



World Population Prospects 2024

Methodology of the United Nations population estimates and projections

[Advance unedited version]

Abstract

This report provides a detailed overview of the methodology used to produce the *2024 Revision* of the official United Nations population estimates and projections, prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. The *2024 Revision* of the *World Population Prospects* is the twenty-eighth round of global population estimates and projections produced by the Population Division since 1951.

For the previous revision in 2022, several major methodological enhancements were implemented to improve the standards, transparency and replicability of the data and in response to growing demand for more granular demographic indicators. The *2024 revision* builds on the progress achieved in 2022 with further enhancements to the analytical methods that underpin the *World Population Prospects*. For the first time, a probabilistic model is applied to project net international migration for all countries. A new approach is implemented to project patterns of net international migration by age and sex, providing better representation of migration dynamics for countries that experience both immigration and emigration. A broader range of analytics and adjustments are applied to improve estimates of mortality in old age. Lastly, three additional projection scenarios are introduced to illustrate the sensitivity of future population to changes in the adolescent birth rate.

This report first describes the way that country estimates have been prepared and then explains the approaches and assumptions that were used to project fertility, mortality and international migration up to the year 2100. The report also provides an overview of the scenarios used in generating the different sets of population projections as well as information on the probabilistic projection methods, which depict the uncertainty of future demographic trends. Making projections to 2100 is subject to a high degree of uncertainty, especially at the country level. In that regard, users are encouraged to focus not only on the medium scenario, which corresponds to the means of several thousand projected trajectories of specific demographic components, but also on the associated prediction intervals, which provide an assessment of the uncertainty inherent in such projections. Detailed information on the 80 and 95 per cent uncertainty bounds for different components at the country level and major geographic aggregates is available on the website of the Population Division, www.unpopulation.org.

Keywords: Population estimates and projections, demographic levels and trends, fertility, mortality, international migrations, sustainable development.

United Nations Department of Economic and Social Affairs, Population Division

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Notes

The designations employed in this report and the material presented in it do not imply the expression of any opinions whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The term “country” as used in this report also refers, as appropriate, to territories or areas.

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PREFACE

This report provides a detailed overview of the methodology used to produce the *2024 Revision* of the official United Nations population estimates and projections, prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. The *2024 Revision* is the twenty-eighth round of global population estimates and projections produced by the Population Division since 1951.

For the previous revision in 2022, several major methodological enhancements were implemented to improve the standards, transparency, and replicability of the data, and in response to the growing demand for more granular demographic indicators. Chief among these enhancements was a transition from the historical practice of estimating and projecting population for five-year age groups and over five-year periods of time towards a framework defined by single-years of age and one-year periods of time. Additional areas of improvement entailed the systematic compilation and evaluation of censuses and other empirical data, probabilistic models for estimating key fertility and mortality indicators, and accounting for the mortality impacts of crises, such as conflicts, natural disasters and epidemics, including the COVID-19 pandemic. The *2024 revision* builds on the progress achieved in 2022 with further enhancements to the methods that underpin the *World Population Prospects*. For the first time, a probabilistic model was applied to project net international migration for all countries. A new approach was implemented to project patterns of net international migration by age and sex, providing a better representation of migration dynamics for countries that experience both immigration and emigration. A broader range of analytics and adjustments has been applied to improve the estimates of mortality in old age. Finally, three additional projection scenarios were introduced to illustrate the sensitivity of the future population to changes in the adolescent birth rate.

This report first describes the way in which country estimates have been prepared and then explains the approaches and assumptions used to project fertility, mortality, and international migration up to the year 2100. The report also provides an overview of the scenarios used to generate different sets of population projections, as well as information on probabilistic projection methods, which depict the uncertainty of future demographic trends. Making projections to 2100 is subject to a high degree of uncertainty, especially at the country level. In this regard, users are encouraged to focus not only on the medium scenario, which corresponds to the means of several thousand projected trajectories of specific demographic components, but also on the associated prediction intervals, which provide an assessment of the uncertainty inherent in such projections. Detailed information on the 80 and 95 per cent uncertainty bounds for different components at the country level and major geographic aggregates is available on the website of the Population Division, www.unpopulation.org.

The *2024 Revision of the World Population Prospects* was prepared by a team led by Patrick Gerland, including Srikanth Athaluri, Helena Cruz Castanheira, Fernando Fernandes, Sara Hertog, Yumiko Kamiya, Vladimíra Kantorová, Pablo Lattes, Kyaw Kyaw Lay, Joseph Molitoris, Suryanarayana Murthy Palacharla, José Henrique Monteiro da Silva, Mark Wheldon, Iván Williams, Chandra Yamarthy and Lubov Zeifman, with the assistance of Fengqing Chao, Jorge Cimentada, Ivan Čipin, Sehar Ezdi, Giulia Gonnella, Petra Medimurec, Adrian Raftery, James Raymer, Tim Riffe, Carl Schmertmann, and Hana Ševčíková, Bruno Schoumaker. The team is grateful to other colleagues in the Population Division for the support they have provided, as well as colleagues from the Latin American and Caribbean Demographic Centre, Population Division of the United Nations Economic Commission for Latin America and the Caribbean (ECLAC), the Demographic Statistics Section of the Statistics Division of the United Nations Department of Economic and Social Affairs, and the teams of the United Nations Inter-Agency Group for Child Mortality Estimation (UN IGME) and the WHO-UN DESA Technical Advisory Group on COVID Mortality Assessment for their inputs and continuous support. The team is additionally grateful to Thomas Spoorenberg for reviewing this report.

CONTENTS

PREFACE	III
EXPLANATORY NOTES	VII
INTRODUCTION	1
I. THE PREPARATION OF POPULATION ESTIMATES	3
A. GENERAL ANALYTICAL STRATEGY AND MAJOR STEPS FOR PRODUCING POPULATION ESTIMATES	3
B. ESTIMATING TOTAL FERTILITY, AGE-SPECIFIC FERTILITY AND THE SEX RATIO AT BIRTH	7
C. ESTIMATING MORTALITY RATES AND LIFE TABLES	12
D. ESTIMATING THE 1950 BASE POPULATION AND POPULATION BENCHMARKS	21
E. ESTIMATING NET INTERNATIONAL MIGRATION	25
II. THE PREPARATION OF POPULATION PROJECTIONS	28
A. PROJECTING THE MEDIUM FERTILITY SCENARIO	28
B. PROJECTING AGE PATTERNS OF FERTILITY.....	33
C. PROJECTING THE MEDIUM MORTALITY SCENARIO	34
D. PROJECTING AGE PATTERNS OF MORTALITY	46
E. INTERNATIONAL MIGRATION IN THE MEDIUM SCENARIO	47
F. THIRTEEN PROJECTION SCENARIOS	53
G. POPULATION PROJECTION METHOD.....	56
ANNEX	57
REFERENCES	60

TABLES

Table I.1 Country-years of empirical data for sex- and age-specific mortality rates, by data source and data process	12
Table I.2 HIV prevalence rates and ART coverage among adults aged 15-49 years in 2022 for countries for which explicit modelling of HIV and AIDS was employed in the 2024 revision (percentages)	16
Table I.3	18
Table II.1 Global default set of parameters for the female life expectancy at birth double-logistic estimation	37
Table II.2 Countries for which adjustments were made to the default mortality projection trajectory in the 2024 revision	43

FIGURES

Figure I.1 Process used to ensure intercensal consistency between demographic components and the total population	4
Figure I.2 Workflow to estimate a full annual time series of each demographic indicator from 1950-2023	6
Figure I.3 Total fertility estimation for Lesotho, 1945 to 2023	9
Figure I.4 Estimation of age-specific fertility rates* for Egypt, 1950 to 2023	10
Figure I.5 Observed and predicted PES net census errors for Bangladesh, 1950 to 2023.....	24
Figure I.6 Difference in net census error by sex and age for Bangladesh, 1981-2011 censuses	24
Figure II.1 Schematic phases of the fertility transition (live births per woman)	29
Figure II.2 Total fertility annual decrements by level of fertility and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part) (live births per woman)	31
Figure II.3 Estimates and projected probabilistic trajectories of total fertility, Bangladesh, 1950-2100 (live births per woman)	32
Figure II.4 Phases of the mortality transition: gains in life expectancy at birth by level of life expectancy at birth (years)	34
Figure II.5 Female gains in life expectancy at birth by level of life expectancy at birth and prediction intervals of estimated double-logistic curve, China (years).....	36
Figure II.6	38
Figure II.7 Estimates and projected probabilistic trajectories of gap between female and male life expectancy at birth, China, 1950-2100 (years)	39
Figure II.8 Estimates and projected probabilistic trajectories of male life expectancy at birth, China, 1950-2100 (years)	40
Figure II.9 Comparison of probabilistic projections of female and male life expectancies at birth, selected periods, China (years)	41

EXPLANATORY NOTES

The following symbols have been used in the tables throughout this report:

A full stop (.) is used to indicate decimals.

Years given refer to July 1 or the civil calendar year by default.

References to countries, territories and areas:

The designations employed in this publication and the material presented in it do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The term “country” as used in this publication also refers, as appropriate, to territories or areas.

In this table, data for countries or areas have been aggregated in six continental regions: Africa, Asia, Europe, Latin America and the Caribbean, Northern America, and Oceania. Further information on continental regions is available from <https://unstats.un.org/unsd/methodology/m49/>. Countries or areas are also grouped into geographic regions based on the classification being used to track progress towards the Sustainable Development Goals of the United Nations (see: <https://unstats.un.org/sdgs/indicators/regional-groups/>).

The designation of “more developed” and “less developed” regions is intended for statistical purposes and does not express a judgment about the stage reached by a particular country or area in the development process. More developed regions comprise all regions of Europe plus Northern America, Australia and New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (excluding Japan), and Latin America and the Caribbean as well as Oceania (excluding Australia and New Zealand).

The group of least developed countries includes 45 countries: 32 in Sub-Saharan Africa, 2 in Northern Africa and Western Asia, 4 in Central and Southern Asia, 3 in Eastern and South-Eastern Asia, 1 in Latin America and the Caribbean, 3 in Oceania (as accessed on 8 May 2024). Further information is available at <https://www.un.org/ohrlls/content/least-developed-countries>.

The group of Landlocked Developing Countries (LLDCs) is composed of 32 countries or territories: 16 in Sub-Saharan Africa, 2 in Northern Africa and Western Asia, 8 in Central and Southern Asia, 2 in Eastern and South-Eastern Asia, 2 in Latin America and the Caribbean, and 2 in Europe and Northern America (as accessed on 8 May 2024). Further information is available at <https://www.un.org/ohrlls/content/landlocked-developing-countries>.

The group of Small Island Developing States (SIDS) is composed of 57 countries or territories: 29 in the Caribbean, 20 in the Pacific and 8 in the Atlantic, Indian Ocean and South China Sea (AIS) (as accessed on 8 May 2024). Further information is available at <https://www.un.org/ohrlls/content/small-island-developing-states>.

The country classification by income level is based on the GNI per capita from the World Bank (as accessed on 8 May 2024). Further information is available at <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519>.

The following abbreviations have been used:

AIDS	Acquired immunodeficiency syndrome
API	Application Programming Interface
ART	Antiretroviral therapy
ASFR	Age-specific fertility rate
BHM	Bayesian hierarchical model
CCMPP	Cohort Component Method for Projecting Population
CDR	Crude Death Rate
COVID-19	Coronavirus Disease 2019
CPS	Contraceptive Prevalence Surveys
CRVS	Civil Registration and Vital Statistics
DHS	Demographic and Health Surveys
DTP	Diphtheria, Tetanus, and Pertussis
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GNI	Gross National Income
HDSS	Health and Demographic Surveillance Systems
HFD	Human Fertility Database
HIV	Human immunodeficiency virus
HMD	Human Mortality Database
IGME	Inter-agency Group for Child Mortality Estimation
IPUMS	Integrated Public Use Microdata Series
LAMBdA	Latin American Mortality Database
LC	Lee-Carter method for mortality forecasting
MAC	Mean age at childbearing
MICS	Multiple Indicator Cluster Survey
MLT	Model life table
PAPFAM	Pan-Arab Project for Family Health
PASFR	Proportionate age-specific fertility rate
PES	Post-Enumeration Survey
PI(s)	Prediction interval(s)
PMA	Performance Monitoring and Accountability
PMD	Pattern of Mortality Decline
RHS	Reproductive Health Surveys
SAR	Special Administrative Region
SRB	Sex ratio at birth

SQL	Structured Query Language
SVD	Singular Value Decomposition
TFR	Total fertility rate
UN	United Nations
UNAIDS	Joint United Nations Programme on HIV/AIDS
UNDESA	United Nations Department of Economic and Social Affairs
UNFPA	United Nations Population Fund
UNHCR	Office of the United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
VR	Vital Registration
WFS	World Fertility Survey
WHO	World Health Organization
WPP	World Population Prospects

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INTRODUCTION

The preparation of each new revision of the official population estimates and projections of the United Nations involves two distinct processes: (a) the incorporation of new information about the demography of each country or area of the world, involving a reassessment of past estimates where warranted, and (b) the formulation of detailed assumptions about the future paths of fertility, mortality, and international migration for every country or area of the world.

The population estimates and projections in this revision cover a 150-year time horizon. Estimates refer to the period from 1 January 1950 to 1 January 2024 and projections are for the period from 1 January 2024 to 1 January 2101. For each of the 237 countries or areas, the population estimates and projections were produced by starting with a base population by age and sex for 1 January 1950 and advancing the population through successive single-year intervals of time using the cohort-component method for projecting population (CCMPP). The CCMPP relies on information about: fertility by age of mother to determine the number of births taking place each year; mortality by sex and age to determine the number of deaths; and net international migration by sex and age to determine the levels and patterns of population shifts across international borders.

For estimates, complete annual series of fertility, mortality and net international migration for calendar years 1950 through 2023 were developed based on available sources of empirical information, including civil registration and vital statistics, censuses, demographic surveys, and administrative records, to name several. The estimates also considered the impact of the COVID-19 pandemic on the components of demographic change, including by incorporating estimates of excess mortality through 2021, produced by the WHO (Msemburi and others, 2023; World Health Organization, 2024), and through 2023 for a subset of countries with high-quality data available through vital registration (Karlinsky and Kobak, 2021, 2024). Population counts by age and sex from periodic censuses were used to benchmark the CCMPP results for most countries. These counts were adjusted, where necessary, for coverage gaps, deficiencies in age reporting, and over- or under-enumeration. For some countries, population counts from registers or estimates served as supplemental benchmarks.

For the projection horizon covering calendar years 2024 through 2100, the annual series of total fertility, life expectancy at birth, and total net international migration were developed through probabilistic models. These models considered the historical levels and trends estimated for each country to provide a central projected trajectory, as well as statistical bounds of uncertainty¹ (prediction intervals or PIs), for each of these indicators. Together with assumptions about how patterns of fertility shift over the age of women and patterns of mortality and international migration are distributed by age and sex, the central model results provide the necessary inputs to the CCMPP for the “medium” variant projection. Alternative scenarios describe the effect of changes in assumptions about fertility, mortality, and net international migration on the projected size and age structure of the population.

The report begins with a description of the methods employed to revise the estimates during the preparation of the *2024 revision*. It then examines the approaches and assumptions used to project fertility, mortality and international migration up to the year 2100. The report contains information on probabilistic projection methods as well as an overview of the different deterministic scenarios used to generate multiple sets of population projections.

¹ For further discussion about uncertainty in future population projections, see also United Nations (2019a).

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I. THE PREPARATION OF POPULATION ESTIMATES

A. GENERAL ANALYTICAL STRATEGY AND MAJOR STEPS FOR PRODUCING POPULATION ESTIMATES

With each revision of the *World Population Prospects*, the Population Division of UN DESA reviews its methods and procedures to identify and prioritize areas for improvement. In light of the latest standards and expectations regarding transparency and replicability (Stevens and others, 2016), and in response to the growing demand for demographic indicators that are disaggregated by ever smaller units of age and time (Committee for the Coordination of Statistical Activities, 2020), the Division undertook a major overhaul of the data, processes and methods implemented in the *2022 revision*. Chief among these improvements was the transition from the historical practice of estimating and projecting population for five-year age groups and over five-year periods of time (5x5) towards a framework defined by single years of age and one-year periods of time (1x1).

For the *2024 revision*, the core methods and data processes remained the same as in the previous revision, but select amendments were implemented to improve or refine some components of the estimation process. Key examples include the refinement of probabilistic models of age-specific fertility, additional options for smoothing mortality schedules over age and time, and an expansion of the use of official population estimates as benchmark populations for estimating net international migration. These methodological changes are described in detail in sections B through E of this chapter.

