches that foster healthy and age-friendly environments promote the quality of life for older individuals and benefit all ages.[149]

"Policies and approaches that foster healthy and age-friendly environments promote the quality of life for older individuals and benefit all ages."

Ageing in place is a practical approach that provides older people with opportunities to continue living in their community with some independence while staying active in their own homes, environments and social networks.[150-152] Variations of the concept include ageing in the right place and ageing in community, but they all incorporate concepts of choice and support.[153,154] Principles for ageing in place are vital components of the Global Network for Age-Friendly Cities and Communities, promoted by the World Health Organization.[148,155] A people-centred physical environment with low levels of pollution, accessible green spaces and age-friendly facilities can complement ageing in place.[146,156]

In pursuing sustainable development goals, the 15-Minute City approach is another liveable city planning strategy focusing on local neighbourhoods and accessibility.[157,158] This approach supports locating everyday destinations – home, workplace, schools, shops and public green spaces – within a fifteen-minute walk or cycle, a feature that can be quite appealing to older people with mobility concerns. Such a compact living style reduces car dependency and lowers emissions of carbon and air pollutants from traffic, improving air quality.[157,159] In an ageing society, the most liveable environment for ageing in place is to make all services available within a short-distance and familiar neighbourhood.[160]

Green infrastructure – a network of multi-functional green and blue features and spaces that deliver ecosystem services to cool urban areas, manage water and store carbon – has been widely adopted as a nature-based solution for liveable cities and climate resilience.[161] Green infrastructure goes beyond green parks in urban settings. When well-implemented, the practice creates a natural cooling effect through mixed vegetation covers and water bodies and integrates urban rain gardens to absorb rainwater runoffs, filter pollutants and reduce flood risks, among other features.[162-165] Research demonstrates that contact with urban green and blue infrastructure promotes healthy ageing among residents.[166-169]

However, efforts to create more liveable and healthier cities can have a double-edged effect if not managed well. One such issue is the the digital divide among older populations that may affect their capacity to live in smart cities and be adequately informed of possible extreme events that may affect their survival.[170,171] In addition, environmental gentrification can occur when urban regeneration and green infrastructure improvements attract investors and wealthy people to a formerly marginalized area—resulting in increased property values and soaring rents.[172-175] Such heightened socioeconomic inequalities could emerge from efforts such as the 15-Minute City, green infrastructure implementation and urban regeneration.[173,176] In some cities, many disadvantaged groups have experienced residential and social displacement as property near green infrastructures became attractive to investors.[172,173] Finally, intensifying floods in many coastal cities could trigger outmigration among those who can afford to relocate, while many low-income households and vulnerable residents get trapped in hazard zones.[177]

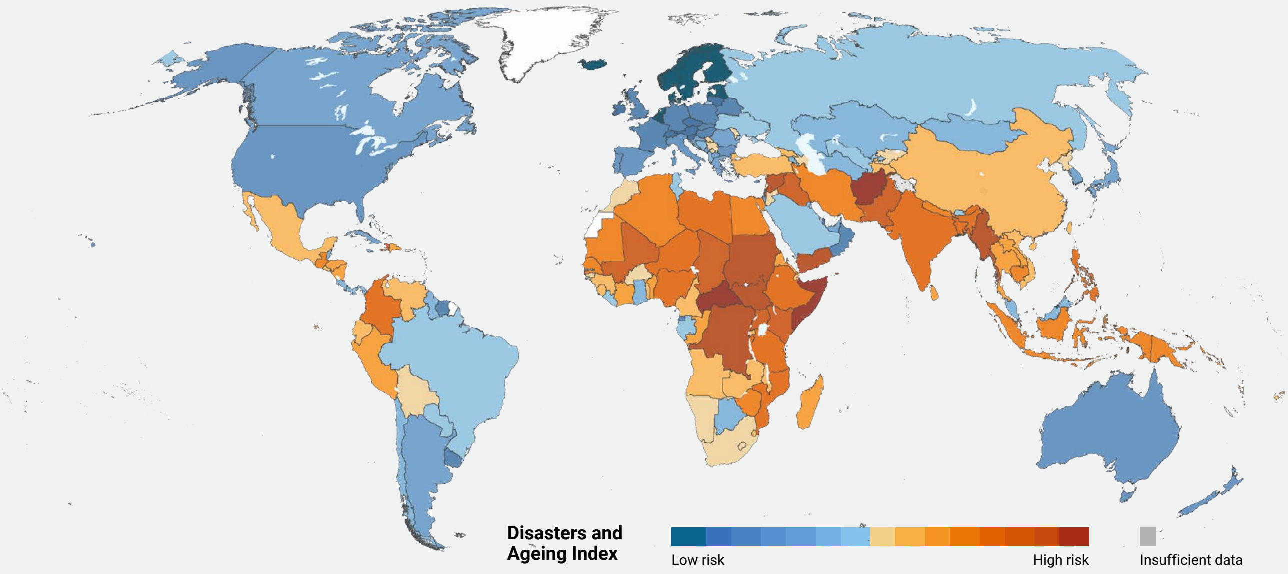
In the post-pandemic society, pursuing a more uncomplicated and environmentally sound lifestyle could ease pressure on older people's finances.[178] At the same time, many researchers see promise in the complementary effects of climate adaptation actions on building the resilience of the physical environment and reducing risk exposure and socioeconomic vulnerability within a city or a community.[179]