As in previous revisions, the core approach underlying the population estimates and projections in the *2024 revision* is the cohort-component method for projecting population (CCMPP). It is the most common projection method among demographers today and has been employed by the Population Division to produce country-level projections since the *1963 revision*. CCMPP provides an accounting framework for the three demographic components of population change — fertility, mortality and international migration — and applies it to the population in question (United Nations, 1956) such that the “demographic balancing equation” is preserved (Preston and others, 2001; Whelpton, 1936):

$$P(t+n) = P(t) + B(t \text{ to } t+n) - D(t \text{ to } t+n) + NM(t \text{ to } t+n)$$

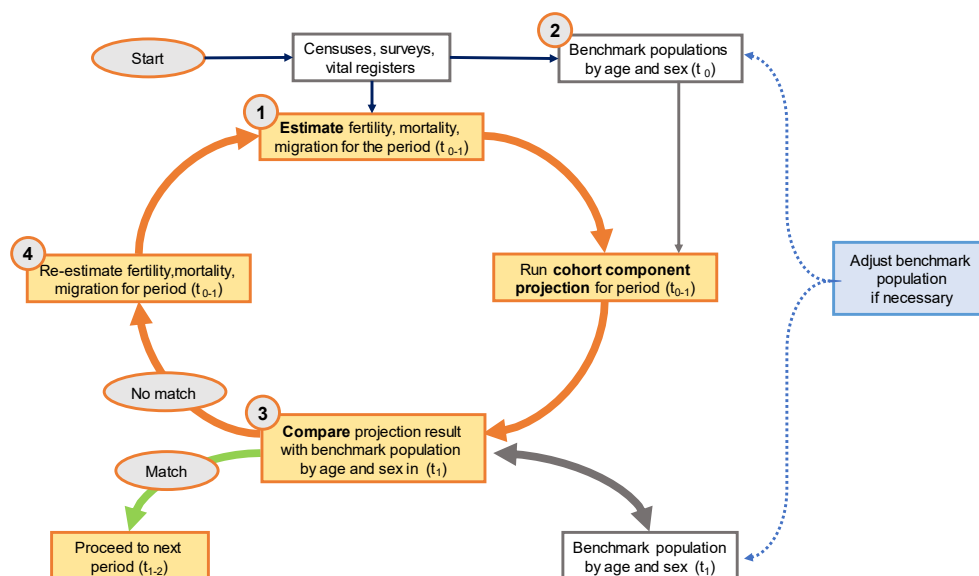
where n is the length of the projection interval, $P(t)$ is the population at the beginning of the projection interval, $P(t+n)$ is the population at the end of the projection interval, $B(t \text{ to } t+n)$ is the births within the projection interval, $D(t \text{ to } t+n)$ is the deaths within the projection interval, and $NM(t \text{ to } t+n)$ is the net international migration within the projection interval (immigrants less emigrants).

Technically, CCMPP is not a complete projection method on its own, as it requires the components of change to be projected in advance. Rather, it is an application of matrix algebra that enables demographers to calculate the effects of the assumed future patterns of fertility, mortality, and international migration on a population at some given point in the future (Preston and others, 2001; Whelpton, 1936).

While CCMPP is commonly understood as a method for projecting future populations, it also provides a useful framework for reconciling historical population estimates for consistency with time series of estimated levels and trends in fertility, mortality, and net international migration. In this way, the Population Division additionally employed the CCMPP as the engine to produce and validate the population estimates,

including as a key approach to estimate the levels and patterns of net international migration. This process is described in figure I.1 and in the steps detailed below.

Figure I.1 **Process used to ensure intercensal consistency between demographic components and the total population**



NOTE: The diagram above illustrates how individual estimates of fertility, mortality and net-migration were subjected to tests of internal consistency using a cohort-component projection framework for the period between t_0 and t_1 . This procedure has been applied to each new revision of the *World Population Prospects*. Past estimates are re-evaluated when new information becomes available; therefore, with every revision past demographic trends may be adjusted.

1. *Estimate the components of demographic change*: Analysts collected available data from censuses, surveys, vital and population registers, analytical reports and other sources for a given country². In many cases, estimates derived from different sources or using different methods varied significantly, and all available empirical data sources and estimation methods were compared. Various techniques, described later in this chapter, were used to identify the most likely time series for fertility, mortality, and international migration data for each country.
2. *Estimate benchmark populations by age and sex*: Population counts from censuses were evaluated for geographical coverage, completeness and several common data problems. Post-enumeration surveys were used, if available, to assess the degree and pattern of under-enumeration. Counts were adjusted, as necessary, according to the protocol described later in this chapter. Counts from population registers or other high-quality sources of population by age and sex were additionally compiled to use as benchmarks for countries where such data were available. Supplemental benchmarks considered for specific age groups included: third-dose DTP immunizations administered to children under 1 year of age (WHO/UNICEF, 2020); primary and secondary school

² Traditionally, the data are obtained from the United Nations Statistics Division (Demographic Yearbook), national statistical offices and regional ones (e.g., Eurostat, OECD), United Nations Regional Commissions, other United Nations entities (e.g., UNAIDS, UNFPA, UNESCO, UNICEF, WHO, World Bank), and complemented using international databases (e.g., the Human Mortality Database (Max Planck Institute for Demographic Research (Germany) and others, 2023b) and Human Life Table Database (Max Planck Institute for Demographic Research (Germany) and others, 2023a), the Human Fertility Database (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2023), Short-Term Fertility Fluctuations (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2024) and Human Fertility Collection (Max Planck Institute for Demographic Research (Germany) and Vienna Institute of Demography (Austria), 2020), the Latin American Mortality Database–LAMBdA (Palloni and others, 2021), the International Data Base (U.S. Bureau of the Census, 2020), the Global Burden of Disease project (Institute for Health Metrics and Evaluation, 2020), and public use microdata archives (e.g., DHS, MICS, IPUMS-International).

enrolment (UNESCO Institute for Statistics, 2020); and national ID registration (World Bank, 2018) as well as voter registration data (International IDEA, 2020) for adults.³

3. *Compare the CCMPP population against benchmarks.* The previous steps provided the initial sets of independent estimates of the population and each demographic component. In the third step, the estimates of fertility, mortality and net migration are integrated into the CCMPP where these demographic rates are applied to a base population to compute subsequent populations by age and sex. A comparison of the population counts by age and sex estimated through the CCMPP against the set of benchmark populations provides an assessment of whether the relationships between the benchmark populations and the estimated fertility, mortality and net migration obtained in steps 1 and 2 are internally consistent.
4. *Re-estimate the demographic components (as necessary):* If, in step 3, the benchmark populations were not adequately matched by the CCMPP, adjustments to one or more demographic components were made. In some cases, the initial base population itself was revised. Consistency was achieved through an iterative “project-and-adjust” process from one benchmark to the next to ensure optimal consistency across all inputs to CCMPP. Once all components of each country’s estimates were calculated, the results were aggregated by geographical region, and a final round of consistency checking took place, which involved comparing the preliminary estimates against those from other countries in the same region or at similar levels of fertility or mortality. When inconsistencies were identified, the necessary adjustments were made. An important component of the work at this stage was ensuring the consistency of information on the net number of international migrants, which must sum to zero at the world level for each period.

As in the *2022 revision*, the internal CCMPP framework for the *2024 revision* tracked cohorts over single ages, from 0 to 130 years. Published estimates and projections were summarized using an open-ended age group of 100+ years. CCMPP population inputs and outputs all referred to 1 January of the reference year and vital rates referred to calendar years from 1 January to 31 December. Published estimates with reference date 1 July represent the arithmetic mean of the values estimated for 1 January. For all countries and time periods, net international migration was accounted for at the end of each projection cycle (e.g., 31 December). This approach facilitates both the recovery of benchmark populations and the balancing of net migration across countries such that the world total sums to zero for all periods. For that reason, it is preferred over alternatives that distribute migration more evenly over the period.

As for the previous revision, the *2024 revision* included publication of population exposures by sex and age⁴. Together with counts of vital events, the population exposures by single year of age can be used to recompute the age-specific fertility and mortality rates that were input to the CCMPP. Because net migration is accounted for at the end of each period, exposures are not equivalent to the mid-year population. Rather, population exposures are approximately equal to the mid-year population without international migration.

Estimates for groups of countries defined by geographic region or level of economic development, among other criteria, were computed by aggregating the vital events and exposures among constituent

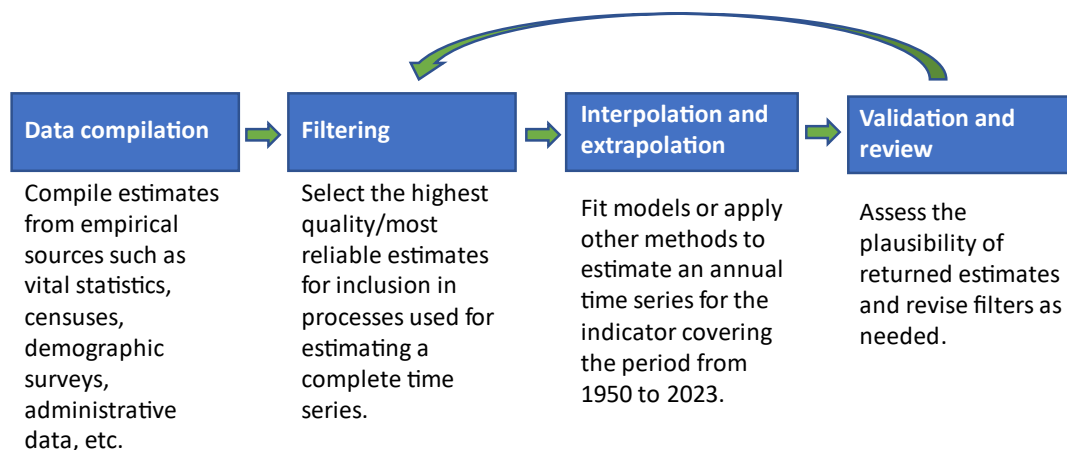
³ These administrative data often suffer from incomplete coverage yet may still provide a useful lower baseline reference to validate CCMPP population counts for specific age groups, especially in countries lacking recent censuses or population registers.

⁴ See annex B for a description of how population exposures were recovered in the CCMPP.

countries⁵. As such, aggregate age-specific fertility rates were computed by dividing aggregated (summed) births by mothers' single-year of age by aggregated exposures of women by age. Total fertility and other fertility indicators for each country grouping were derived from age-specific fertility rates. Similarly, aggregate age-specific mortality rates by single year of age were computed by dividing aggregated deaths by age and sex by aggregated sex- and age-specific person-years of exposure. Complete life tables and related indicators were then derived from those mortality rates.

The CCMPP requires a full annual time series of key demographic indicators as inputs, including the total fertility rate and associated age-specific fertility rates by single year of age, the sex ratio at birth, mortality rates by sex and single year of age, and counts of net international migration by sex and single year of age. The processes used to estimate the time series vary according to the indicator, but a common general approach was applied (figure I.2). In brief, this approach entailed first compiling all available empirical data, such as from vital statistics, censuses, demographic surveys, administrative data or other sources. Next, these estimates were filtered or weighted according to their quality or reliability for inclusion in the later steps. Once a preliminary set of empirical estimates was identified for the given country, models or other methods were applied to reconcile the series and interpolate or extrapolate for periods without empirical observations. In a final step, the returned time series was reviewed for plausibility and consistency. If indicated by this assessment, analysts returned to the filtering step to further refine the reference data set used to estimate the time series for the specific demographic indicator.

Figure I.2 **Workflow to estimate a full annual time series of each demographic indicator from 1950-2023**



The Population Division continued to use several data information systems to implement the 2024 revision. These systems included: (a) an inventory of available data (DataCatalog), (b) a repository (DataArchive) of input data sources, (c) a database (DemoData⁶) to store and update the information used in preparing estimates of population estimates and of the components of population change (fertility, mortality, migration), (d) a structured set of metadata used for data analysis, statistical modelling and public documentation (ShortNotes), and (e) a dissemination platform (DataPortal⁷) to give access to all output and

⁵ In addition to a default set of standard aggregates, see additional aggregations for economic and trading groups, geographical groups, political groups, and UN-related groups from <https://population.un.org/wpp/Download/SpecialAggregates/> and detailed group membership with parent-child relationships available from the "Aggregation_Lists" datasheet from the Locations metadata online worksheet available at: https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F01_LOCATIONS.XLSX

⁶ <https://popdiv.dfs.un.org/DemoData/web/>

⁷ <https://population.un.org/dataportal/>

input data in tabular form, as well as to provide tools for creating interactive visualizations and to query data via an open Application Programming Interface (API)⁸.

For the previous revision in 2022, the Population Division used for the first time a suite of R libraries developed in collaboration with various academic researchers and contributors to perform various demographic computations and analyses in a more transparent manner. These include libraries that: dynamically query the DemoData open API⁹; standardize and harmonize empirical counts of population, deaths and births to streamline the analyses of fertility and mortality, and to evaluate and adjust population censuses; estimate intercensal net migration and compute age and sex distributions of net migration; and apply the CCMPP by single years of age and one-year periods time. The use of these libraries continued for the implementation of the *2024 revision*, including some refinements to improve precision and efficiency.

The following sections describe the specific methods applied to estimate the annual time series of demographic indicators required by CCMPP.

B. ESTIMATING TOTAL FERTILITY, AGE-SPECIFIC FERTILITY AND THE SEX RATIO AT BIRTH

Bayesian hierarchical models were used to estimate the annual time series of total fertility, age-specific fertility and the sex ratio at birth from 1950 through 2023 for all countries. These models incorporated available empirical evidence from vital statistics, population censuses and demographic surveys. The data and model specifications for each indicator are described below.

1. Data availability

The preferred source of data on fertility is counts of live births, by age of mother, from a system of civil registration with national coverage and a high level of completeness (United Nations, 2014a). In cases where birth registration is deficient or lacking, fertility estimates are typically obtained through sample surveys. Demographic sample surveys may provide estimates of fertility by asking women detailed questions to obtain their complete childbearing histories, or just summary information about the total number of children ever born. Current global survey programmes collecting detailed birth histories include the Demographic and Health Surveys (DHS) and Multiple Indicator Cluster Surveys (MICS)¹⁰. Separate from the global programmes, some countries field their own national demographic surveys and a few have established sample vital registration systems. Population censuses serve as additional sources of information on fertility through questions about the number of children ever born. Moreover, the census population counts themselves can be used to estimate total fertility by the “reverse survival” method (Moultrie and others, 2013).¹¹ For most countries, recent direct or indirect information on fertility was available to inform the *2024 revision*. Among the 236 countries or areas with 1,000 inhabitants or more in 2023, all but 40 had available fertility data collected in 2019 or later. For 2023, 35 countries and areas had total fertility and age-specific fertility data, and an additional 6 countries had data on the number of births.

⁸ See DataPortal open API user guide (<https://population.un.org/dataportal/about/dataapi>) for R and Python tutorials and technical documentation.

⁹ See DemoData open API documentation (<https://popdiv.dfs.un.org/Demodata/swagger/ui/index#>) and DDSQLtools R package (Riffe and others, 2022b) to query empirical data for selected locations and indicators using R.

¹⁰ Fertility estimates from some other international survey programs were also considered, for example the Performance Monitoring and Accountability (PMA) surveys. Other international survey programs that provided fertility estimates in decades prior to 2010 included the World Fertility Survey (WFS), the Contraceptive Prevalence Surveys (CPS), the Reproductive Health Surveys (RHS), and the Pan-Arab Project for Family Health (PAPFAM).

¹¹ The reverse survival method was implemented using the fertestr package for R (Lima and Monteiro da Silva, 2021).

For the 32 of the 40 countries, the most recent data were collected between 2014-2018, and only for 8 the most recent national data were from 2012 (Barbados, Djibouti, Nicaragua), 2011 (Trinidad and Tobago), 2010 (Eritrea, Micronesia (Fed. States of), South Sudan) and 2009 (Syrian Arab Republic). The metadata associated with the *2024 revision*, available online, provides further details about the specific fertility data that were used for each country¹².

2. Total fertility

Total fertility is the mean number of live births a woman would have by age 55 if she survived to age 55 and were subject, throughout her life, to the age-specific fertility rates observed in a given year. It is expressed as the number of children per woman. For the *2024 revision*, an annual time series of total fertility from 1950 to 2023 was estimated for each country using a Bayesian hierarchical model, built on the theoretical model used by the United Nations to model fertility change. This model considers the biases and uncertainty associated with empirical estimates from different types of data sources, direct and indirect estimation methods, and other factors that contribute to systematic biases and non-sampling errors (Liu and Raftery, 2020). Estimates were computed using an updated version of bayesTFR (Liu and others, 2023; Ševčíková and others, 2024a). The data used by the model to estimate and correct for biases are country-specific. The model uses either the estimates from the previous revision of the *World Population Prospects* or some other data source(s) deemed unbiased by the analyst as a baseline reference. The model takes into account two types of data characteristics: (1) several time-invariant categories that describe the type of data source (e.g., census, survey, vital registration), the type of estimation method (e.g., recent births, birth histories, adjusted fertility using P/F ratio method, own-children or reverse survival estimates, etc.), and the corresponding education level for estimates based on the reverse survival of enrolled school children, and (2) several time-dependent covariates such as the number of years of recall lag for retrospective estimates, the proportion of live births registered for vital statistics, the school enrolment rate for indirect estimates from education statistics, and the proportion of deaths due to conflicts or natural disasters one year prior.

Fertility from vital registration were used only for country-years with at least 60 per cent completeness of birth registration (Preston, 1984). The fertility time series for countries with at least 98 per cent completeness of birth registration since 1950 were treated as unbiased.

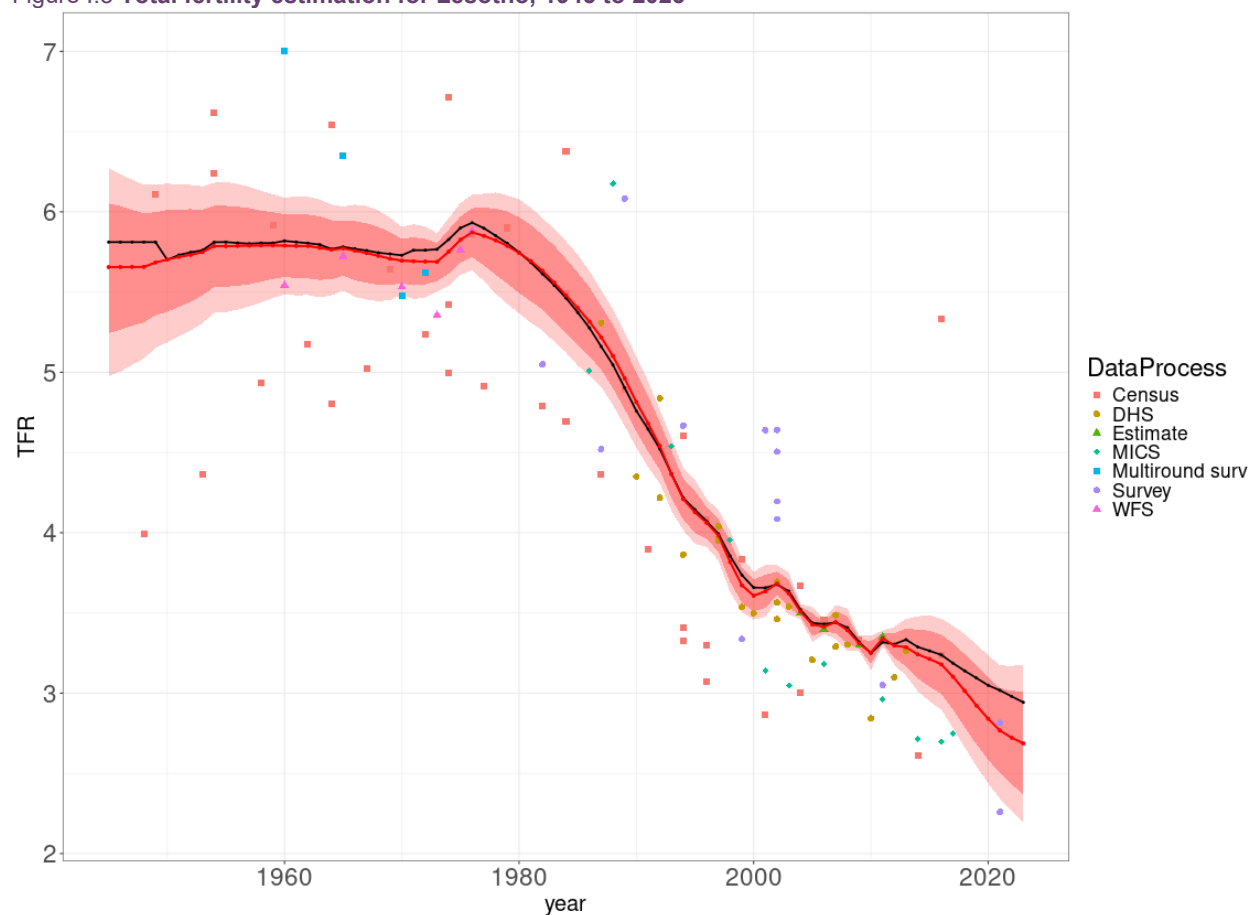
For each country, the median estimate of total fertility was based on a sample of 2,000 trajectories of the model fitted to the observed data after considering the various types of biases. For selected countries and periods, additional adjustments to the posterior distributions returned by the model were applied to constrain the median estimate to reflect the fluctuations in the sizes of specific birth cohorts, as enumerated in successive population censuses.¹³

The results of the total fertility estimation for Lesotho are shown in figure I.3. The plotted series begins in 1945, but only estimates for 1950 and later are used in the *World Population Prospects*. The shapes represent the cloud of empirical data points from censuses and surveys, the red line traces the annual time series of total fertility estimates for the *2024 revision*, the red shaded areas represent the 80 and 95 per cent uncertainty intervals surrounding those estimates, and the black line shows the annually interpolated total fertility estimated for the *2022 revision*.

¹² <https://population.un.org/wpp/Download/Metadata/Documentation/>

¹³ The adjustment for a country and time period corresponds to the ratio between the unadjusted median TFR and adjusted median TFR, and is applied to each TFR probabilistic trajectory for the corresponding country and period.

Figure I.3 Total fertility estimation for Lesotho, 1945 to 2023



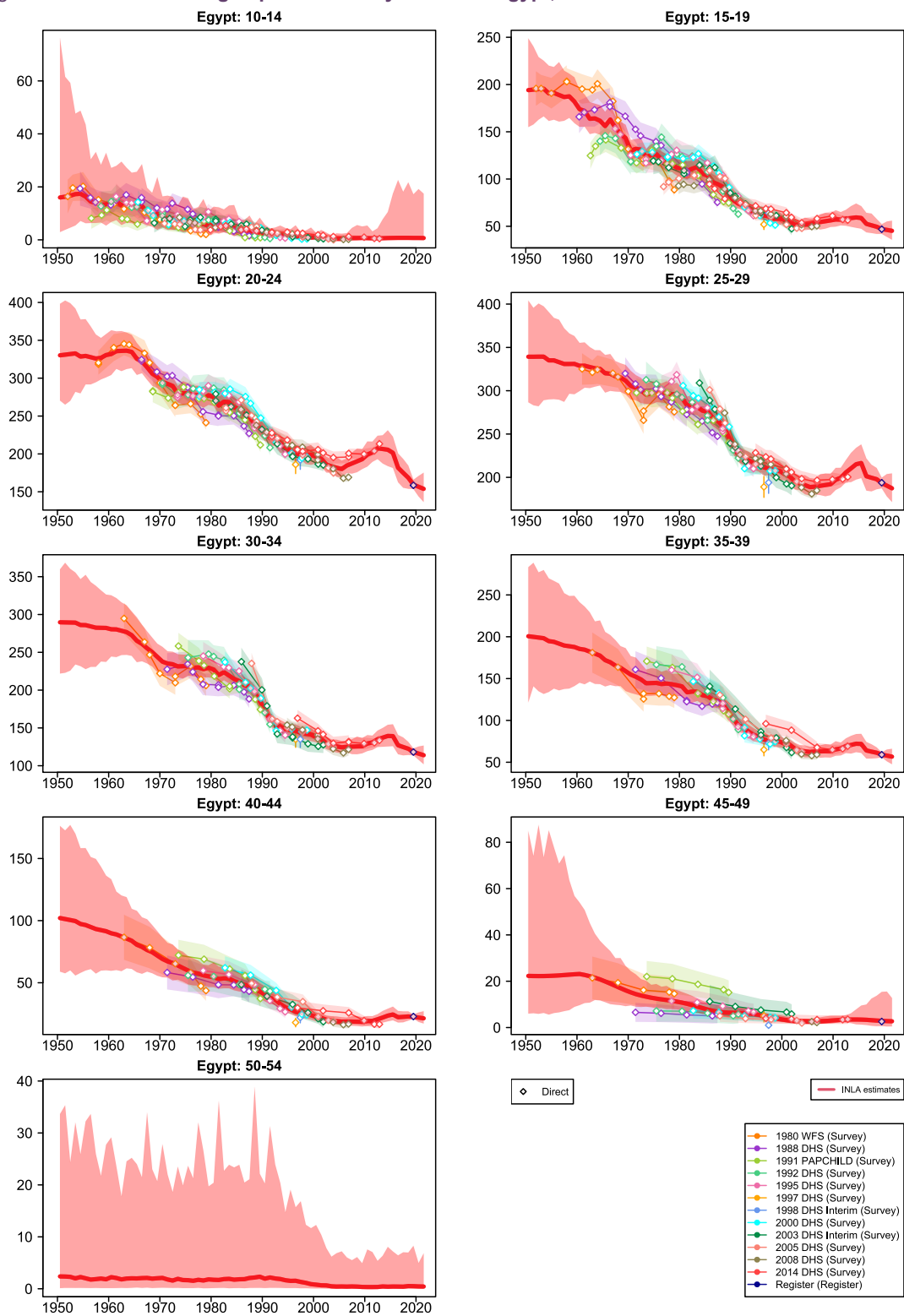
3. Age-specific fertility

Age-specific fertility rates (ASFR) describe the number of births per woman at each age. For the 2024 revision, ASFR were estimated by single year of age from 10 years to 54 years. Three main steps were implemented to derive ASFR estimates for each country.

First, for each five-year age group from 15 to 49 years, the logit-scaled fertility rate was estimated through a Bayesian hierarchical time-series model fit to empirical estimates of the fertility rate from vital statistics and demographic surveys, considering also the level of female educational attainment and the total fertility rate (Chao and others, 2023). As for the total fertility, age-specific fertility from vital registration was used only for country-years with at least 60 per cent completeness of birth registration, and rates were adjusted by the reciprocal of the proportion of registered births (Preston, 1984).

For each country, the median estimate was based on a sample of 10,000 trajectories of the model fitted to the observed data, after considering various types of biases. Most countries had little, if any, empirical data for age groups 10-14 and 50-54, thus the estimation process for these ages additionally assumed a correction with neighbouring age groups (e.g., to estimate fertility rates for ages 10-14, model predictions for ages 15-19 were used as covariates, and to estimate fertility rates for ages 50-54, model predictions for ages 45-49 were used as covariates). Model estimates of fertility rates for each five-year age group for Egypt are shown in figure I.4.

Figure I.4 Estimation of age-specific fertility rates* for Egypt, 1950 to 2023



* "INLA estimates" in legend refer to model-based estimates

Once the full annual time series of fertility rates by five-year age group of mothers was obtained through the modelling process, a second step was implemented to graduate those rates to single year of age via the Calibrated Spline (CS) method (Schmertmann, 2014). It identifies a smooth curve of single-year ASFR based on fit to the five-year fertility rates as well as similarity to known single-year fertility rates. For the 2022 revision, the Population Division assembled a set of empirical single-year fertility rates, representing a diverse range of fertility age patterns, to calibrate the CS model. That set included fertility rates by single year of age from vital statistics disseminated through the Human Fertility Database, EuroStat vital statistics, and the Human Fertility Collection. These sources provided more than 4,000 time series of single-age fertility rates for 71 countries, covering ages 12 to 54 years and time periods from 1891 to 2018. In addition, the calibration data set included 451 full birth history time series compiled from demographic surveys, including the Demographic and Health Surveys, Multiple Indicator Cluster Surveys, World Fertility Surveys, and others (Schoumaker, 2013)¹⁴, as well as 72 series of single-age fertility rates from 30 Health and Demographic Surveillance System sites¹⁵. These supplementary data came from 108 countries, including many in sub-Saharan Africa and Central and Southern Asia, which otherwise would not be represented in the calibration given that they lack reliable vital registration data. Prior to their use in calibrating the CS model, single-age fertility rates from surveys were smoothed via a principal component analysis and cubic spline interpolation (Pantazis and Clark, 2018; Schoumaker, 2020). For each country, graduation models were fit to the range of 5-year age groups used for the input empirical fertility rates for each country (15 to 49 years, 10 to 49 years, or 10 to 54 years, based on data availability and reliability), with four additional constraints that fitted rates should equal zero at the highest and lowest ages, be non-negative at all other ages, should increase monotonically at ages below 20 (i.e., non-decreasing at ages below 20), and should decrease monotonically at ages above 40 (i.e., non-increasing at ages above 40). The results provided single-age fertility rates for ages 10 through 54. For the subset of countries with high completeness of birth registration and high-quality empirical time series of single-age fertility rates, empirical age distributions were used in lieu of graduated age patterns. The metadata associated with the 2024 revision, available online, provides further details about the graduation model used for each country.¹⁶

The third and final step in estimating ASFR entailed adjusting the graduated rates, as needed, for consistency with the total fertility rate in each year. That is, the single-year ASFR in each year were adjusted proportionally such that the sum over age of the single-year ASFR was equal to the total fertility in each period.

4. Sex ratio at birth

The sex ratio at birth (SRB) is defined as the ratio of male to female live births and, in most populations, is fairly stable within the range of 1.03 to 1.07, with some small variations by ethnicity (Chahnazarian, 1988; Dubuc and Coleman, 2007; Garenne, 2002, 2008; Graffelman and Hoekstra, 2000; James, 1984, 1985, 1987; Kaba, 2008; Ruder, 1985; Marcus and others, 1998; Mathews and Hamilton, 2005; Visaria, 1967). In some populations, however, the observed SRB is well above this range because of sex-selective abortion, driven by the concomitant preference for sons over daughters, along with readily available technology for prenatal sex determination and fertility decline. In general, the 2024 revision used the same values for the SRB as in the 2022 revision. The SRB for all countries was estimated from 1950 to 2023 and projected from 2024 to 2100 using a Bayesian hierarchical time-series mixture model (Chao and others, 2019, 2021). The model considers the stochastic variation in the empirical time-series of the SRB as well as the uncertainty associated with SRB estimates.

¹⁴ Rates were computed using the `tfr2` stata module for the period spanning 10 years before each survey.

¹⁵ Rates were computed using public use microdata available from the INDEPTH-iSHARE repository (<https://www.indepth-ishare.org/>) and processed with the `tfr2` module for Stata.

¹⁶ <https://population.un.org/wpp/Download/Metadata/Documentation/>

C. ESTIMATING MORTALITY RATES AND LIFE TABLES

Whereas a common approach was used across all countries to estimate the key indicators of fertility required for the CCMPP, the methods used to estimate mortality and life tables varied across countries depending on the type and quality of available empirical data. These methods can be described according to two main types: “empirical” and “model-based.” The empirical approach was used for countries with reliable information to describe sex- and age-specific mortality rates from vital registration or estimates across a substantial part of the estimation period from 1950 to 2023. A model-based approach was used for countries that lacked sufficient information for the empirical approach. The metadata associated with the *2024 revision*, available online, provides further details about the data and approach used to estimate mortality rates and life tables for each country.¹⁷

1. Estimation for countries with long historical series of high-quality vital rates (“empirical”)

For 120 countries, mortality rates derived from vital registration or estimates were deemed to be of sufficient quality and reliability to estimate the time series of sex- and age-specific mortality rates. The sources of empirical information on sex- and age-specific mortality are presented in table I.1. Deaths by abridged age groups and by sex registered through civil and registration systems and reported either to the annual Demographic Yearbook inquiry from the United Nations Statistics Division, the annual mortality database inquiry from the World Health Organization, or other national or regional data sources were consolidated and analysed by the Population Division to obtain 5,854 country-years (46 per cent) of sex- and age-specific mortality rates. The Human Mortality Database supplied 5,260 country-years of data, comprising 41 per cent of the empirical series incorporated in the *2024 revision*. The remaining 12 per cent of the empirical mortality data were obtained from other collections of estimates or vital registration.