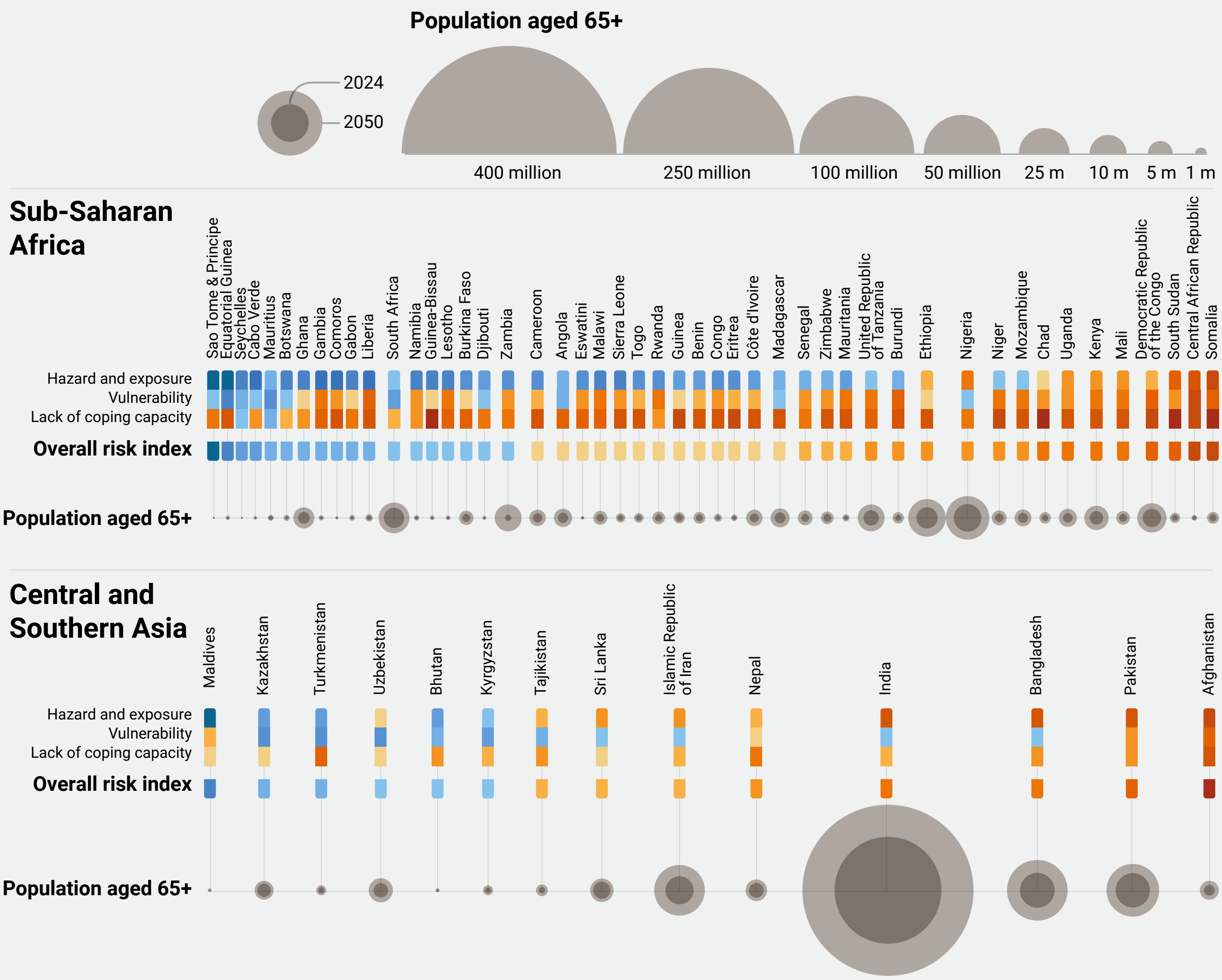

Photo: iStock

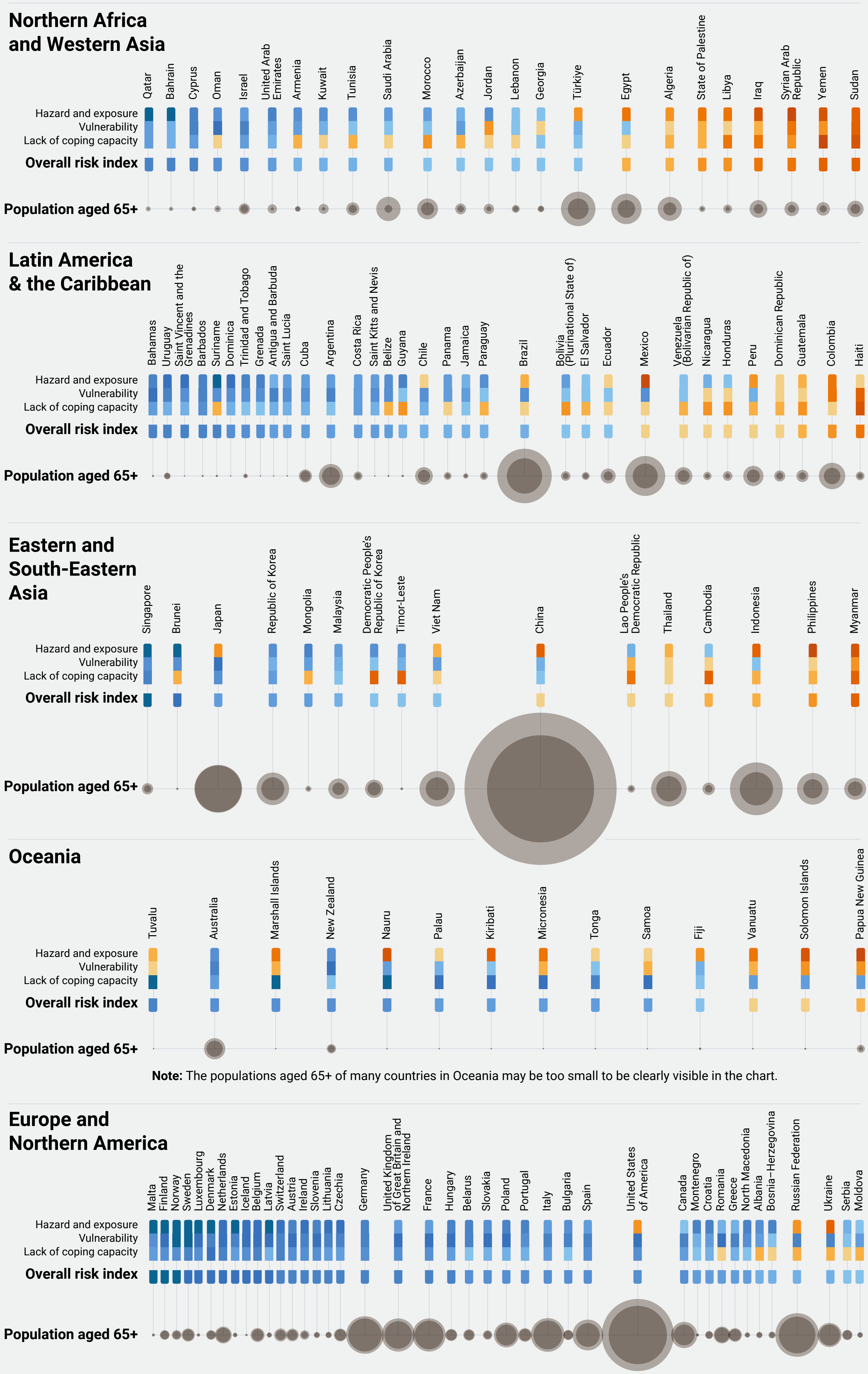
The intersection of aging societies and climate risk

In 2015, HelpAge International developed the Disaster Risk and Age Index to provide a snapshot of the disaster risk faced by older women and men in 190 countries, focusing on three dimensions: hazard and exposure, vulnerability, and lack of coping capacity. All three dimensions are equally weighted to determine risk.[180] The index is based on the INFORM 2015 Disaster Risk Index – a global, open-source risk assessment for humanitarian crises and disasters – developed by the European Commission in collaboration with the Inter-Agency Standing Committee Task Team for Preparedness and Resilience. The detailed analysis can be found in the Disaster Risk and Age Index report.[180]

Below is a graphic representation of HelpAge International's Disaster Risk and Age Index and detailed scores country-by-country. It is also combined with the data on current and projected older populations by 2050.







Note: The populations aged 65+ of many countries in Oceania may be too small to be clearly visible in the chart.

3.4
Towards a more resilient transition for lives, societies and the environment

As populations continue to age alongside increasing environmental risk concerns, adaptation strategies must evolve to address these challenges simultaneously. It is essential to integrate age-friendly, environmentally sound, climate-resilient, and inclusive approaches into future community-based actions to ensure the well-being of older residents while enhancing overall sustainability and liveability. Better urban design – emphasizing more green spaces, water features and open connectivity corridors for wind penetration and thermal comfort – can limit the urban heat island effect and reduce heat-related mortality and morbidity.[161,181,182]

"As populations continue to age alongside increasing environmental risk concerns, adaptation strategies must evolve to address these challenges simultaneously."

Community-based disaster risk management, a locally led bottom-up approach to diminish disaster damage and reduce vulnerability, is practiced by many communities and nations.[183] Empowering the older residents and supporting their capacity to access information, either through digital means or otherwise, allows them to live independently while playing critical roles in effective disaster prevention and damage minimization. Many governments have strongly advocated for community-based, gender-responsive disaster risk management policies in the past decade and acknowledge that they could also be the most effective disaster mitigation approach for communities with ageing populations.[184-187] Understanding interactions involving older populations, socioeconomic constraints, gender-relevant issues, and climate change consequences is essential for creating effective and inclusive policies and strategies.