Table I.1 Country-years of empirical data for sex- and age-specific mortality rates, by data source and data process

Data Source	Data Process	Country-years	Per cent
UN Population Division computed abridged life tables from registered deaths by age and sex	Vital registration	5,854	46.23
Human Mortality Database	Estimate	5,260	41.54
EuroStat	Vital registration	370	2.92
Human Lifetable Database	Estimate	286	2.26
Other sources of estimates	Estimate	268	2.12
Other sources of vital registration	Vital registration	168	1.27
Sample registration System	Vital registration	162	1.28
LAMBdA 2019	Estimate	130	1.03
World Health Organization life tables	Estimate	92	0.73
UN Demographic Yearbook life tables	Vital registration	32	0.25
Global Burden of Disease 2016 life tables	Vital registration	32	0.25
Census or survey reports	Census or survey	8	0.04

To estimate a full annual time series of mortality rates by sex and single year of age from 1950 to 2023, analysts implemented the following procedures, depending on the specifics of data availability and quality for each country:

¹⁷ <https://population.un.org/wpp/Download/Metadata/Documentation/>

- a) Adjust the under-five mortality rates for consistency with the estimates published by IGME in 2023 (United Nations. Interagency Group for Child Mortality Estimation, 2024).
- b) Adjust mortality rates according to the estimated completeness of adult vital registration in each year.
- c) Smooth over time mortality rates from vital registration by computing a moving average with 3-, 5- or 7-year windows.
- d) If the empirical series is abridged, graduate to single year of age using the `lt_abridged2single()` function of the `DemoTools` R package (Riffe and others, 2022a).
- e) Interpolate across any gaps in the time series using the Limited Lee-Carter method (Li and Lee, 2004), implemented through the `interp_lc_lim()` function of the `DemoTools` package.
- f) Extrapolate back to 1950 or forward to 2023, as needed, using the Lee-Carter method adapted for non-sequential or sparse data.
- g) Evaluate old-age mortality and adjust as necessary to address any implausible levels or trends by age (expected to increase monotonically over age), over time (expected to decline over time in the absence of mortality crises), and between sexes (male mortality expected to exceed female mortality at older ages).
- h) Smooth the time series over age-period or age-period-cohort or, alternatively, by using a moving average with 3-, 5- or 7-year windows, or the TOPALS model (De Beer, 2012).
- i) Extend to open-ended age group 130+ using the `DemoTools` life table function, which in turn utilized the `MortalityLaws` R package.
- j) Add any crisis mortality impacts (see section I.C.3).

Even in countries with high-quality mortality data, estimates obtained from vital registration often fail to represent the death rates at older ages. Age misstatement, in particular, is a common problem affecting the accuracy of the ages reported in censuses and vital registers, with a tendency to result in estimated mortality rates that are biased downwards at older ages (Preston and others, 1999). Whether to adjust old-age mortality and what method to use were determined subjectively for each country-year by the analyst according to their assessment of the country's situation, context, data availability, and quality. The array of methods used in the *2024 revision* includes the following:

- a) applying an age extrapolation law (e.g., Gompertz, Makeham, Coale-Guo or Kannisto from the `MortalityLaws` R package, or sex-coherent `coKannisto` from the `MortCast` R package) to replace estimated mortality rates above an age specified by the analyst, fitting a curve to the mortality rates estimated over a range of analyst-specified ages;
- b) for countries for which historical old-age mortality rates are biased, but more recent ones are not, replacing old-age mortality rates in that historical period with rates estimated in relation to the recent unbiased life tables;
- c) replacing old-age mortality rates with rates estimated in relation to the life tables documented in the Human Mortality Database, and indexed by level of under-five and adult mortality in the Logistic-Quadratic (LogQuad) relational life table model (Wilmoth and others, 2012).

For the *2024 revision*, analysts for the first time were given an extra option to specify the level of mortality between ages 60 and 75 ($_{15}q_{60}$) as an additional parameter to apply in relating the country's life table to the set of life tables described in the HMD. To estimate a complete annual time series of sex-specific $_{15}q_{60}$, for each country, the Population Division fit a Bayesian hierarchical model. The model

implementation was identical to that for ages 15 to 60 described in section 2.b, below, with respect to the key data sources and types of empirical estimates (including intercensal survival estimates using the census method (Li and Gerland, 2013)), inclusion criteria for mortality data from vital registration, model parameters, sampling of trajectories, treatment of crisis-affected data points, and representation of uncertainty surrounding the median estimate.

2. Estimation for countries with sparse or deficient mortality data (“model-based”)

For 117 countries, empirical mortality rates by sex and age were too sparse or of insufficient quality to estimate the complete annual time series of mortality rates. Instead, model life tables were used to estimate the mortality rates by single year of age across the full age range from 0 to 130+ and for years 1950 through 2023. These models require one or more mortality indicators as inputs to match a mortality level and age pattern. Each model life table requires at least one parameter that describes the mortality rate among children (e.g., under-five mortality rate) or overall (e.g., life expectancy at birth). An additional parameter that describes mortality among adults is useful to further inform the choice of a model that best describes the true mortality age pattern in a given country and year, especially when the levels and trends for children and adults change differently over time. In order to supply the parameters needed to identify appropriate model life table age patterns of mortality, complete annual time series of child and adult mortality from 1950 to 2023 were estimated for each country.

a. Mortality at ages under 5

Similar to estimates of fertility, estimates of child mortality, measured by the probability of dying between birth and age five, can be derived from direct or indirect questions in surveys or censuses when reliable data from civil registration are not available. For child mortality, the available information is largely up to date. Among the 236 countries or areas with 1,000 inhabitants or more in 2023, the most recent available child mortality data referred to 2019 or later for 184 countries, 2014 to 2018 for 35 countries and 2009 to 2013 for another 7 countries. Six locations lacked child mortality data after 2008 (Gibraltar, Guernsey, Isle of Man, Jersey, Northern Mariana Islands, Wallis and Futuna Islands), and four locations had no infant or child mortality data at all over the period 1950 to 2023 (Bonaire, Sint Eustatius and Saba; Saint Helena, Tokelau, Western Sahara).

However, despite the availability of recent data in the vast majority of countries, the quantity and consistency of the data available to cover the entire estimation period from 1950 to 2023 varied greatly across countries. In preparing estimates of child mortality for the *2024 revision*, the Population Division coordinated closely with the United Nations Inter-agency Group for Child Mortality Estimation¹⁸ (IGME), which is led by UNICEF.

b. Mortality between ages 15 and 60

Compared to information on fertility and child mortality, information on adult mortality was sparser, more likely to be outdated, or, for a few countries, lacking altogether. Estimates of adult mortality were derived from complete data on registered deaths by age and sex whenever possible. In other cases, analysts evaluated data from incomplete registration and from questions on household deaths by age and sex, usually for a 12-month period before a census or survey. Indirect estimates of adult mortality were also considered

¹⁸ The IGME database, including the complete set of available empirical data used to construct the latest global estimates of under-five mortality, is available at www.childmortality.org.

for countries with inadequate death registration. These estimates were derived from assessments of probabilities of survival between two censuses, or from demographic surveys that collected information on the survival of respondents' siblings, parents or spouse. Among the 236 countries or areas with 1,000 inhabitants or more in 2023, the most recent available adult mortality data referred to 2019 or later for 154 countries, 2014 to 2018 for 60 countries, 2009 to 2013 for 15 countries, and six locations had adult mortality data only up to the 2000 to 2008 period (Cook Islands, Marshall Islands, Tonga, Wallis and Futuna, Yemen). No empirical data on adult mortality were available for two locations (Bonaire, Sint Eustatius and Saba; Western Sahara).

A Bayesian hierarchical model was used to estimate the probability of dying between the ages of 15 and 60 years for each sex. Observed adult mortality was modelled on a logit scale to ensure that its value was bounded between 0 and 1. In addition to the empirical observations of adult mortality, the model considered the prevalence of HIV infection, coverage of antiretroviral therapy, and the under-five mortality rate. For the under-five mortality rate, the model considered a non-linear regional effect on the associations between child and adult mortality. This approach facilitated the estimation of adult mortality for countries with limited or no empirical observations by assuming that the associations between child and adult mortality were similar to those observed in neighbouring countries. For countries with vital registration statistics, only years with at least 60 per cent completeness of death registration were included in the analysis, and the rates were adjusted by the reciprocal of the proportion of registered deaths (Preston, 1984). For each country, the median estimate was based on a sample of 10,000 trajectories of the model fitted to the observed data after taking into account the various types of biases. By default, data points for years in which significant mortality crises occurred (crude death rates due to mortality crises of five or more deaths per 1000 persons) were excluded, and the model was fitted to the remaining data. Crisis mortality was added back by age and sex when computing the life tables (see section I.C.3). Similar to the models previously described for total fertility, age-specific fertility, and sex ratio at birth, the adult mortality models model the measurement error to reflect the uncertainty resulting from the survey sampling design for data from surveys and censuses and stochastic uncertainty from administrative records for vital registration data, as well as non-sampling errors that may arise due to non-response, recall bias, or data input errors.

c. Model mortality patterns

Analysts selected from several types of model life table patterns in order to estimate the sex- and age-specific mortality rates. For 61 of the 117 countries for which model-based patterns were used, analysts drew from the Coale-Demeny or United Nations families of model life tables (Coale and others, 1983; Coale and Guo, 1989; United Nations, 1982), which the Population Division extended to advanced life expectancies (United Nations, 2011) and graduated to single year of age (see annex). The number and type of mortality indicators used to match the model life table patterns depended on the quality of the empirical mortality indicators available for each country. For nine of these countries, the model life tables were matched to the under-five mortality rate alone. For 17 countries, the models were matched to two parameters: under-five mortality and the probability of dying between the ages of 15 and 60. For another 20 countries, the models were matched to three parameters: infant mortality, under-five mortality, and the probability of dying between the ages of 15 and 60. For the remaining 15 countries – mostly those with very small populations – the time series of child and adult mortality were not reliable or stable enough to inform mortality age patterns, so the models were instead matched to estimates of the life expectancies at birth, by sex.

For 33 countries, the mortality age patterns were modelled using the Logistic-Quadratic (LogQuad) relational life table approach (Wilmoth and others, 2012), with both under-five and adult mortality parameters as inputs. This method was implemented using procedures available in the DemoTools R package. First, an abridged life table was estimated using the `lt_model_lq()` function, after which the life table was graduated to a single year of age using the `lt_abridged2single()` function.

d. Special considerations for countries highly affected by HIV and AIDS

The general approach described above for deriving estimates and projections of mortality is not appropriate for countries whose recent mortality patterns have been significantly affected by the HIV and AIDS epidemics. The particular dynamics of HIV and AIDS and the severity of their outcomes require explicit modelling of the epidemic. Unlike other infectious diseases, HIV has a very long incubation period, during which an infected person is mostly symptom-free but still infectious. In addition, unlike many other infectious diseases, individuals do not develop immunity; however, in the absence of treatment, they almost always die as a consequence of their compromised immune system. Another reason for the explicit modelling of HIV and AIDS is the avalanche-like process of infection spreading through a population and the particular age pattern of infection exhibited. Additional deaths due to HIV and AIDS occur predominately among adults of reproductive age and, consequently, distort the usual U-shaped age profile of mortality. This atypical age pattern cannot be found in the model life tables available to demographers (Heuveline, 2003).

The 2024 revision made explicit modelling assumptions to incorporate the demographic impact of the HIV and AIDS epidemics on the mortality age patterns for 23 countries that had experienced generalized HIV epidemics¹⁹ (table I.2). This approach used a singular value decomposition (SVD-Comp) model (Clark, 2019) calibrated to a reference set of life tables that represented the relationship between summary indicators of child and adult mortality, adult HIV prevalence, ART coverage, and the mortality pattern across the full age range (Houle and others, 2022). Specifically, the reference data set combined the set of empirical life tables from countries with high-quality historical mortality data (such as the HMD) with a collection of simulated life tables computed using the model developed by the UNAIDS Reference Group on Estimates, Modelling and Projections (Stanecki and others, 2012; Stover and others, 2012; Stover and others, 2014). The simulated life tables represented a range of values for sex-specific adult HIV prevalence and antiretroviral therapy coverage.

Table I.2 HIV prevalence rates and ART coverage among adults aged 15-49 years in 2022 for countries for which explicit modelling of HIV and AIDS was employed in the 2024 revision (percentages)

Country	Adult HIV prevalence (percentage)		Adult ART coverage (percentage)	
	Male	Female	Male	Female
Angola	0.9	2.0	39.7	53.5
Belize	1.3	1.2	40.2	48.7
Botswana	11.8	21.1	87.9	97.9
Cameroon	1.7	3.6	86.6	94.0
Central African Republic	2.5	4.3	43.8	53.8
Congo	2.4	5.8	24.4	24.6
Côte d'Ivoire	1.1	2.6	61.2	79.2
Equatorial Guinea	4.9	8.9	26.3	53.3
Eswatini	17.0	35.2	91.7	96.6

¹⁹ For other countries like South Africa and Thailand that have also experienced the impact of the HIV/AIDS pandemic on their mortality age patterns, empirical life tables have been used when vital statistics from death registration were available.

Country	Adult HIV prevalence (percentage)		Adult ART coverage (percentage)	
	Male	Female	Male	Female
Gabon	1.4	4.5	68.3	57.3
Guinea-Bissau	1.7	3.2	48.3	74.0
Jamaica	1.2	1.3	45.2	54.5
Kenya	2.4	4.9	89.5	97.4
Lesotho	14.2	24.3	80.8	89.3
Liberia	0.7	1.3	66.3	81.2
Malawi	5.2	8.9	86.1	98.6
Mozambique	8.3	14.8	78.3	83.0
Namibia	7.7	14.2	86.6	95.0
Rwanda	1.6	2.9	91.3	93.5
Uganda	3.6	6.5	80.4	88.0
United Rep. of Tanzania	2.8	5.6	91.7	97.6
Zambia	7.7	13.8	90.1	91.6
Zimbabwe	8.2	13.7	93.0	97.4

Source: UNAIDS (2023) (unpublished tabulations made available in July 2023).

See also: https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F01_LOCATIONS.XLSX

3. Accounting for excess mortality due to crises

Beginning with the previous revision in 2022, the *World Population Prospects* include systematic accounting of the mortality impacts of crises that have occurred since 1950. For the 2024 revision, the number of distinct crises represented in the crisis mortality dataset increased, and the implied crisis mortality impacts and age patterns were refined as needed. Altogether the mortality effects of about 7,300 crisis-years were identified and accounted for in producing the annual time series of estimated mortality rates over the period 1950 to 2023. Types of crises include conflicts and battles, mass killings, flooding, cyclones, tsunamis, earthquakes, epidemics²⁰ (e.g. Cholera, Ebola, Measles, Meningococcal disease, Dengue, Meningitis, Yellow fever, etc.), COVID-19 pandemic, heatwaves, famines, and droughts.

Empirical mortality rates by age and sex from vital registration were used to estimate mortality during crisis-affected periods if two conditions were met: (1) 100 per cent of deaths were registered; and (2) no smoothing over time was applied to the data input to or output from the empirical estimation process described in section I.C.1.

For the remaining countries, estimates of excess mortality by age and sex due to crises or shocks were added to the sex- and age-specific mortality rates estimated through the processes described in sections I.C.1 and I.C.2. The approach relied on two sets of information: (1) annual time series of total estimates of deaths by type of mortality crisis for each country or area and (2) distributions by age and sex of crisis deaths by type of mortality crisis based on some model assumptions.

For the first set of information, the Population Division consolidated global datasets that described the number of deaths due to: (1) conflicts, including wars, mass killings (including genocides), battle deaths, etc. and (2) natural disasters, such as floods, cyclones, tsunamis, earthquakes, epidemics, famines, droughts and heatwaves. Table I.3 provides a summary of the major data sources used. Other sources were also

²⁰ Excluding HIV/AIDS mortality which is already included in vital registration statistics or direct/indirect estimates of adult mortality from censuses and surveys.

considered²¹. From the consolidated data, estimates of the number of deaths from each crisis event by country and year were computed, with associated uncertainty bounds²². Various analytical methods were applied to reconcile overlaps across different data sources, gaps and discontinuities due to changes in definitions or territorial boundaries of countries, non-annual reference periods, and sources that provided a broad range of crisis-related deaths rather than a point estimate, among other challenges.

Table I.3
Global databases on mortality crises

Type of events	Name	Unit of measure	Timeframe	Geographic coverage	Type of estimates	Periodic updates
Natural disasters	EM-DAT / The International Disaster Database ²³	Country-event	1900-2023	Worldwide	Point estimates	Weekly
COVID-19	European Centre for Disease Prevention and Control - Data on 14-day notification rate of new COVID-19 cases and deaths (ECDC) ²⁴	Country-week-event	2020-2021	Worldwide	Point estimates	Weekly
COVID-19	World Mortality Database (WMD) ²⁵	Country-week/month-event	2020-2023	Worldwide	Point estimates	Daily
COVID-19	World Health Organization (WHO) - Excess mortality associated with COVID-19 ²⁶	Country-year-age-sex-event	2020-2021	Worldwide	Low, high and point estimates	Twice yearly
Cholera (epidemics)	World Health Organization (WHO) ²⁷	Country-year-event	1949-2016	Worldwide	Point estimates	Yearly until 2016
Conflicts and genocides	CSP/INSCR. Political Instability Task Force (PITF) - State Failure Problem Set: Internal Wars and Failures of Governance, 1955-2018 ²⁸	Country-year-event	1956-2018	Worldwide	Intervals only. No point estimates.	Yearly until 2019
Conflicts	UCDP Georeferenced Event Dataset (GED) Global version 23.1 ²⁹	Country-year-event	1946-2022	Worldwide	Low, high and point estimates	Yearly in June
Battles	UCDP/PRIO Armed Conflict Dataset (ACD) version 23.1 ³⁰	Country-year-event	1946-2022	Worldwide	Intervals only. No point estimates.	Yearly in June

²¹ The list of supplementary sources includes: Altez and Revet (2005); Arnold (2019); Ball and others (2002); Checchi and Robinson (2013); (2018); Devereux (2000); Doocy and others (2013); Gang and others (2023); Gráda (2007; 2009); Harff (2017); Heuveline (2015); Human Rights Council (2024b); (2024a); Hunter College (2018); IHME (2020); Kane (1988); Kishore and others (2018); Li and Yang (2005); (2019); Mediazona and Meduza (2023); (2023); OHCHR (2022); (2023); Rivera and Rolke (2019); Rummel (1999); Santos-Lozada and Howard (2018); Silva and Ball (2006); United Nations (1973); UNOCHA (2024); Valentino (2004); Warsame and others (2023); Watson and Checchi (2023); World Peace Foundation and Tufts University (2020); Yang (2013); Zwierchowski and Tabeau (2010).

²² It is worth noting that for various types of crises many locations experience more than one of these events in a given year, especially in respect to the impact of natural disasters. Therefore, one crisis-year for a given location corresponds to the sum of all deaths attributed to a specific type of crisis during that calendar year (e.g., 6453 people died in India in 2013 due to five floods).

²³ <https://public.emdat.be/>

²⁴ <https://www.ecdc.europa.eu/en/publications-data/download-historical-data-20-june-2022-weekly-number-new-reported-covid-19-cases>

²⁵ https://raw.githubusercontent.com/akarlinsky/world_mortality/main/world_mortality.csv

²⁶ <https://www.who.int/data/sets/global-excess-deaths-associated-with-covid-19-modelled-estimates>

²⁷ <https://apps.who.int/gho/data/node.main.176?lang=en>

²⁸ <http://www.systemicpeace.org/inscrdata.html>

²⁹ https://ucdp.uu.se/downloads/index.html#ged_global (Davies and others, 2023; Sundberg and Melander, 2013)

³⁰ <https://ucdp.uu.se/downloads/index.html#armedconflict> (Davies and others, 2023; Gleditsch and others, 2002)

Type of events	Name	Unit of measure	Timeframe	Geographic coverage	Type of estimates	Periodic updates
Battles	PRIO Battle Deaths Dataset (BDD), version 3.1. ³¹	Country-year-event	1946-2008	Worldwide	Low, high and point estimates	No planned update
Conflicts and battles	Armed Conflict Location & Event Data Project (ACLED) ³²	Country-day-event	1997-2023	Selected regions	Point estimates	Daily

Annual time series of excess mortality due to crises were compiled for 7,306 location-years from 1950 to 2023 (representing about 44 percent of all 237 countries or areas over 74 years). The distribution of location-years by major types of mortality crises is as follows:

- Conflicts and Battle deaths: 3,630 location-years (174 locations)
- Mass killings (including genocide): 82 location-years (17 locations)
- Floods: 2,444 location-years (163 locations)
- Cyclones: 1,704 location-years (172 locations)
- Epidemics (not including HIV/AIDS and COVID-19): 2,010 location-years (151 locations)
- Earthquakes: 1,150 location-years (124 locations)
- COVID-19: 642 location-years (229 locations)
- Heatwaves: 218 location-years (56 locations)
- Famines/Droughts: 183 location-years (33 locations)
- Tsunami: 45 location-years (25 locations)

Details about data sources and breakdown by locations and years of the estimated number of deaths attributable to each type of events is available from the online metadata³³ for the 2024 revision, and cover about 66 million excess deaths that are grouped into these four broad categories:

- 20.5 million due to conflicts (31%),
- 20.6 million due to famines (31%),
- 6.5 million due to natural disasters (10%),
- 18.5 million due to COVID-19 (28%).

The mortality effects of conflicts and natural disasters tend to be most acute in countries that lack high-quality vital registration. Moreover, crises sometimes disrupt normal death registration processes such that estimates of crisis deaths are not available by age and sex. For the second set of information required to estimate sex- and age-specific crisis mortality rates, a literature review was conducted to inform a set of model age-sex patterns of crisis deaths by type of event. These model patterns were used to distribute the total number of deaths due to each crisis by sex and age.

To develop the model for age-sex patterns of crisis mortality, the Population Division and UNICEF assembled a comprehensive database of age-sex distributions of crisis death rates. The sources included crisis mortality studies, as well as empirical data from population surveys and death registration. The average relative risks of mortality by age and sex were estimated for nine categories of crisis event (battle deaths, conflicts, genocide (including mass killings), cyclones, earthquakes, epidemics, famine/droughts, floods, and tsunamis). Age-sex mortality distributions were compiled for 164 crisis events in 57 countries: 53 conflicts, 4 genocides, 3 cyclones, 32 earthquakes, 27 epidemics, 31 famines, 10 floods and 4 tsunamis

³¹ <http://www.systemicpeace.org/inscrdata.html>

³² <https://acleddata.com/data-export-tool/>

³³ See "Mortality_Crises" datasheet from https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F02_Metadata.XLSX

from 74 data sources covering the period 1348-2019, with 64 per cent since 1950 and 37 per cent since 2000. Statistical models (Seemingly Unrelated Regression with bootstrap resampling) were fitted to these empirical series to derive a standard set of age-sex distributions for nine types of crisis events (Mathers and others, 2023). In the *2024 revision*, the Population Division estimated an additional age/sex pattern for heatwaves³⁴ based on death registration from WHO mortality database³⁵. Additional empirical information informed the age-sex patterns for specific location-years with recent crises: China 2022-2023 COVID-19 excess deaths based on vital registration statistics from Hong Kong SAR; Gaza 2023 conflict (Palestinian Ministry of Health - Gaza, 2023); Russian Federation 2022-2023 battle deaths (Mediazona, 2023; Mediazona and Meduza, 2023); and Ukraine 2022-2023 civilian casualties (OHCHR, 2023).

The analytical strategy used to incorporate the impact of each mortality crisis in the *2024 revision* was aligned with the approaches used by the UN-IGME³⁶ and WHO/GBD³⁷ to account for mortality crises and shocks:

1. For each type of major event, use the total number of deaths (and lower/upper bound for probabilistic methods) attributable to the specific type of crisis.
2. Compute the overall crisis crude death rate for this type of crisis using the total population.
3. Apply the model-based age-sex mortality rates for this type of crisis (in the standard population) to the associated population by age and sex for this year and obtain the total crisis death rate for the above age-specific death rates in the target population.
4. Compute an adjustment factor to match the actual crisis death rate (i.e., ratio of the crisis CDR from step 2 to the crisis CDR from step 3) to factor the difference in population age distributions between the target location and the standard population used to compute the model-based mortality pattern.
5. Rescale the model-based age-sex mortality rates for this type of crisis by applying the adjustment factor from step 4 to obtain the age-sex-specific death rates (and uncertainty) for this type of crisis in the target population.
6. Repeat the process from steps 1 to 5 for each type of mortality crisis occurring during a given period of time.
7. Aggregate the excess mortality rates by age and sex from the various types of mortality crises (using the results from step 6).
8. Add the excess mortality rates (from step 7) to the normal background mortality rates by age-sex.
9. Graduate into single age the mortality pattern by abridged age group (from step 8) using a piecewise cubic Hermite interpolating polynomial function.

4. Accounting for excess mortality due to the COVID-19 pandemic

In May 2023, the World Health Organization published updated estimates of “excess mortality” by country for the period from 1 January 2020 through 31 December 2021³⁸. For many countries, these

³⁴ Deaths taken into account and associated with exposure to natural heat, as the underlying and contributing causes of death, are coded as X30 and T67, excluding code W92 (exposure to excessive heat of manmade origin) according to the International Classification of Diseases, Tenth Revision.

³⁵ <https://www.who.int/data/data-collection-tools/who-mortality-database>

³⁶ <https://childmortality.org/wp-content/uploads/2024/03/UNIGME-2023-Child-Mortality-Report.pdf>

³⁷ https://www.who.int/docs/default-source/gho-documents/global-health-estimates/ghe2019_daly-methods.pdf

³⁸ <https://www.who.int/data/sets/global-excess-deaths-associated-with-covid-19-modelled-estimates>

estimates indicated sizable increases in deaths associated with the COVID-19 pandemic, including those directly attributable to the virus itself as well as those attributable to other causes, but that would not have occurred without the detrimental effects of the pandemic on healthcare systems and patient access to care. In other countries where the spread of COVID-19 was limited due to lockdowns or other measures, some potential causes of death were reduced (e.g., those related to air pollution, traffic injuries or infectious diseases such as influenza), resulting in fewer deaths than would have been expected without the pandemic (Knutson and others, 2022; Karlinsky and Kobak, 2021).

For countries for which vital registration data were not available or adequate to accurately represent mortality risks during the COVID-19 pandemic, the excess mortality (positive or negative) estimated by the WHO for years 2020 and 2021 were added to the baseline mortality rates estimated for 2020 and 2021 in the absence of a pandemic, consistent with the approach taken for other mortality crises. A similar approach was extended for 2022 and 2023 for the subset of countries with weekly or monthly death registration data covered by the *World Mortality Database*, and assuming the country-specific age-sex pattern estimated by the WHO for 2021.

As of March 2024, the information on age- and sex-specific deaths from vital registration (with 90 per cent or higher completeness of death registration) was available for 2020 only for 106 countries covering 35 per cent of the global number of deaths estimated for 2020 in the *2024 revision*, and for the year 2023 only for 5 countries covering 1 per cent of the global number of deaths in 2023 (table I.4).

Table I.4 **Number of countries with data on age- and sex-specific deaths from complete vital registration for the years 2020 to 2023 (as of March 2024).**

	Number of countries	Number of countries with 90 per cent or higher death registration	Proportion of total global deaths covered by complete VR (per cent)
2020	128	106	35
2021	116	100	30
2022	58	51	15
2023	6	5	1

D. ESTIMATING THE 1950 BASE POPULATION AND POPULATION BENCHMARKS

Recent population counts are critical for obtaining accurate estimates of the population size and its composition by age and sex. The principal data source used for this purpose was the population census. Following the *UN Principles and Recommendations on Population and Housing Censuses* (United Nations, 2017b) most countries conduct a census about once per decade. Altogether, 2,025 censuses have been conducted worldwide between 1950 and 2023, providing a wealth of data for the analysis and monitoring of population change at the national level, and the Population Division was able to use for the *2024 revision* data from 1,910 of them, which is 79 more than in the *2022 revision*.

In some countries, population registers based on administrative data systems are sufficiently well developed to serve as a basis for population estimates.

1. Data availability

At the global level, population data from censuses or registers referring to 2019 or later were available for 114 countries or areas, representing 48 per cent of the 237 countries or areas included in this analysis (and 54 per cent of the world population). For 43 countries or areas, the most recent available population

count was from the period 2014-2018, and for another 57 locations from the period 2009-2013. For the remaining 23 countries or areas, the most recent available census data were from before 2009, that is more than 15 years ago. These 23 countries (with date of last census) were Lebanon (1932), Afghanistan (1979), Democratic Republic of the Congo (1984), Eritrea (1984), Somalia (1987), Uzbekistan (1989), Iraq (1997), Ukraine (2001), Haiti (2003), Syrian Arab Republic (2004), Yemen (2004), Cameroon (2005), Nicaragua (2005), United Arab Emirates (2005), Libya (2006), Nigeria (2006), El Salvador (2007), Ethiopia (2007), Algeria (2008), Burundi (2008), Dem. People's Republic of Korea (2008), South Sudan (2008) and Sudan (2008).

2. Protocol for evaluation and adjustment of census populations

Even the highest-quality population censuses may suffer from data quality problems that require some correction or adjustment to accurately represent the population size and age structure. Common data issues associated with censuses include under- or over-enumeration, age misstatement, including, for example, a digit preference for ages ending in zero or five, and the under-enumeration of very young children. To address these common errors in a systematic and standardized manner, the Population Division developed and implemented a new protocol for the evaluation and adjustment of population census counts by age and sex (Johnson and others, 2022). The main steps of this protocol are summarized below.

a. Data series priorities

For any given population census, there are often multiple sources of data available that detail the census population counts by age and sex. These may include census results reported to the Demographic Yearbook of the United Nations, tabulations published by the National Statistical Offices, counts from microdata archived in the IPUMS collection, or other sources. The Population Division developed a series of procedures to standardize the census population information to the data structures required for the CCMPP workflow, and to select the preferred data series from the available choices. In brief, the criteria preferred, in order of priority, counts disaggregated by single year of age over abridged age groups, higher data reliability assessment, *de facto* population over the *de jure*, a higher open-ended age group, official statistics reported in the Demographic Yearbook, and a more recent data source.

b. Coverage adjustments

When a population census does not cover the full territory of the population referenced for a country or area in the *World Population Prospects*, a coverage adjustment is required. This adjustment was implemented via a single adjustment factor (based on information from previous censuses or complementary data sources) that was multiplied by the census population counts by age and sex. Examples include the historical censuses of Pakistan, which were adjusted upwards to account for the population residing in the Pakistani-administered parts of Jammu and Kashmir, the 1980, 1985 and 1991 censuses of South Africa to include the homelands (Transkei, Bophuthatswana, Venda, Ciskei), and the 1975 census of Yemen, which was adjusted to additionally include the population of South Yemen.

c. Under- or over-enumeration adjustments

Post-enumeration surveys, conducted following a population census, provide essential information on the degree and patterns of enumeration errors and facilitate post-adjustment to correct for these errors (United Nations, 2010). Of the 1,910 census populations by age and sex used for the *2024 revision*, 320 had associated post-enumeration survey results available, and 120 of them had some demographic

evaluation covering 130 countries altogether between 1946 and 2022. These data formed the basis of a model to predict enumeration adjustments and patterns by sex and age for the remaining censuses.

First, the overall net enumeration error was modelled as a linear function of the average number of years of education by sex, GDP (Institute for Health Metrics and Evaluation, 2020), the under-five mortality level (both in log scales), and whether the assessment comes from a PES or demographic analysis. These data were fitted using a multilevel linear mixed-effects model that considered the regional and sub-regional geographical hierarchy used by the United Nations. This approach used a mixture of available data (variable number of observations by country and between regions covering different time periods) to predict overall net enumeration errors for countries and time periods without PES, while controlling for various country characteristics.

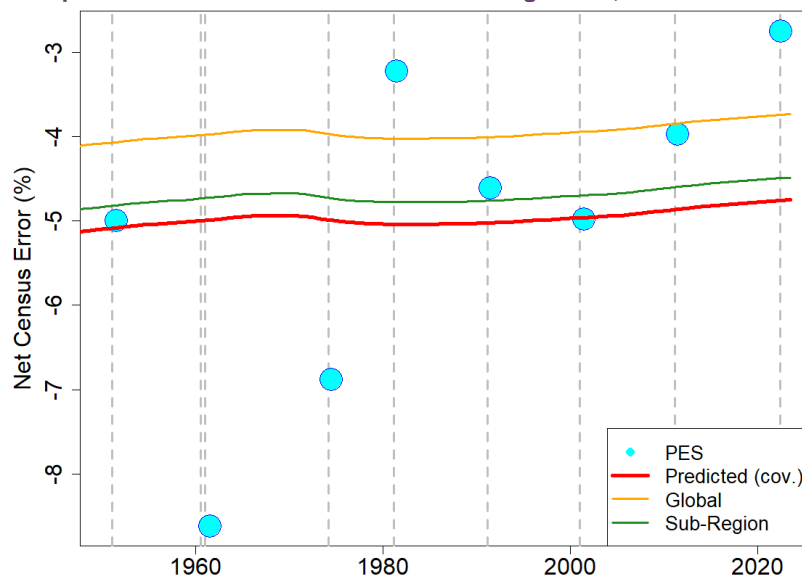
Based on the set of time-dependent covariates, several time series of expected net enumeration errors were predicted for each country³⁹. Figure I.5 shows the results for Bangladesh. The respective years with censuses are plotted with vertical gray dashed lines, and the PES estimates are shown as blue circles. The predicted (or expected) net census error is shown for (1) the country-specific expected values as the bold red line and only as a baseline reference for informative purposes for (2) the UN sub-region as the green line and (3) the overall global model (i.e., world) as the yellow line.