While much of the research has focused on more developed countries and regions, less-developed countries have demonstrated their commitments, abilities, and ambition in protecting and promoting the health of their citizens by integrating health with climate actions and policies as described in their submitted Nationally Determined Contributions.[188] Also, with the foreseeable financial challenges resulting from increasing demand for medical services among those over 65, it is more financially feasible to integrate health and climate projects that may help to make the best use of available funds by maximizing co-benefits.[189]

Policymakers and city planners should be aware of the potential negative repercussions of green strategies for vulnerable groups. Investments in the green infrastructure necessary for environmental and climate resilience should also determine the adaptive capacity of vulnerable residents to likely impacts and possible displacement. Designs and mechanisms should empower vulnerable groups, including the older population, to defend and improve their well-being in this era of environmental change. While older age groups may have higher percentages of vulnerable persons than younger age groups, a significant proportion of seniors with years of valuable experience remain competent and healthy past the age of 65. However, holistic environmental policies supporting healthy ageing and delaying decline and disability are rare.[190-192]

Despite this, a 2021 study conducted in 31 countries found that older people actively participate in resource conservation and environmental protection worldwide. While their environmental activities contribute to environmental quality and reduce risks, living in a sustainable and pleasant environment promotes their physical and mental health and the health of others.[193] Many older women, especially, are at the forefront of community resilience efforts, acting as agents of change, and they can be instrumental in adapting to environmental challenges.[194] Recognizing older women's unique challenges and leveraging their strengths and knowledge can contribute to more resilient, sustainable, and equitable communities for all.[153]

Acknowledging that older people can be active agents in tackling climate change responses is essential. Our communities should "…free these marginalized elderly residents from this community isolation by initiating projects that properly employ the unique talents and skills of senior citizens".[195] This acknowledgement involves a new climate change preparedness framework that considers older people essential for generating better adaptation and mitigation outcomes that reduce vulnerability to environmental hazards and disasters, increase collaboration among older people and other stakeholders, and organize collaborative climate change mitigation planning.

Photo collage: Carlos Reyes, 2024. Created with the assistance of generative tools.

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The Global Foresight Report and Process identified the unforeseen impacts of harmful chemicals and materials. The ways in which these substances enter the environment play a significant role in determining the extent of their effects. At the same time, the incidence of flooding, driven by climate-induced extreme weather, is increasing the likelihood of uninhabitable areas. The intersection of these two phenomena offers a glimpse into how environmental challenges can converge into a polycrisis. In this chapter, we examine how these two signals of change interact, leading to potentially severe consequences.

Between 29 April and 4 May, relentless rainfall devastated Rio Grande do Sul, Brazil, triggering widespread floods, landslides, and mudslides. Photo: iStock

04 Forgotten but not gone

Remobilization of legacy pollutants by flood events

Authors

Markus Brinkmann (Toxicology Centre, University of Saskatchewan, Saskatoon, Saskatchewan, Canada)
Animesh Kumar Gain (School of Environmental and Conservation Sciences, College of Environmental and Life Sciences, Murdoch University, Australia)

"While direct effects of these floods are widely recognized and reported in the aftermath of flood events, indirect outcomes are often overlooked."

Photo: iStock

4.1 After a deluge

In recent years, many regions of the world have faced an increase in the frequency and magnitude of severe storm events with extreme rainfall and consequential floods. Bangladesh, a country frequently assailed by natural disasters, was struck by cyclones such as Mora in 2017, Amphan in 2020 and Yaas in 2021, which led to massive inundations.[1-3] Southeast Asia witnessed high-magnitude floods in 2011 that affected multiple countries, with particularly severe economic impacts in Cambodia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Thailand, and Viet Nam.[4] In China, substantial rains in June 2020 triggered some of the most devastating floods experienced in over two decades.[5] Similarly, Australia grappled with extreme flooding following intense droughts in early 2020.[6] Some parts of the country received a year's rainfall within a week.

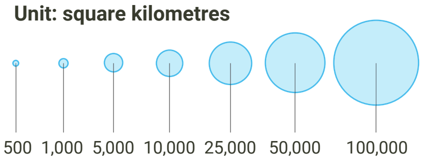
East Africa was not spared either, with the 2019 and 2024 floods disastrously affecting the region's populations and ecosystems.[7,8] As well, unprecedented rainfall produced by Hurricane Ida in September 2021 caused one of the most extreme floods in the eastern United States of America.[9] The heavy rainfall of 2021 in Europe transformed even smaller rivers and streams in Austria, Belgium, France, Germany, Italy, Poland and Romania into raging torrents.[10] These flood events caused severe injuries and fatalities, temporary or permanent displacement of people, and substantial infrastructure and economic damage.

Scientific evidence indicates that global climate change is a primary driver behind the increased amount and intensity of rainfall.[11] As average global temperatures rise, extreme rainfall will likely amplify the severity of flooding in many regions.[11-14] The risk of flooding is further magnified by poor land-use practices, burgeoning populations in urban and coastal regions, and the increasing economic value of flood-prone areas in many countries.[15] Without adaptive measures, global flood damage by the end of this century could be up to 20 times more severe.[16-19]

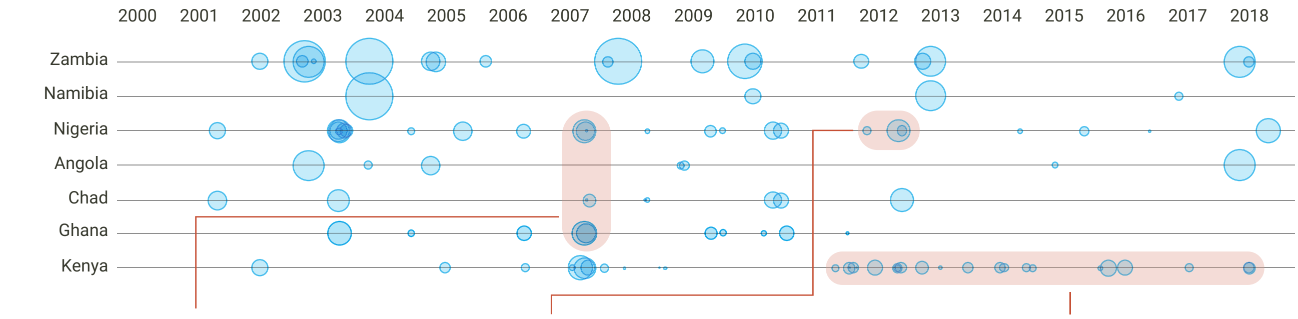
While the direct effects of these floods on life and infrastructure are widely recognized and reported in the aftermath of flood events, indirect outcomes are often overlooked.[20-21] A major flood can carry a significant volume of sediment and debris along its path, subsequently depositing suspended particles when the flow of floodwater slows down or stops. Upstream flooding can undermine slopes and cause landslides that introduce further sediments to complicate downstream flooding. A crucial yet frequently underestimated issue is the toxicological effects of chemical contaminants bound to the sediment that are mobilized and redistributed by increasingly frequent and severe flooding.[20,22-27] These mobilized chemicals pose formidable environmental challenges, possibly with lasting socio-economic and health repercussions.[29-34]

The spatial extent of selected flood events from 2000 to 2018

Destructive floods are increasing in severity, frequency and duration. These changes are due to modified land use and land cover, infrastructure, urban expansion, population and human settlements and, increasingly, changes in extreme weather patterns that are often due to climate change. Tellman *et al*. (2021) analyzed 12,719 daily satellite images taken from 2000 to 2018 and successfully mapped 913 large flood events observed under mostly cloud-free conditions.[35] The research group estimated the extent of each flood event in square kilometers. The complete result of this study is available at [this link](). In the chart below, we present a selected set of countries with a relatively high number of observed flood events, and where available, provide information related to specific events and flooded regions found in recent scientific literature.