Information on sex-specific net census errors was available for about 110 censuses covering 50 countries. To leverage these data, a second model was estimated by building on the first model of overall net census errors to fit the sex-specific differences and to predict them for all countries from 1950 to 2023. The functional form was similar to that of the first model, but the overall net enumeration error was included as an additional covariate.

For approximately 80 censuses across 34 countries, net census errors disaggregated by both sex and age group were available. A third model was fitted to these data to predict net census errors by sex and age for all countries from 1950 to 2023. This model was sex-specific, with the same covariates as in the first model but with an age interaction, as well as the overall net census error and sex-specific difference. The initial predicted values for the abridged age groups were smoothed using a spline function to obtain the values by single ages.

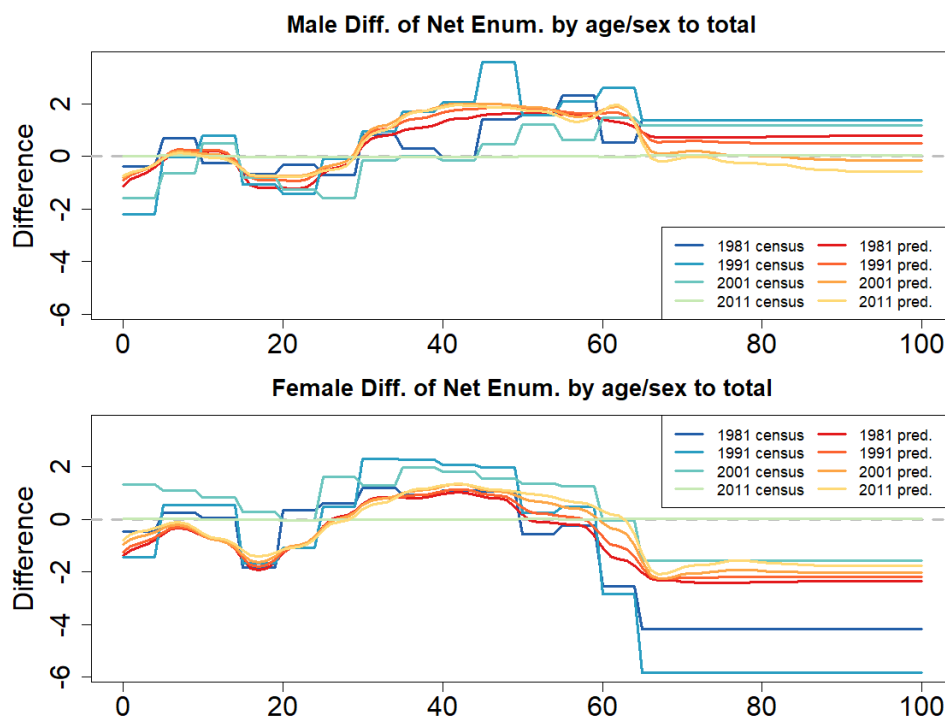
³⁹ See “Population_by_Age” datasheet from https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F02_Metadata.XLSX for details about each census and whether the census figures used for WPP were adjusted for net enumeration errors (“Census_PES_adjusted”), the magnitude and source of the adjustments for “PES_adjustment” (assumed PES adjustment based on PES or statistical model), “PES_Net_Error” (percentage of net enumeration error based on PES if known), and “WPP_Net_Error” * percentage of expected net enumeration error based on WPP modelling).

Figure I.5 Observed and predicted PES net census errors for Bangladesh, 1950 to 2023



In figure I.6, the patterns of deviation between the overall PES net enumeration error and the age and sex net enumeration errors are shown as blue/green lines, and the predicted model values are shown as red/yellow lines for the respective censuses with available PES results. Reported PES results for some censuses referenced broad age groups; thus, the age distributions were first standardized into single age distributions, assuming uniform assumptions within each age group (shown as extended horizontal blue lines in the plots below).

Figure I.6 Difference in net census error by sex and age for Bangladesh, 1981-2011 censuses



d. Age misstatement adjustments

The degree to which age misstatements affect census population counts varies considerably across countries and time periods. Such errors might reflect a preference for a certain digit (e.g., ages ending in zero or five) that produces a “heaping” of population counts in specific parts of the age range. Many censuses also exhibit evidence of age understatement or exaggeration, particularly at older ages. Several methods are available to demographers to assess the degree of age heaping and smoothing accordingly. In its protocol, the Population Division considered the Bachi index (for counts by single year of age) or the age ratio score (for counts by five-year age group), together with the average level of education completed by adults in the population, to determine the degree of smoothing over age to apply via a moving average. Age-heaping assessments and smoothing were performed separately for children and adults, and the resulting series joined post-adjustment.⁴⁰ When the census data series was grouped by five-year age group, the adjusted, smoothed series was ultimately graduated to single year of age using a monotonic spline. Where necessary, counts were redistributed to the open-ended age group 105+ using the OPAG function of the DemoTools R package, which applied the life table estimated for the country and census year as a stable standard.

e. Missing children adjustments

It is quite common for young children to be systematically under-enumerated in censuses to a substantially greater extent than in other age groups (Ewbank, 1981; O'Hare, 2017; Pelletier, 2020; Robinson, 2017; Tomkinson, 2023; Toulemon, 2017). To detect such under-enumeration and adjust accordingly, the protocol considered the estimated fertility and mortality rates together with the enumerated and adjusted counts of women of reproductive age to predict the number of children that the census would be expected to capture.⁴¹ This step was implemented using the `basepop_five()` function of the DemoTools R package, with the returned counts of children by age graduated to single years via a monotonic spline.

3. Estimating the 1950 base year population

The approach taken to estimate the 1950 base year population for each country depended on the type and quality of census data available in or around that period of history. For countries with a high-quality census between 1945 and 1950, those counts were projected forward to 1 January 1950. For some of those without a pre-1950 census but with a high-quality census between 1950 and 1965, the earliest available high-quality census was back-projected to 1 January 1950. For many countries with a high-quality benchmark population estimate for the base year 1950 (e.g., HMD), that estimate was adopted for the base year.

E. ESTIMATING NET INTERNATIONAL MIGRATION

When a person moves from one country to another, that person is an emigrant from the country of origin and an immigrant to the country of destination. International migration is ideally studied as the flow of people moving between countries. However, in practice, data on international migration flows exist for

⁴⁰ See “Population_by_Age” datasheet from https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F02_Metadata.XLSX for details about each census and whether the census figures used for WPP were adjusted for age heaping and digits preference (“Census_age_heaping_adjusted”), the degree of age heaping measured by Bachi index or the age ratio score (for under age 15 and 15 and over) and average number of years of education for adults, the type of input data available (complete or abridged age distribution) and open age group, and type of smoother or graduation used.

⁴¹ See “Population_by_Age” datasheet from https://population.un.org/wpp/Download/Files/4_Metadata/WPP2024_F02_Metadata.XLSX for details about each census and whether the census figures used for WPP were adjusted for under enumeration of children under age 15 using demographic analysis methods and recent fertility and mortality time trends.

only a small number of countries. Therefore, international migration in the *2024 revision*, as well as in previous ones, was incorporated as net migration only. Net migration—the difference between the number of immigrants arriving in and the number of emigrants leaving from a particular country during a certain period of time—shows the net effect of international migration on the size and composition of the population in both the country of origin and destination. In other words, the net international migration indicator in the *World Population Prospects* is not based on, nor does it allow for, a disaggregation of arriving immigrants and departing emigrants. In countries where the number of immigrants equals the number of emigrants, net migration will amount to zero even if immigration and emigration levels for that country are significant.

In preparing trends in international migration, attention was given to official estimates of net international migration or its components (immigration and emigration), to information on labour migration or on international migration flows recorded by receiving countries, to data about refugee (and asylum-seeker) stocks and flows prepared by the Office of the United Nations High Commissioner for Refugees (UNHCR)⁴², and to estimates of stocks of foreign-born persons prepared by the Population Division of UN DESA⁴³. Given the absence of empirical data on inflows and outflows of international migrants, it was difficult to produce comprehensive and consistent estimates of net migration over time. Therefore, in many cases, net international migration was estimated as the residual not accounted for by the natural increase between successive census enumerations, after the protocol adjustments for net coverage errors and data quality issues. This approach computes the difference between the growth in population as recorded in successive censuses (total increase) and the growth implied by the estimated levels of fertility and mortality (natural increase).

Strategies to define the sex and age patterns of net international migration vary according to the country context and time period. Given the limited empirical data available, model age patterns of migration were applied to estimate net international migration for many country-years (Rogers and Castro, 1981). The simplified models used in the *World Population Prospects*, implemented using the `mig_un_fam()` function of the DemoTools R package, include: a “family” model characterized by fairly even proportions of male and female migrants, a concentration of migrants in the working ages, but sizable numbers at childhood and older ages as well; a “male labour” model dominated by migration of males of working age; and a “female labour” model dominated by migration of females of working age. Alternatively, for many other country-years, a “population distribution” pattern was applied, in which the sex-age distribution of net migration was assumed to be identical to the sex-age distribution of the population. For countries and periods over which the residual migration methods returned reliable results by age and sex, those residual sex-age distributions were applied to estimated totals of net migration to derive estimates of net international migration by age and sex.

For a subset of countries with high-quality empirical data on population, a deterministic approach was implemented to estimate net international migration by age and sex such that the 1 January populations constructed through the CCMPP match the benchmark populations described in section I.D above. This approach was carried out in two steps. First, using the `interp_coh()` function of the DemoTools R package, the benchmark populations for a given country were interpolated to generate a time series of annual population counts by age and sex corresponding to 1 January of the period between benchmarks. Then,

⁴² For refugee statistics from the Office of the United Nations High Commissioner for Refugees (UNHCR), see <https://www.unhcr.org/refugee-statistics/> - Note that UNHCR figures were available only up to mid-2023 when the *2024 revision* was prepared.

⁴³ For estimates of international migration flows and stocks of foreign-born from the United Nations, see <https://www.un.org/development/desa/pd/content/international-migrant-stock> - Note that migrant stock estimates were available only up to 2020 when the *2024 revision* was prepared.

given the estimated fertility and mortality rates for each year, the net residual migration by sex and age was computed such that the CCMPP exactly reproduced the interpolated population series.

Finally, net migration balancing was carried out to ensure that at the global level, the sum of all net international migration flows equaled zero for each year of the estimation period. Balance was achieved by applying small adjustments to net international migration estimates for countries where such estimates were highly uncertain.

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II. THE PREPARATION OF POPULATION PROJECTIONS

In the *2024 revision*, the future population of each country was projected beginning from 1 January 2024. To project the population forward until 2101, various assumptions were made regarding future trends in fertility, mortality and international migration. Probabilistic methods were used to project future fertility and mortality levels and international migration, specifically to derive the trajectories of the total fertility rate, life expectancy at birth for each sex, and total net migration rates and counts. In addition, several different projection scenarios were produced to convey the sensitivity of the projections to changes in the underlying assumptions. The following sections summarize the assumptions used for each scenario and associated projection methods.

A. PROJECTING THE MEDIUM FERTILITY SCENARIO

As part of its work on probabilistic projections, the Population Division has also published 80 and 95 per cent prediction intervals of future fertility levels, along with the mean trajectory. The mean trajectory constitutes the medium-fertility assumption.

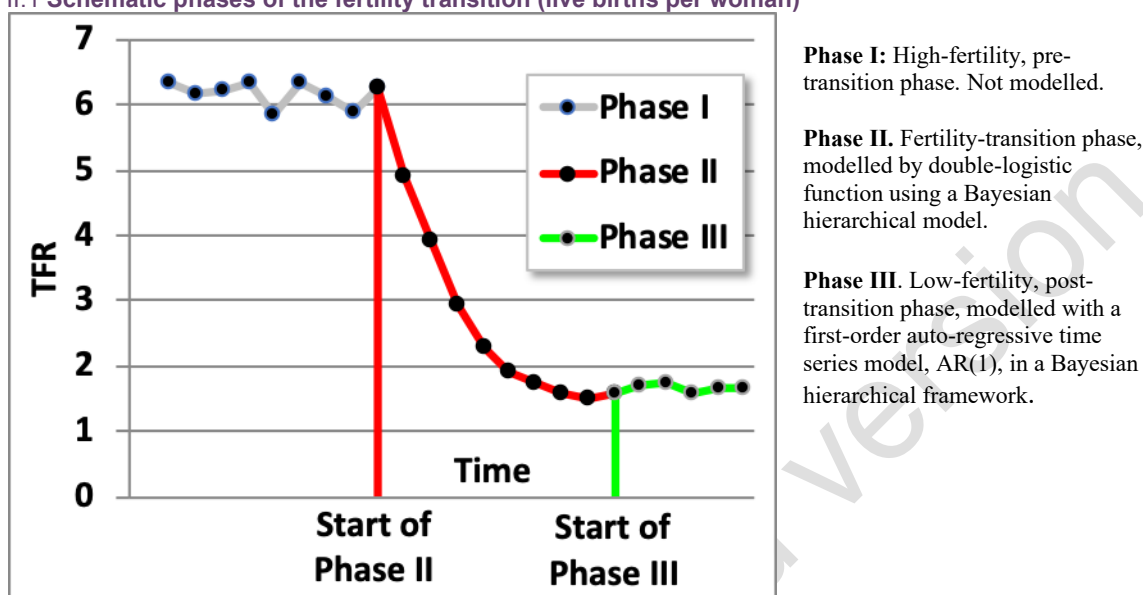
The *2024 revision* of the *World Population Prospects* also includes several scenarios with different fertility assumptions: (1) medium-fertility assumption; (2) high-fertility assumption; (3) low-fertility assumption; (4) constant-fertility assumption; (5) instant-replacement assumption; (6) an instant-replacement zero migration scenario, which additionally assumes zero net international migration; (7) a momentum scenario which has a different treatment of the mortality assumptions as compared to the instant-replacement zero migration scenario; (8) no fertility below age 18 years; (9) accelerated decline of adolescent birth rate (ABR); (10) accelerated decline of ABR with recovery. In preparing the different scenarios, making the medium-fertility assumption is the most significant first step.

The *2024 revision* used probabilistic methods for projecting total fertility that were first employed in the *2010 revision* (Alkema and others, 2011; Raftery and others, 2009) and updated in subsequent revisions (Raftery and others, 2014a; United Nations, 2014b, 2015, 2017c, 2019b), especially since the *2022 revision* to take into account the uncertainty in past empirical estimates and to use annual time series (Liu and Raftery, 2020; United Nations, 2022; Liu and others, 2023). The method utilizes the fertility levels and trends estimated for the *2024 revision* for all countries of the world for the period 1950 to 2023.

Projections of future country-specific fertility levels are based in the demographic transition theory. Overall, there is a consensus that the historical evolution of fertility includes three broad phases: (i) a high-fertility, pre-transition phase (phase I), (ii) a fertility transition phase (phase II), and, (iii) a low-fertility, post-transition phase (phase III). Figure II.1 illustrates the three phases of the fertility transition. For each country, the start of phase II was determined by examining the maximum total fertility during the estimation period from 1950 to 2023. Countries where this maximum was less than 5.5 births per woman were deemed to have entered phase II prior to 1950. All other countries were deemed to have entered phase II in the period of their local maximum. To find the end of phase II, and thus the beginning of phase III, first the TFR is averaged over 5-year time periods. Then for each country the time period is identified where the first two successive increases were observed, after the level of the averaged TFR had fallen below 2 births per woman. If no such increase was observed, a country was deemed to still be in phase II in 2023. If such increase was observed in the last time period, phase III was assumed to start in 2023. Otherwise, it is assumed that the country's phase III has started at the midpoint of such time period. Based on the most recent population and demographic data available, it was determined that all countries had begun or already

completed their fertility transition, being in either phase II or phase III. Thus, fertility transition in these two phases were modelled separately, while phase I was not modelled in the 2024 revision.