Sub-Saharan Africa

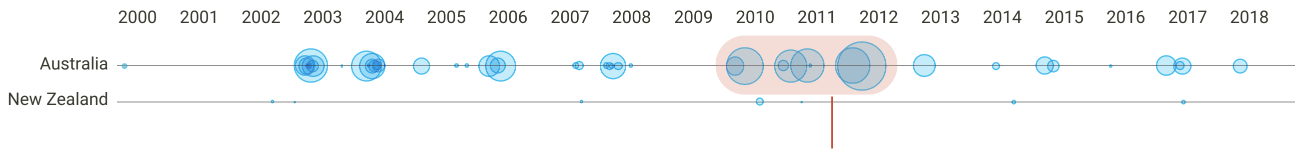


Since 1990, the Sahelian West Africa has experienced extreme climate swinging between extreme dry spells and intense rainfalls causing severe flood events.[36,37] It is estimated that the 2007 record-breaking rainfalls during the rainy season responsible for widespread flooding across 17 countries were anomalous events with a return period of 200 years.[38]

Extreme rainfalls in 2012 displaced over two million people in 27 Nigerian states. A study of average rainfalls from 1975 to 2013 observed a significant increase in the intensity and frequency of rainfall extremes responsible for recurrent flood events in Nigeria.[39]

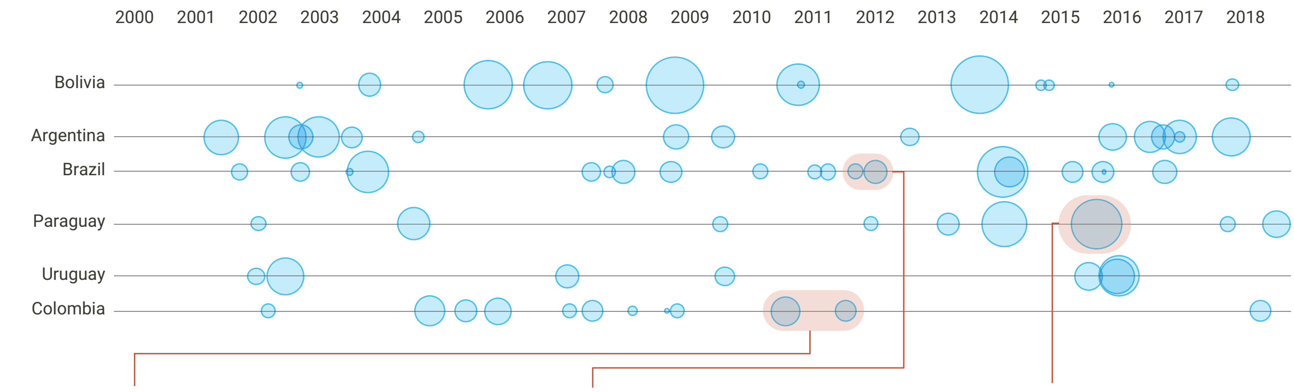
In 2012, 2016 and 2018 seasonal rainfall extremes caused localised and widespread flooding in Kenya. A study found a shift towards intensification of extreme rainfall events, but this trend was not attributed to anthropogenic climate change.[40] Factors linking to unprecedented rainfalls and extensive floods in Kenya in early 2024 are yet to be analysed.[41]

Oceania



Eastern Australia experienced record-breaking rainfalls and subsequent severe flooding in 2010-2012. Research suggested that the precipitation anomalies were attributable to double La Niña events in the eastern equatorial Pacific Ocean during that period.[42-45] Similarly, the 2020-2023 triple La Niña event brought unusually wet conditions and flooding to eastern and southeastern Australia.[41]

Latin America and the Caribbean

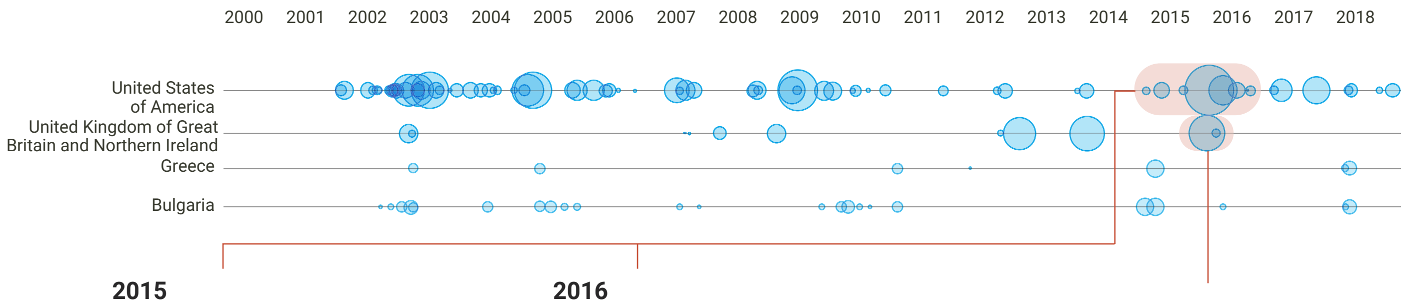


From 2010 to 2011 Colombia experienced one of the most intense La Niña—the cold phase of El Niño Southern Oscillation or ENSO. This La Niña event brought intense and abundant rainfall, high river discharge and subsequent flooding and landslides to the region.[46]

Climate change made the 2012 historic flood in the Amazon basin more likely to occur.[47] Heavy rainfall and extreme floods over the Madeira River basin in early 2014 were linked to exceptional warm conditions in the western Pacific and south Atlantic.[48] The strong El Niño event of 2015/2016 caused excessive rainfall in the state of Paraná in southern Brazil and a part of Paraguay.[49]

The 2015 El Niño event caused intense rainfall and severe floods in the Paraguay River basin in December and made 2015 the wettest year since 2001.[50]

Europe and Northern America



2015

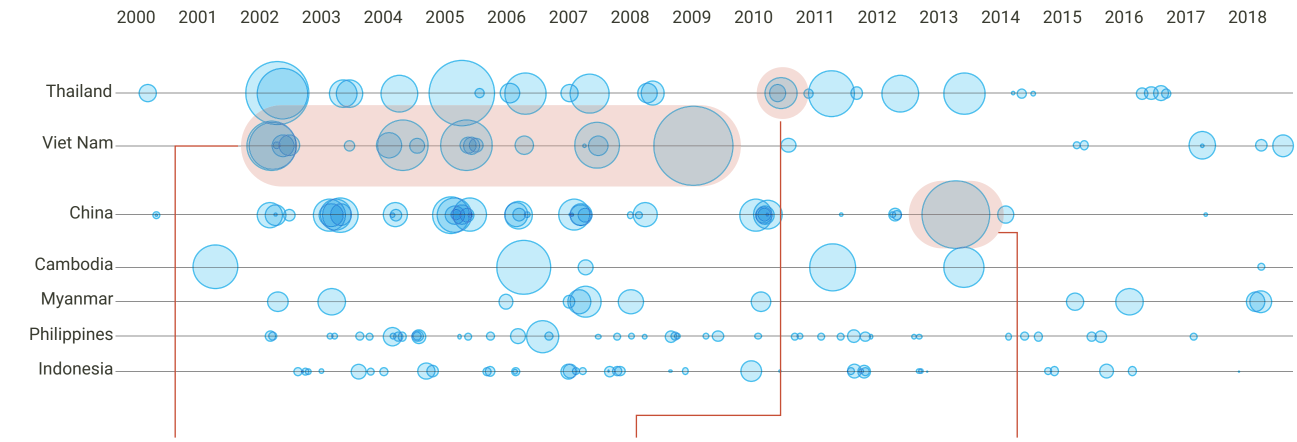
A highly unusual cold season heavy rainfall in late December 2015 in the central United States of America caused widespread flash flooding in the Missouri River basin. The event was found associated with anthropogenic warming.[51] An analysis of rainfall records from 1950 to 2019 showed an increase in the frequency and intensity of extreme events across the basin.[52]

2016

The prolonged, heavy downpour in August 2016 caused historic flooding across Louisiana and southwestern Mississippi.[53] Anthropogenic climate change increased the probability of such extreme precipitation which may occur more frequently as global temperatures rise.[54,55] Land development without proper planning also increased flood risks.[56]

Exceptional rainfall and gale-force wind brought by storm Desmond in December 2015 caused widespread flooding and destruction in northern England and southern Scotland. Three independent climate models suggested that climate change made extreme events like this storm 40 per cent more likely.[57]

Eastern and South-Eastern Asia



The El Niño Southern Oscillation (ENSO) cycle significantly influences monsoonal rainfall over mainland Southeast Asia.[58] A review of rainfalls in Viet Nam during El Niño and la Niña episodes from 1960 to 2009 suggested that heavy rainfall and flooding occurred twice as frequent during La Niña, compared to El Niño conditions, particularly in Central Viet Nam.[59]

Anomalously heavy rainfall from the 6-month monsoon in 2011 combined with four tropical storm remnants led to rivers bursting their banks in Thailand. The 2011 flood was the country's most devastating flood to date. It is estimated that the return period for a flood of this magnitude is between 10-20 years.[60]

About 62 per cent of 351 cities China experienced floods at least once between 2008-2010. An analysis of 68 million rainfall observations from 1971 to 2013 in China suggests that maximum hourly rainfall intensity across a large part of China had increased by 11.2 per cent. Under the 1.5˚C warming, the intensification of rainfall extremes would likely rise by another 10 per cent, further increasing risks of urban flooding.[61]

Central and Southern Asia

An analysis of flood magnitudes in 70 catchments of Peninsular India from 1979 to 2018 suggested that reservoir flow regulation played a more prominent role in determining flood severity, compared to rainfall extreme and soil moisture.[62,63]

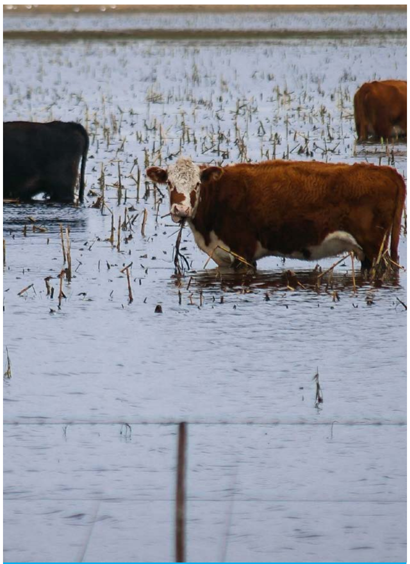
The 2010 monsoon season brought unusually intense rainfalls to Pakistan and northwestern India.[64,65] A large numerical simulation suggested that anthropogenic climate change increased the likelihood of extreme flood occurrence in eight river basins in Asia, Europe and North America from 2010 to 2013, including the Indus Valley in Pakistan.[47]

The 2017 pre-monsoon heavy rainfall event over northeast Bangladesh in March and April triggered flash floods, damage to harvestable crops and human displacement. Anthropogenic climate change doubled the likelihood of the 2017 extreme conditions.[66] Later in August during the monsoon season, Bangladesh experienced one of the worse river flooding events in 40 years.[67] A model study suggested that both 1.5°C and 2.0°C warming are likely to amplify the probabilities of extreme rainfall during the pre-monsoon and monsoon seasons across Bangladesh.[68]

Photo: iStock

4.2 Uncovered, remobilized, redistributed

Various groups of contaminants accumulate in soil, water and sediments. Heavy metals such as arsenic, cadmium, chromium, lead, manganese and mercury are widespread inorganic pollutants known for their persistence and toxicity. Heavy metals do not break down naturally so they remain in the environment until remobilized. Another class of pollutants widely present in the environment are persistent organic pollutants, known as POPs. These highly toxic pollutants include dioxins, furans, organochlorine pesticides, perfluorinated compounds or PFCs, polycyclic aromatic hydrocarbons or PAHs, and polychlorinated biphenyls, commonly known as PCBs. They can cause neurotoxicity, immunotoxicity, hepatotoxicity, reproductive toxicity, and various cancers.[69-72] Persistent organic pollutants break down very slowly in the environment[73,74] and they can remain in sediments for years to centuries.[33,75,76] There is also a diverse range of emerging contaminants that are largely unregulated and increasingly present in terrestrial and aquatic ecosystems.[77]



"Many sediment-bound pollutants can also enter the food chain and accumulate in plants and animals, including humans."

Photo: iStock

Erosion of soils and disturbance of riverbed sediment continuously supply suspended particulate matter to downstream river systems. Due to their properties, suspended particles can bind and accumulate a variety of pollutants. The flow of water, particularly during high flows and floods, can carry and deposit these contaminated sediments downstream along a river or in areas of low flows, such as on floodplains and wetlands, in harbours and estuaries, and behind dams.[78-81] Sediments can accumulate and preserve pollution over centuries.[81] Many sediment-bound pollutants can also enter the food chain and accumulate in plants and animals, including humans.[22,82] These contaminated sediments could be triggered during any flood event and remobilized suddenly and at a landscape scale.

Many regions are increasingly exposed to river and coastal flooding due to the upward trend in rainfall intensity and magnitude associated with tropical storms.[83] In recent years, extreme rainfall and subsequential flooding have demonstrated their ability to remobilize legacy pollutants accumulated in the environment. When Hurricane Harvey struck the Texas coast in August 2017, the floodwaters delivered an enormous load of sediment into the Galveston Bay area of Texas along with significantly high concentrations of carcinogenic polycyclic aromatic hydrocarbons and mercury with a toxic potential to estuarine and marine organisms.[84-88] Extensive petroleum operations and incidences of oil spills in the Niger Delta of Nigeria over decades has led to severe contamination with ecological and human health consequences.[89] A catastrophic flood event in the Niger Delta in 2012 mobilized sediments contaminated with carcinogenic polycyclic aromatic hydrocarbons and deposited them over extensive portions of the floodplain.[90,91] Evaluating the polluted sediments and other pollutant deposits in inland and coastal waters and their ability to resist erosion and release contaminants is crucial to understanding the potential hazards to human and environmental health from flood events. Future studies should prioritize investigating these aspects.

Historical and current sources of legacy contaminants in sediments are problematic and continue to accumulate, including those from industrial and mining activities, landfills, and agriculture.[27,92-98] For example, millions of tons of persistent organic pollutant waste from organochlorine and organofluorine production are deposited in landfills globally, with 4.8 to 7.0 million tonnes of hexachlorocyclohexane waste disposed uncontrolled mainly at former manufacturing sites of the pesticide lindane.[99-101] This historical waste material can significantly contribute to the total pollutant load in adjacent rivers.[31,102,103] For instance, after the worst flooding in over 100 years along the Elbe River in the Czech Republic and Germany in 2002, hexachlorocyclohexane concentrations in fish downstream of former production sites of pesticide lindane increased more than 20-fold.[104-108] The same flood also mobilized legacy radionuclides and heavy metal pollutants from former uranium-mining waste dumps and tailing ponds in the Elbe region.[109]. Similarly, examples from around the world, including Australia, Brazil, China and Europe, highlight the pervasiveness of metal pollution through historical ore and coal mining operations that have been mobilized and transported by floods.[93,98,110-114]

"The redistribution of pollutants during floods often produces a cascade of harmful effects on ecosystems and human health."

Photo: iStock

The Pakistan flood of 2010 inundated approximately a fifth of the country's total land area.[115] The 2010 flood together with a series of smaller flash floods, swept away a significant but unknown portion of 2,835 metric tonnes of obsolete pesticides and other persistent organic pollutants kept in storage facilities for proper disposal.[116] The release of these obsolete chemicals into the environment will likely cause further contamination in soils, water, and sediments, and the damage needs to be monitored and assessed. As of December 2023, additional threats introduced by floods in 2022, which affected a full third of Pakistan's area, had not yet been assessed.[117,118]

The redistribution of pollutants during floods often produces a cascade of harmful effects on ecosystems and human health. Particularly dangerous threats come from contaminated sites – historical and current – especially in areas prone to hydrological shifts due to climate change. In May 2021, the Subcommittee on Environment and Climate Change, Committee on Energy and Commerce of the United States House of Representatives heard testimony about listed sites of hazardous substances, pollutants, or contaminants known throughout the country and its territories.[119] It is estimated that approximately 60 per cent of all nonfederal Superfund National Priorities List sites are in areas vulnerable to climate-related hazards like wildfires, river and coastal flooding, storm surge, and sea-level rise. This recognition highlights the risks of flood-induced remobilization of contaminants that present significant toxicological threats to humans and the environment. However, the geospatial diversity and complexity of extreme flooding events limit our ability to understand and manage the risks they bring to environmental and human health. The remobilization and distribution of highly polluted sediments throughout flood plains, agricultural fields, pastures, and cities can cause devastating damage to human, animal, and environmental health and render some areas unsuitable for growing foods for human consumption for many years.