Figure II.1 Schematic phases of the fertility transition (live births per woman)



Source: (Alkema and others, 2011).

Although the process of fertility decline differs across countries, a common general pattern has been observed. Overall, the rate of fertility decline is usually the fastest immediately after the onset of the decline. The pace typically slows as fertility falls to “intermediate” levels and slows further as it approaches the replacement level. Variations in this general pattern have been observed, associated with the pace of fertility decline both at the beginning and end of the fertility transition. Empirical evidence of this pattern opened the door to first predict the pace of fertility decline at different fertility levels as an intermediate step towards projecting future levels of fertility, rather than directly projecting future levels of fertility alone (United Nations, 2006).

The probabilistic framework for projecting total fertility, first applied in the 2010 revision, consists of two separate processes:

The first process models the sequence of change from high to low fertility (phase II of the fertility transition). For countries undergoing a fertility transition, the pace of fertility decline is divided into a systematic decline and various random distortion terms. The pace of the systematic decline in total fertility is modelled as a function of its level, based on a double-logistic decline function. The parameters of the double-logistic function were estimated using a Bayesian hierarchical model, which resulted in country-specific distributions for the parameters of decline. These distributions are informed by historical trends within the country, as well as the variability in historical fertility trends of all countries that have already experienced a fertility decline. This approach not only takes into account the historical experience of each country (including the uncertainty in past estimates), but also reflects uncertainty about future fertility decline based on the past experience of other countries at similar levels of fertility. Under the model, the pace of decline and the limit to which fertility could decline in the future varied for each projected trajectory. The model is hierarchical because, in addition to the information available at the country level, a second level, which is the global experience of all countries, is used to inform the statistical distributions of the parameters of the double-logistic function. This is particularly important for countries at the beginning of

their fertility transition because limited information exists on the pace of their fertility decline. For these countries, fertility projections are informed mainly by the world's experience and the variability in trends experienced in other countries with similar levels of fertility in the past.

Once projected fertility reaches phase III (figure II.1), the second component of the projection procedure implements a time-series model to further project fertility, assuming that the fertility level would approach and, in the long run, fluctuate around an ultimate country-specific level. This level is determined for each country using a Bayesian hierarchical model (Raftery and others, 2014a) informed by empirical evidence from low-fertility countries that have experienced fertility increases from a sub-replacement level. In the 2024 revision, 39 countries or areas⁴⁴ had entered phase III by 2023. Thus, future long-run fertility levels in the 2024 revision are country-specific, accounting for the country's own historical experience, and also informed by statistical distributions that incorporate the empirical experience of all low-fertility countries that have already experienced a recovery from sub-replacement fertility levels. The world mean parameter for country-specific asymptotes was restricted to a fertility level no greater than 2.1 births per woman.⁴⁵ The model was fitted to all locations with more than 90,000 inhabitants in 2023, and smaller locations with fewer than 90,000 inhabitants were treated as supplementary locations (i.e., their experience did not inform the world distribution of other locations).

A long-term assumption of a fertility increase in low-fertility countries (phase III) is supported by the experience of many countries in Europe and East Asia (Goldstein and others, 2009; Sobotka, 2011; Bongaarts and Sobotka, 2012; Myrskylä and others, 2013; Sobotka and Beaujouan, 2014; Beaujouan, 2020; Bergsvik and others, 2021; Sobotka and Beaujouan, 2022). However, such an increase is not universal (Billari, 2018; Reher, 2019; Sobotka and others, 2019; Gaddy, 2021). For countries that have experienced extended periods of low fertility with no empirical indication of an increase in fertility, fertility was projected to continue at low levels in the near future. This assumption is supported by research on the "low fertility trap hypothesis", observed among some low-fertility countries in Europe (Billari and Kohler, 2004; Lutz, 2007; Lutz and others, 2006; Goldstein and others, 2009) and East Asia (Jones and others, 2008; Frejka and others, 2010; Basten, 2013).

To construct projections for all countries still in phase II, the Bayesian hierarchical model was used to generate 250,000⁴⁶ double-logistic curves for all countries that have experienced a fertility decline (figure II.2), representing the uncertainty in the double-logistic decline function of those countries⁴⁷. This sample of double-logistic curves was then used to calculate 2,000 total fertility projections for all countries that had not reached phase III by 2023. For each trajectory at any given time, the double-logistic function provides the expected decrement in total fertility in relation to its current level. A distortion term was added to the expected decrement to reflect the uncertainty inherent in the estimated model of fertility decline.

In historical revisions of the *World Population Prospects*, projections up to and including the 2010 revision assumed a long-run fertility level of 1.85 children per woman. In subsequent revisions, including

⁴⁴ The 2024 revision of the WPP was informed by the experience of 39 countries or territories (with 90,000 inhabitants or more in 2023) that had entered phase III: Australia, Austria, Barbados, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, China (including Hong Kong SAR, Macao SAR), Cuba, Czechia, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Japan, Jersey, Latvia, Lithuania, Luxembourg, Montenegro, Netherlands, Norway, Portugal, Republic of Moldova, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United States of America.

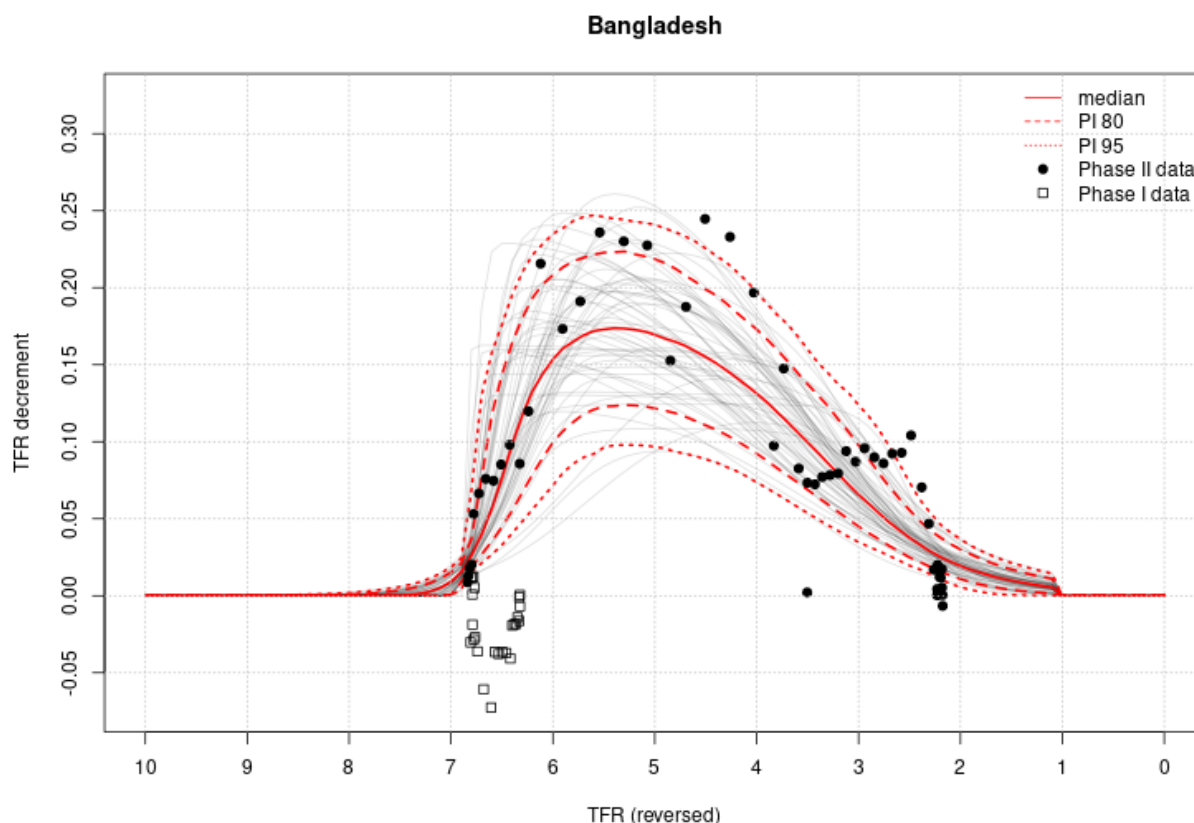
⁴⁵ While the asymptote does not have an explicit lower bound, it does implicitly because any given total fertility trajectory is restricted not to be smaller than 0.5 child.

⁴⁶ Ten Markov chain Monte Carlo (MCMC) simulations are run in parallel to find the various combinations of parameters with 25,000 iterations performed for each simulation, and the first 2,000 iterations for each simulation are discarded as burn-in trials so that the effect of initial values on the final results is minimized.

⁴⁷ Graphs of this double-logistic curve are available online at: <https://population.un.org/wpp/Graphs/Probabilistic/FERT/CHG/50>.

the 2024 revision, the projected level of total fertility has been allowed to fall below that threshold, reflecting uncertainty regarding the historic minimum level of fertility at the end of phase II before the start of a recovery as part of phase III. The pace of fertility change, level of fertility, timing of the end of phase II, and start of phase III vary for each of the 2,000 projected fertility trajectories for a country that had not reached phase III by 2023. Future trajectories consist of a combination of cases with total fertility in phase II or III, until eventually all trajectories are in phase III. For countries that were already in phase III by 2023, the time-series model for that phase was used directly. The unweighted mean value for the world distribution based on the 39 countries or areas that have entered phase III is 1.62 children per woman in 2100 while the 95 per cent prediction interval ranges between 1.33 and 1.85.

Figure II.2 Total fertility annual decrements by level of fertility and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part) (live births per woman)



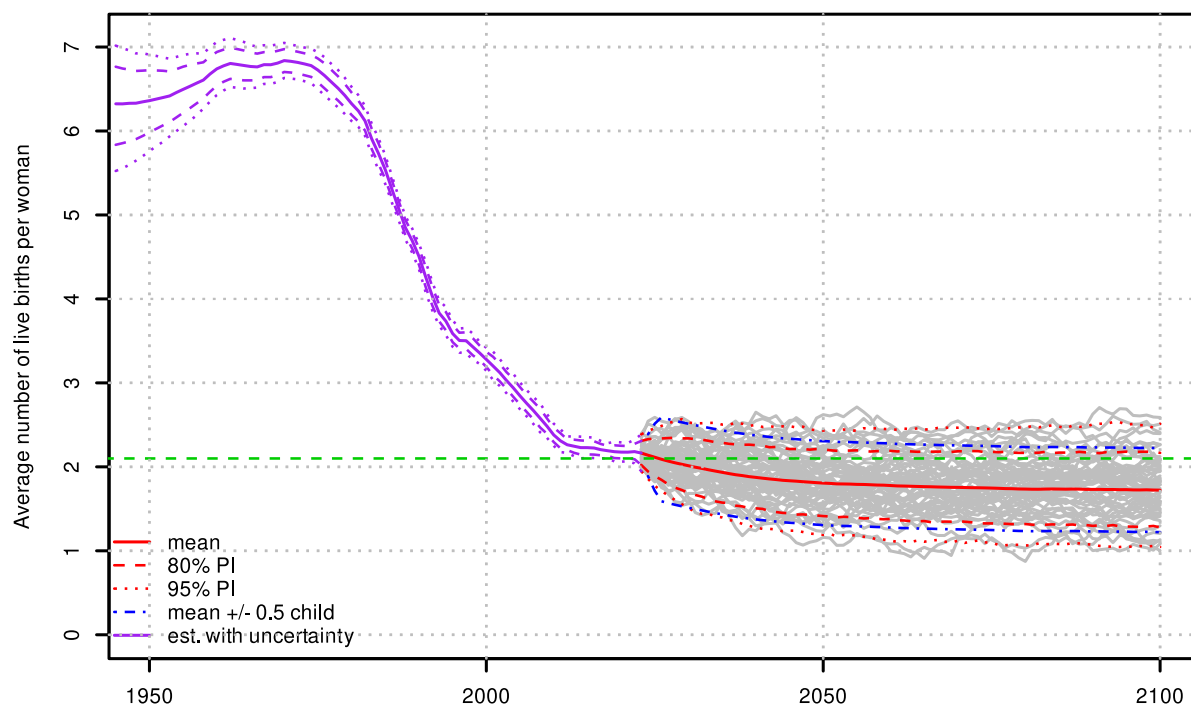
Note: Observed annual decrements by level of total fertility (TFR) are shown as black dots for those that occurred since the start of Phase II (decline), and as empty black squares for those that occurred before the start of Phase II. For clarity, only 60 of the 250,000 calculated trajectories are shown here. The median projection is depicted by the solid red line, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

The probabilistic projections of total fertility have been computed using “bayesTFR” (Ševčíková and others, 2011; Liu and others, 2023; Ševčíková and others, 2024a) an open-source and portable software implementation based on the R statistical language, and the full dataset used for the 2024 revision (United Nations, 2024b).

The mean of these 2,000 trajectories was used as the medium fertility scenario projection in the 2024 revision. To express the uncertainty surrounding future trends in fertility, 80 and 95 per cent prediction

intervals were also calculated (figure II.3). Additional tables⁴⁸ and graphs⁴⁹ are available online for all countries. For countries that had not reached phase III by 2023, the projected mean of the trajectories reflects the uncertainty as to when the fertility transition will end and at what level.

Figure II.3 Estimates and projected probabilistic trajectories of total fertility, Bangladesh, 1950-2100 (live births per woman)



Note: For clarity, only 60 of the 2,000 calculated trajectories are shown here for the period 2024 to 2100. The mean estimate is depicted by the solid purple line, and by the solid red line for the projections, while the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted purple lines for the estimation period, and red lines for the projection period, respectively. The high- and low-fertility scenarios of the 2024 revision correspond to the plus or minus 0.5 births around the mean trajectory, shown here as blue dashed lines. The replacement-level of 2.1 births per woman is plotted as a green horizontal dashed line for reference purposes.

The fertility projections produced in the 2024 revision have been informed by historical trends in fertility and reflect an implicit assumption that the conditions facilitating fertility decline will persist in the future. For countries still undergoing the fertility transition (in Phase II), there is widespread agreement in the demographic literature that increasing female education and increasing use of contraception are the two main factors that may help accelerate fertility decline. The population projections created using the conditional TFR projections suggest that increasing secondary female education and the use of modern contraception are likely to have substantial long-term effects on fertility decline and population growth in the high-fertility setting (Liu and Raftery, 2024). Similarly, as shown in the scenarios regarding adolescent birth rates presented in section F, the reduction in fertility in this age group will have an additional impact on the overall TFR. Should improving gender equality and women's empowerment, eliminating child marriage, and scaling up the access to education and family planning information, supplies and services be

⁴⁸ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online tables of stochastic projections of total fertility: mean, median, and 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Download/Probabilistic/Input/>.

⁴⁹ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of projections of total fertility: mean, 80 and 95 per cent prediction intervals, high and low WPP fertility scenarios; see <https://population.un.org/wpp/Graphs/Probabilistic/FERT/TOT/50>.

realized at faster pace than observed in the past, then future fertility decline might be faster than the medium fertility projections. Conversely, should prevailing conditions underlying fertility decline deteriorate (for example, if there is a slowdown in modern contraceptive method uptake or a persistent or resurgent desire for early marriage and large families), then the median projected levels of fertility in this revision may be too low.

B. PROJECTING AGE PATTERNS OF FERTILITY

Once the path of future total fertility was determined, age-specific fertility rates for mothers' single years of age were calculated. For some low-fertility countries with mean age at childbearing greater than 32 years in 2023⁵⁰, the projected age patterns of fertility pattern were held constant at those estimated for 2023. For all other countries, age-specific patterns of fertility were projected based on country-specific trends in the estimation period, leading towards a global model age pattern of fertility⁵¹ (Ševčíková and others, 2016). The projection method was implemented on the proportionate age-specific fertility rates (PASFR) by mothers' single years of age from 10 to 54.

The final projection of the PASFR for each age group is the weighted average of the two preliminary projections:

- A first preliminary projection, assuming that the PASFRs converge to the global model pattern, and
- A second preliminary projection, assuming that the observed national trend in PASFRs continues indefinitely.

The method was applied to each of the trajectories that constituted the probabilistic projection of the total fertility rate of each country, based on the estimated PASFRs for 1950-2023 from the *2024 revision* and the mean values were used as the resultant mean age at childbearing (MAC).

It was assumed that the transition in each trajectory from the observed national trend to the global model age pattern of fertility was dependent on (a) the timing of when the country entered phase III of the fertility transition, and (b) whether the projected fertility for a given period is higher than the ultimate TFR (2100) in the medium scenario projection (Ševčíková and others, 2016).