Forgotten but not gone

Persistent contaminants in water and sediment can enter and accumulate in plants and animals (bioaccumulation), and subsequently make their way up the food chains with increased concentrations (biomagnification), exposing top predators to greater risk of toxic effects and jeopardizing ecosystem health.[120]

Heavy metals are important pollutants recognized for their omnipresence, persistence and toxicity even at very low concentrations.[121] Certain organic compounds, such as pesticides, synthetic chemicals, by-products of industrial processes and waste incineration, are also highly resistant to natural degradation processes.[122] Although these persistent pollutants, to some extent, have been under national and international regulations for their production, usage, release and disposal, or even outright ban, their legacy effects last decades.[123-126]

Sediments of polluted rivers, lakes and estuaries are prone to accumulate diverse persistent contaminants over time.[127] The flow of water, particularly during high flows and floods, can re-suspend, disperse and re-deposit contaminated sediment further downstream and across landscape. Riverine sediments effectively become both a significant sink and a secondary source of pollution.

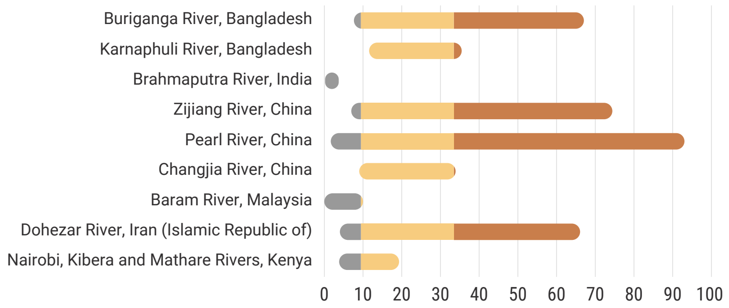
Concentrations of various persistent pollutants in sediments of selected rivers and estuaries

The series of graphs below present ranges of concentrations of various persistent pollutants in sediments collected from rivers and estuaries across regions. The compilation draws from numerous studies and review papers published in recent years with the aim to provide a snapshot of a variety of persistent pollutants accumulated in riverine and estuarine sediments. See the References section. Where available, the graphs also indicate two types of sediment quality indicators relevant to each pollutant.[128,129]

The Threshold Effect Concentration (TEC) is the concentration of a substance in sediment below which harmful effects on sediment-dwelling organisms are rarely observed.

The Probable Effect Concentration (PEC) is the concentration of a substance in sediment above which harmful effects sediment-dwelling organisms are likely to occur frequently.

Arsenic (mg/kg)

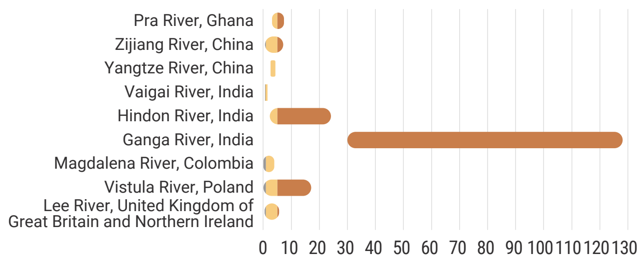


TEC: 9.79 mg/kg **PEC:** 33.0 mg/kg

Sources: Coal-fired power plants, glass production, pesticides, fungicides, wood preservatives,

Effects: Arsenic is carcinogenic. Any level of exposure constitutes a risk. Food intake, particularly rice, wheat and vegetables, is an important exposure pathway, second only to drinking groundwater naturally contaminated by arsenic.[130] Arsenic exposure causes damage to skin, heart, blood, nervous and reproductive systems as well as genetic material.[131]

Cadmium (mg/kg)

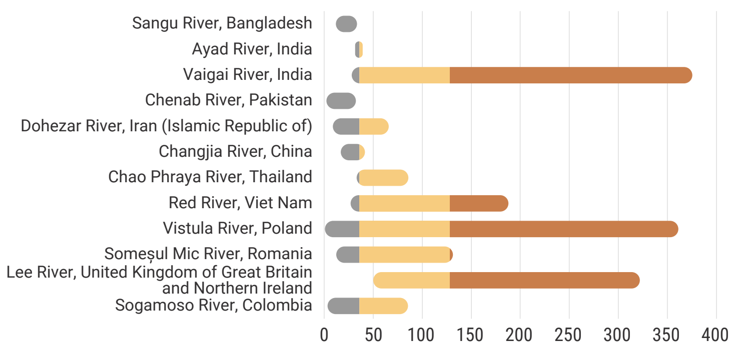


TEC: 0.99 mg/kg **PEC:** 4.98 mg/kg

Source: Batteries, fertilizers, pesticides, alloys, plastic stabilizers, nuclear reactors,

Effects: Cadmium exposure in the general population is mainly through plant-derived food including grains, leafy and root vegetables.[132,133] Cadmium is a carcinogenic with potential endocrine disrupting effects. It can cause kidney and bone damage as well as adverse pregnancy outcomes.[134]

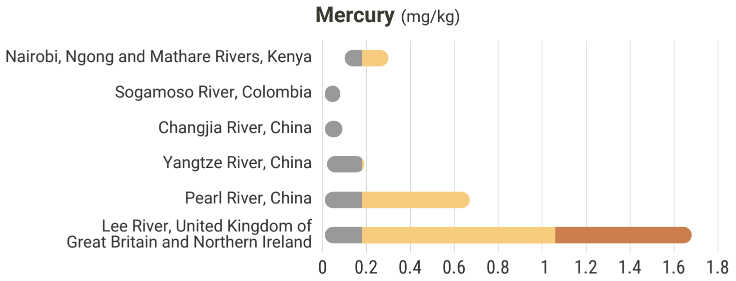
Lead (mg/kg)



TEC: 35.8 mg/kg **PEC:** 128 mg/kg

Source: Paints, lead-acid batteries, pesticides, ammunition, construction materials, lead piping,

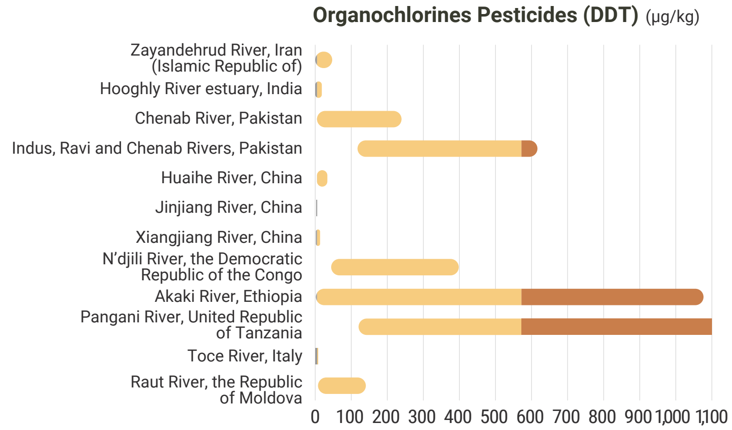
Effects: Lead is possibly carcinogenic. Chronic exposure to lead causes damage to cardiovascular, hematological and central nervous systems; abnormalities in fertility and pregnancy; along with cognitive impairment and reduced brain development in children. Because of normal physiological changes during pregnancy and lactation, women with elevated lead levels can transfer lead to the fetus through the placenta and the baby through breast milk.[133,135]



TEC: 0.18 mg/kg **PEC:** 1.06 mg/kg

Source: Artisanal, small- and large-scale gold mining, biomass burning, industrial processes

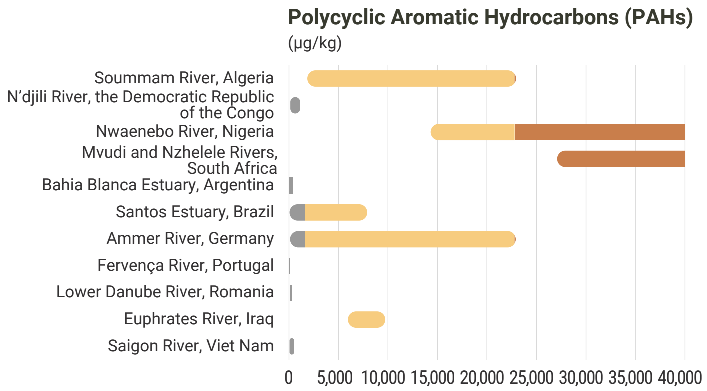
Effects: The nervous and cardiovascular systems and kidneys are primary targets for mercury toxic effects. Mercury toxicity severely affects developing organ systems, especially the fetal brain and nervous system, putting pregnant women, new mothers, and unborn children at high risk.[136]



TEC: 5.28 µg/kg **PEC:** 572 µg/kg

Use: Organochlorines including DDTs are used as pesticides and insecticides.

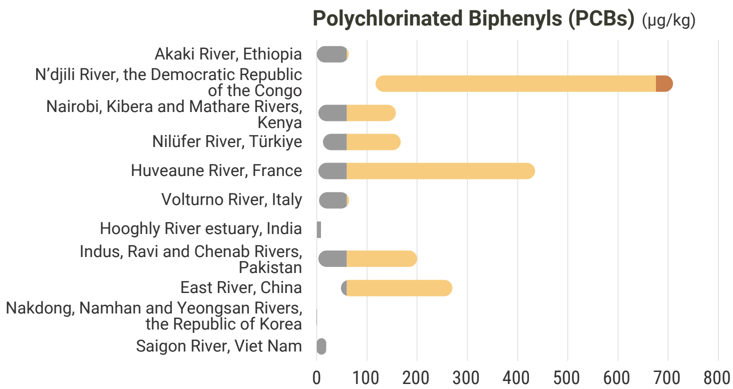
Effects: Many organochlorine compounds are carcinogenic, neurotoxic and endocrine-disrupting. Organochlorines also cause cardiovascular disorders, hypertension, diabetes, obesity and birth defects.[142-144]



TEC: 1,610 µg/kg **PEC:** 22,800 µg/kg

Sources: Incomplete combustion of coal, oil and biomass, petroleum refineries, oil spills, waste incineration, asphalt production, fungicide and insecticide production.

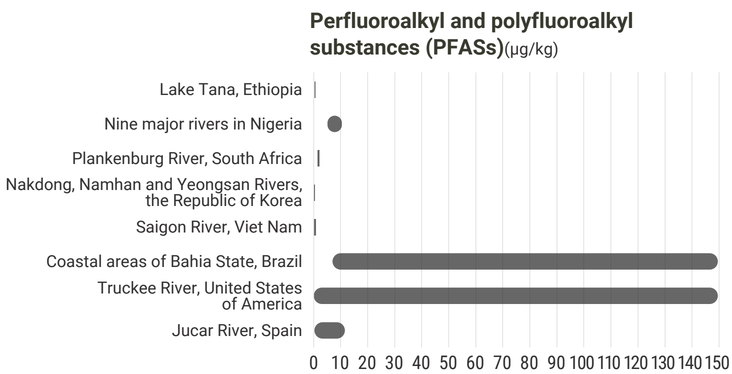
Health effects: PAH compounds cause cancers, disrupt the immune systems, permanently damage genetic materials, and causes abnormality in fetus.[71]



TEC: 59.8 µg/kg **PEC:** 676 µg/kg

Use: Used in electrical and hydraulic equipment; as coolants and lubricants; as plasticizers in plastics, paints and rubber products.

Effects: PCBs are linked to neurological disorders, neurodevelopmental and reproductive abnormalities, immunological alterations, and endocrine interference.[71,137]



Source: Known as forever chemicals, at least 600 PFASs are currently in commercial and industrial use for their friction-resistant properties including food packaging, flame retardants, textile coatings, kitchenware, metal plating, paints and others.

Effects: Adverse effects on immune, thyroid, kidney and liver functions; abnormalities in reproductive and developmental outcomes; and endocrine disruption.[138-141]

Going with the flow

The map below presents a small selection of studies worldwide that investigate the remobilization of legacy chemicals by floods and extreme weather events.

Gardon River, France

Over 50 years after their closure, mining sites were still found to contaminate the Gardon River with antimony, arsenic, cadmium, lead, mercury, thallium and zinc through extreme flood events that remobilized and resuspended the contaminants trapped in sediments.[146]

Trent and the Aire/Ouse river systems, United Kingdom of Great Britain and Northern Ireland

A study found elevated levels of dioxins and polychlorinated biphenyls in livestock raised on flood-prone areas with a history of industrial emissions, potentially exposing consumers to the immunotoxic, carcinogenic, and reproductive effects of these chemicals.[145]

Elbe River, Germany

An analysis of pesticide concentrations in the Elbe River from 2002-2014 and soil samples from an adjacent floodplain detected 13 pesticides in water and some of them in floodplain areas with frequent inundations, including metabolites of a pesticide that had been banned since early 1990s.[147]

The Main River, Germany

In the upper soil of frequently inundated floodplains, a study found high levels of legacy polycyclic aromatic hydrocarbons (PAHs) originating from the dye industry that released untreated wastewater into the Main River for over 100 years.[148]

Galveston Bay, United States of America

Hurricane Harvey caused massive erosion in Scott Bay and Patrick Bayou, removing between half to a metre of sediment layer. This erosion released over three tons of legacy mercury deposits previously buried in the sediment into Galveston Bay. These deposits originated from industrial wastewater. The remaining sediment layers have become more susceptible to further erosion and contaminant release during future large storms.[85]

Chattanooga Creek, United States of America

An analysis found that coal tar from former manufactured gas plants served as a high-concentration reservoir for polycyclic aromatic hydrocarbons and other organic contaminants, which were transported to adjacent floodplains during large seasonal floods.[149]

Ribeira de Iguape River, Brazil

In the northern sections of the Ribeira de Iguape river, tailings from abandoned mines release zinc and cadmium downstream when tailing dams overflow into the main channel during storms and floods.[150]

River Cinca in the Ebro catchment, Spain

An analysis revealed that a flood event of 2016 had remobilized flame retardants, polychlorinated biphenyl, and DDT pesticides and their degradation products from the riverbed. Although the ban on flame retardants is in place, the legacy effects of these contaminants will likely linger as contaminated sediments continue to move and accumulate over time in the lower river basin.[151]

Jinjiang River, China

Heavy rainfall and high runoff from Typhoon Fung-Wong in 2008 increased heavy metal concentrations in Quanzhou Bay by 2-10 times. The recorded elevated levels of these metals in the inner bay came from sediment resuspension, likely due to intensified vertical mixing and stronger tidal currents after the typhoon.[152]

Moreton Bay, Australia

The 2011 flood significantly increased copper, lead and zinc levels in central Moreton Bay, likely due to the remobilization of metal-rich sediments from the lower Brisbane River estuary, along with additional inputs from agricultural and industrial floodplains.[153]

View of Sabarmati Riverfront in Ahmedabad, India
Photo: iStock

4.3 Flood management and adaptation

"Flood retention practices allow floodwaters to flow to designated holding areas where floodwater is temporarily detained..."

Initiatives aimed at minimizing the impacts of floods follow different priorities according to regional circumstances. In Europe, current flood protection laws that follow the European Union's Floods Directive of 2007 prioritize flood retention to minimize the harm from floods to human health, the environment, and economic activities.[154] In Bangladesh, the tidal river management approach aims to manage floods with the goal of balancing development needs against flood risks.[155] In African countries like Mozambique after Cyclones Idai and Kenneth in 2019, flood risk management plans that involve rehabilitating existing drainage systems and building new ones have moved up the priority list for development programmes.[156-158]

In the Asia-Pacific region, China with its 4,000-year history of flood-control challenges is adopting more nature-based management, including refinement of the sponge city approach designed to mitigate urban flood risk by restoring the city's natural capacity to drain, absorb, filter and store rainwater.[159-161] Approaches taken by Japan to protect densely populated cities from floods combine hard river engineering, such as super embankment, with non-structural measures, such as protection and restoration of wetlands, forests, and floodplains to increase flood retention capacity and delay peak discharge.[160]

The Room for the Rivers approach, a nature-based solution concept applied in the Netherlands, is an example of a collaborative and multi-stakeholder initiative to reduce flood risk by increasing flood detention and drainage capacity of the river.[162-164] Flood retention practices allow floodwaters to flow to designated holding areas where floodwater is temporarily detained known as flood-detention basins, flood polders, flood-peak polders, emergency-storage polders and other terms in different regions. To create extra space for floodwaters, various measures selected for site-specific and condition-specific suitability include relocating existing levees, dikes and other obstructing features to widen the floodplain, creating flood by-passes to increase discharge capacity.[164,165]

"When relocating dikes for flood-management objectives in densely populated areas, difficulties can arise due to conflicts of interest that involve land use for settlements, transportation infrastructure, agriculture, and forestry."

Moving levees or dikes to new locations further inland enhances flood retention capacity and helps restore floodplain ecosystems. This restoration context benefits biodiversity and habitat resilience, ecosystem functions and services, and lateral connectivity between land and water.[166] In some cases, it also helps to achieve a broader policy goal in conservation. In the European Union, flood retention practices align with the Water Framework Directive's goal of protecting and restoring water bodies for sound ecological and chemical status.[167] Many European river basins fail to achieve a good ecological status because of engineering modifications to rivers like dikes, dams, weirs, and embankments.[168] However, the impact of such restoration measures on the Directive's second goal – to achieve a good chemical status – concerning the retention and remobilization of contaminated sediment and suspended particulate matter – remains largely unknown.[24]

When relocating dikes for flood-management objectives in densely populated areas, difficulties can arise due to conflicts of interest that involve land use for settlements, transportation infrastructure, agriculture, and forestry. To manage these challenges, practitioners suggested creating shared landscapes, such as pastures functioning as flood polders when needed.[169-171] Allowing animals to graze on flood polders can help control the vegetative succession rate and maintain open landscapes. However, findings from longer-term studies suggest that such shared landscapes may not always be good practice. Research in the European Union has found that meat and dairy products from livestock grazing on contaminated floodplain soils can exceed the maximum levels of dioxins and other contaminants established by European regulations for food and feed.[145,172-174] When the European Food Safety Authority lowered the tolerable weekly intake of dioxins and some PCBs with toxicological properties similar to dioxin by seven-fold a large proportion of EU residents suddenly exceeded the recommended safe levels of exposure to dioxins and dioxin-like PCBs, mainly through food consumption.[173-175] Similarly, in African, Asian and Latin American countries, there are concerns about the safety of food products from areas affected by flooding and contamination.[89,176-179] More efforts are required to assess the risks and develop strategies to ensure food safety in these regions.

Wall of sandbags for flood defense, sandbag barricaded
Photo: iStock

The daily life of the local people against flooding in the streets of Cambodia.
Photo: iStock

4.4 Managing contamination

> **"Monitoring should also include water sampling and checking the compliance of meat and milk products from grazing animals with existing food legislation..."**

We need a fundamental rethinking of flood protection, in which nature-based solutions play a central role. Although the risk potential of flood events cannot be eliminated, innovative combinations of flood-control infrastructure and protection measures guided by nature-based solution principles can reduce the number and intensity of flood events and associated damages.[159,180,181] Traditional flood control measures such as polders, dikes, and retention basins can restore riparian ecosystems by allowing floodplains, wetlands and forests to re-emerge or establish water-conscious urban development. Flooding should be increasingly permitted, where damage to humans can be avoided, to relieve the burden on downstream areas and strengthen biodiversity.[182,183]

However, these measures do not make contaminated sediments disappear – they simply relocate and, ideally, confine the problem to areas that pose less threat to human and environmental health. Managing the risks associated with these contaminated sediments requires the development of river basin management plans that balance flood retention, river conservation, and the multiple pressures on water resources. Regular monitoring regimes for river basin-specific pollutants, especially those with legally binding numerical standards for water and sediment qualities, should be established when constructing flood control structures for retention purposes.[184] Monitoring should also include water sampling and checking the compliance of meat and milk products from grazing animals with existing food legislation, especially for dioxin-like compounds and persistent organic pollutants. A river basin-wide assessment of the erosion potential of contaminated sediment deposits under a range of flood scenarios will inform estimates of contamination risks to drinking water production or to floodplains and polders used for pastures. The potential for dioxin-like compounds to exceed maximum concentrations in free-ranging animals that graze on contaminated floodplains is a significant issue that has not yet received proper attention. Last, an ideal scenario would also include investments in clean-up efforts for in situ or ex situ remediation of highly contaminated sediments.[185-188] Nature-based techniques such as phytoremediation and bioremediation which use plants and microbes to clean up contaminated soil, sediment and water are examples of feasible, non-invasive and cost-effective methods in some settings.[189,190,191]

As climate-related storms intensify, an adaptive management approach is essential for addressing the compounded and cascading effects of flood events, especially when addressing contaminant remobilization risk.[192] This approach involves continuously monitoring and reassessing the effectiveness of implemented measures and adjusting them as necessary based on new information and changing conditions. Integrating local knowledge and engaging local communities, including citizen science efforts, in environmental monitoring and decision-making processes is essential to ensure that management strategies address local needs and priorities and are socially acceptable.[193] Additionally, investing in capacity building among local stakeholders and decision-makers will enhance their ability to manage compounded and cascading effects in their community when flood events arrive. Ultimately, a comprehensive and adaptive management approach that integrates technical, ecological, social, and economic considerations can address the complex and multifaceted challenges posed by flood events.[159]

"These issues highlight the need for better and globally coordinated efforts to establish proper chemical management..."

More efforts are needed to better understand the economic implications of balancing flood management measures with preventing the remobilization of hazardous substances in sediments and restoring affected areas to an environmentally healthy state. Conducting economic evaluations would support communicating the adverse effects of contaminant remobilization during floods to stakeholders at various levels. Some established methods are available to evaluate environmental damage costs, such as OECD cost-benefit analysis.[194-197]

However, significant challenges remain. For example, evaluating the economic impacts requires reliable information about the locations, amounts, and toxicity of hazardous substances, as well as potential economic vulnerabilities.[197,198] More transdisciplinary research involving multiple stakeholders, scientists, citizens, and policymakers is needed to improve economic evaluations of these risks.

This chapter covered retrospective strategies to deal with chemical contamination of sediments after they have been remobilized by flooding. It is pertinent to emphasize that these issues highlight the need for better and globally coordinated efforts to establish proper chemical management, thereby prohibiting current-use chemicals from becoming the legacy contaminants of the future. Global efforts towards establishing a global intergovernmental science-policy panel on chemicals, waste, and pollution prevention are a welcome first step in this process.[199]

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Special thanks to UNEP's funding partners. For more than 50 years, UNEP has served as the leading global authority on the environment, mobilizing action through scientific evidence, raising awareness, building capacity and convening stakeholders. UNEP's core programme of work is made possible by flexible contributions from Member States and other partners to the Environment Fund and UNEP Planetary Funds. These funds enable agile, innovative solutions for climate change, nature and biodiversity loss, and pollution and waste.

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