Out of 20 major methods to project fertility by age, this overall approach has been confirmed to be one of the four best performing methods (Bohk-Ewald and others, 2018) with the greatest accuracy to predict completed cohort fertility (i.e., how many children will be born on average by women over their entire reproductive lifetime).

⁵⁰ Countries or areas for which projected PASFR was held constant at the 2023 pattern include: : Andorra, Bermuda, China, Hong Kong SAR, China, Macao SAR, Ireland, Italy, Liechtenstein, Luxembourg, Republic of Korea, San Marino, Singapore, Spain and Switzerland. ⁵¹ The global model pattern in the *2024 Revision* is based on the unweighted average of the proportionate distribution of the age-specific fertility rates mothers' single year of age for the following low fertility countries or areas that (a) have reached phase III; and (b) display childbearing patterns with a mean age at childbearing between 30 and 32 years in 2023;: Australia, Austria, Belgium, Canada, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Guernsey, Japan, Jersey, Latvia, Lithuania, Montenegro, Netherlands, Norway, Portugal, Slovenia and Sweden.

⁵¹ The global model pattern in the *2024 Revision* is based on the unweighted average of the proportionate distribution of the age-specific fertility rates mothers' single year of age for the following low fertility countries or areas that (a) have reached phase III; and (b) display childbearing patterns with a mean age at childbearing between 30 and 32 years in 2023;: Australia, Austria, Belgium, Canada, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Guernsey, Japan, Jersey, Latvia, Lithuania, Montenegro, Netherlands, Norway, Portugal, Slovenia and Sweden.

C. PROJECTING THE MEDIUM MORTALITY SCENARIO

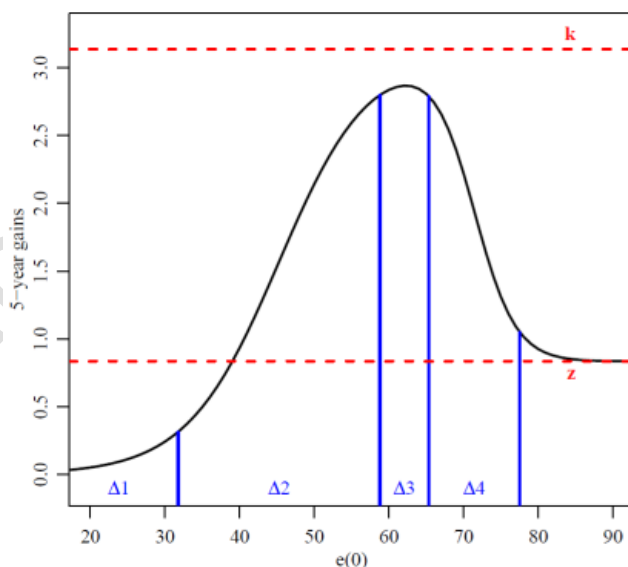
Assumptions for the projection of mortality were specified in terms of life expectancy at birth by sex. As part of the probabilistic population projections, the Population Division publishes 80 and 95 per cent prediction intervals for future levels of life expectancy at birth, along with the mean of the trajectories derived from a statistical model describing mortality change over time. The mean of the trajectories provides the mortality trend used in the various deterministic fertility scenarios (e.g., high-, medium- and low-, instant-replacement-fertility, no fertility below age 18 years, accelerated decline of adolescent birth rate (ABR), accelerated decline of ABR with recovery), but also for instant-replacement-zero-migration, and zero-migration scenarios. As in previous revisions, life expectancy was generally assumed to increase over the projection period.

The *2024 revision* used probabilistic methods for projecting life expectancy at birth, including modifications made to the implementation of the models in the *2017 revision* (Castanheira and others, 2017; United Nations, 2017c).

4. Projecting female life expectancy at birth

The probabilistic methods used in the *2024 revision* to project life expectancy at birth comprise two separate models. The first model depicts a gradual increase over time in female life expectancy at birth (Raftery and others, 2013). In this model, the transition from high to low mortality levels is divided into two phases, each of which is approximated by a logistic function that models the gains in life expectancy (figure II.4).

Figure II.4 Phases of the mortality transition: gains in life expectancy at birth by level of life expectancy at birth (years)



Source: Raftery and others (2013).

Note: The deltas (Δ) in the figure represent changes in the magnitude of 5-year gains against increases in life expectancy at birth.

The first phase, modelled through the first two delta terms in figure II.4, consists of the initial slow growth in life expectancy associated with the diffusion of improved hygiene and nutrition, followed by a period of accelerated improvement, especially in the mortality of infants and children, associated with social

and economic development accompanied by interventions in public health and basic medical care, including infant feeding, water and sanitation, and childhood immunization programmes. The second phase, modelled through the third and fourth delta terms in figure II.4, begins once the easiest gains, mainly from fighting infectious diseases that often strike in childhood, have been achieved. The second phase is characterized by a combination of continued gains from defeating infectious diseases across the age range and from combating non-communicable diseases that strike primarily at older ages. Given the greater challenges in preventing deaths from non-communicable diseases and the lower payoff in years of life expectancy gained from saving the life of an older person compared to that of a child, the rise in life expectancy is slower in the second phase (Fogel, 2004; Riley, 2001).

For all countries undergoing a mortality transition, the pace of improvement in life expectancy at birth described by the model is composed of two parts, which are depicted by a systematic decline term and a random distortion term:

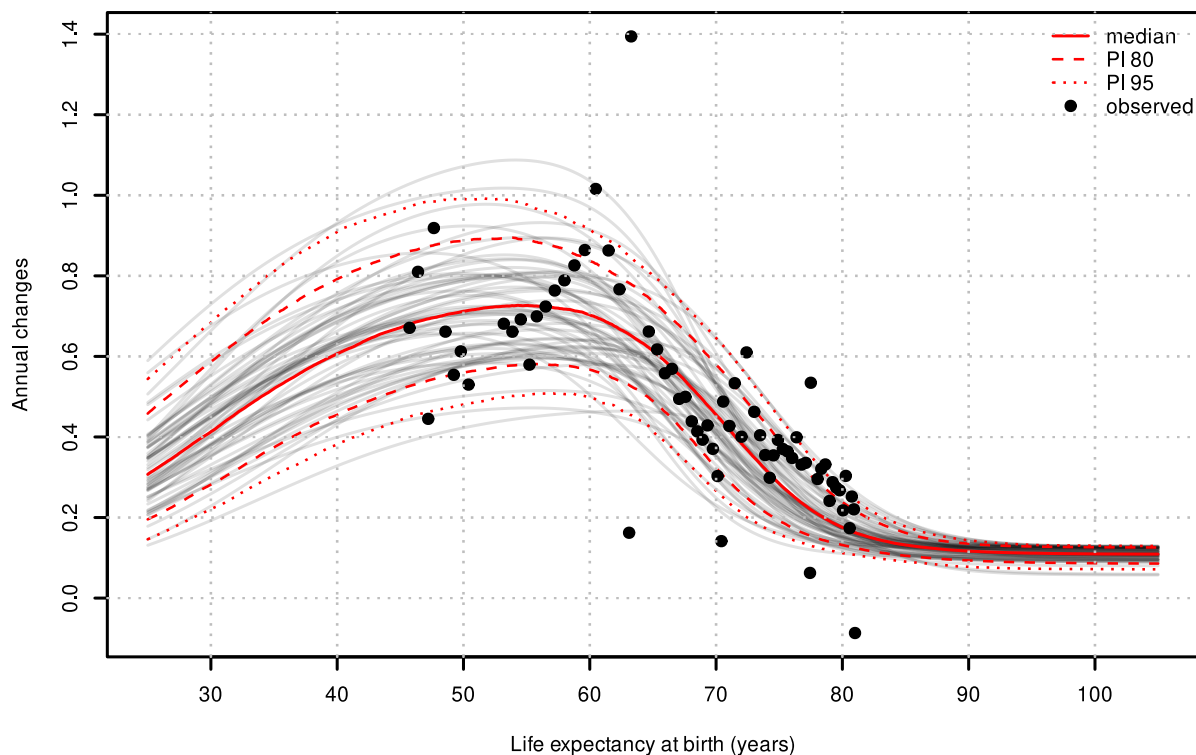
- First, the pace of systematic gains in life expectancy at birth is modelled as a function of the level of life expectancy, based on a double-logistic improvement function developed in earlier revisions of *World Population Prospects* (United Nations, 2006). The parameters of the double-logistic function were estimated based on the observed gains in female life expectancy from 1950 to 2023 for each country,⁵² using a Bayesian hierarchical model that yields country-specific distributions for all estimated parameters and for future trends in life expectancy. The model is hierarchical because, in addition to the information available for a particular country, a second level of information derived from the average global experience is used to estimate each country-specific double logistic curve.
- Second, given the estimated double-logistic curve for a particular country or area, each projected value of life expectancy at time $t+1$, the next year of projection period, was derived using a random walk with drift (Raftery and others, 2013), where the drift parameter, which specifies the pace of change over time, was taken from the estimated country-specific double-logistic function.

Under these conditions, the pace of improvement and the asymptotic limit to future gains in female life expectancy vary for each projected trajectory, but ultimately are informed and constrained by the finding that the rate of increase in maximum female life expectancy over the past 150 years has been approximately linear (Oeppen and Vaupel, 2002; Vaupel and Kistowski, 2005), albeit at a slower pace after female life expectancy at birth in vanguard countries started to exceed 75 years in the 1960s (Vallin and Meslé, 2009). Additional evidence used to guide decisions about the future rate of increase in life expectancy at birth included information on the historic increase in the maximum recorded age at death for women, or the maximum observed female lifespan, among countries with high life expectancies and reliable data on mortality at very old ages. The maximum recorded female age at death in countries such as Sweden and Norway has been increasing at a steady pace of about 1.25 years per decade since around 1970 (Wilmoth and others, 2000; Wilmoth and Robine, 2003; Wilmoth and Ouellette, 2012). Since the increase in average lifespan cannot exceed the increase in maximum lifespan indefinitely, the historic pace of increase in the

⁵² Life expectancies in the years 2020 and 2021 were highly affected by the COVID-19 pandemic, thus estimates for these years have been excluded from the model for all countries.

observed maximum lifespan of women from selected countries was used to set the value of the model parameter that helps determine the asymptotic average rate of increase in female life expectancy.⁵³

Figure II.5 Female gains in life expectancy at birth by level of life expectancy at birth and prediction intervals of estimated double-logistic curve, China (years)



Note: The observed yearly gains by level of life expectancy at birth ($e(0)$) are shown by black dots. For ease of viewing, only 60 of the 800,000 simulated trajectories are shown here. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

To construct projections of female life expectancy at birth for all countries, the Bayesian hierarchical model was used to generate 800,000⁵⁴ double-logistic curves for each country or area (figure II.5), representing the uncertainty in the estimated curve describing the country-specific relationship between the current value of life expectancy and the pace of increase in life expectancy⁵⁵. The model was fitted on all locations with more than 90,000 inhabitants in 2023, and smaller locations with less than 90,000 inhabitants were treated as supplementary locations (i.e., their experience did not inform the world distribution or other locations).

A systematic sampling of double-logistic curves was then used to calculate 10,000 projected values of life expectancy at birth for each country or area in each time period. All the probabilistic projections of

⁵³ Following the notation used in Raftery and others (2013), to obtain a posterior median of the annual gain in life expectancy of around 0.125 year, the parameter constraining the maximal value of the asymptote of the double-logistic curve at high levels of life expectancy was set to 0.1326, both for the global parameter (z) and for each country-specific parameter (z_c), during both the estimation and subsequent use of the collection of country-specific double-logistic curves.

⁵⁴ Actually, ten Markov chain Monte Carlo (MCMC) simulations were run in parallel to find the various combinations of parameters with 80,000 iterations performed for each simulation, and the first 2,000 for each simulation were discarded as burn-in trials so that the effect of initial values on the final results is minimized.

⁵⁵ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York. Online plots of double-logistic curves depicting annual gains in female life expectancy at birth, estimated using a Bayesian hierarchical model (BHM): median, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp20/Graphs/Probabilistic/EX/CHGFEM/156>.

female life expectancy at birth were computed using “bayesLife” (Ševčíková and others, 2024e), an open-source and portable software implementation based on the R statistical language, and the full dataset used for the 2024 revision (United Nations, 2024b). The transition from 5-year periods to annual time periods necessitated some changes to the implementation of the life expectancy projections, including a new criterion for annual outliers of ± 5 years and a new set of default global priors estimated jointly as follows (assuming $U_z=0.1326$ and the sum of deltas is equal to 86):

Table II.1 Global default set of parameters for the female life expectancy at birth double-logistic estimation

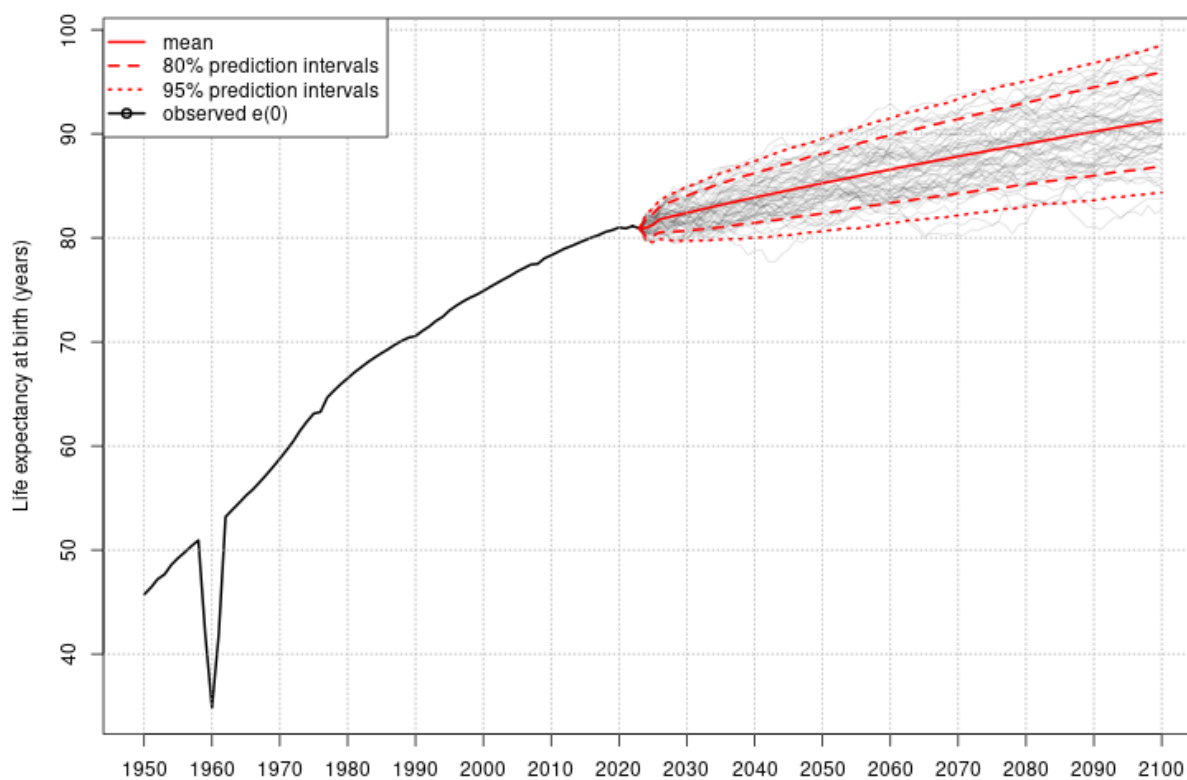
	Δ_1	Δ_2	Δ_3	Δ_4	k	z
a_i	13.218	40.912	9.462	22.104	2.748	0.627
δ_i	12.231	7.839	13.784	5.628	2.768	0.071
τ_i	19.157	22.410	14.867	21.518	2.768	0.265

The mean of the 10,000 trajectories was used as the standard mortality projection for the 2024 revision. To evaluate the uncertainty of future trends in female life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.6). Additional tables⁵⁶ and graphs⁵⁷ for all countries are available online.

⁵⁶ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. Online tables of probabilistic projections of female life expectancy at birth: mean, median, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp20/Download/Probabilistic/Input/>.

⁵⁷ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York. Online plots of probabilistic projections of female life expectancy at birth: mean, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp20/Graphs/Probabilistic/EX/Female/156>.

Figure II.6
Estimates and projected probabilistic trajectories of female life expectancy at birth, China, 1950-2100 (years)



NOTE: For ease of viewing, only 60 trajectories of the 10,000 simulated trajectories are shown here for 2024 to 2100. The mean trajectory is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

5. Modelling the gap between female and male life expectancy

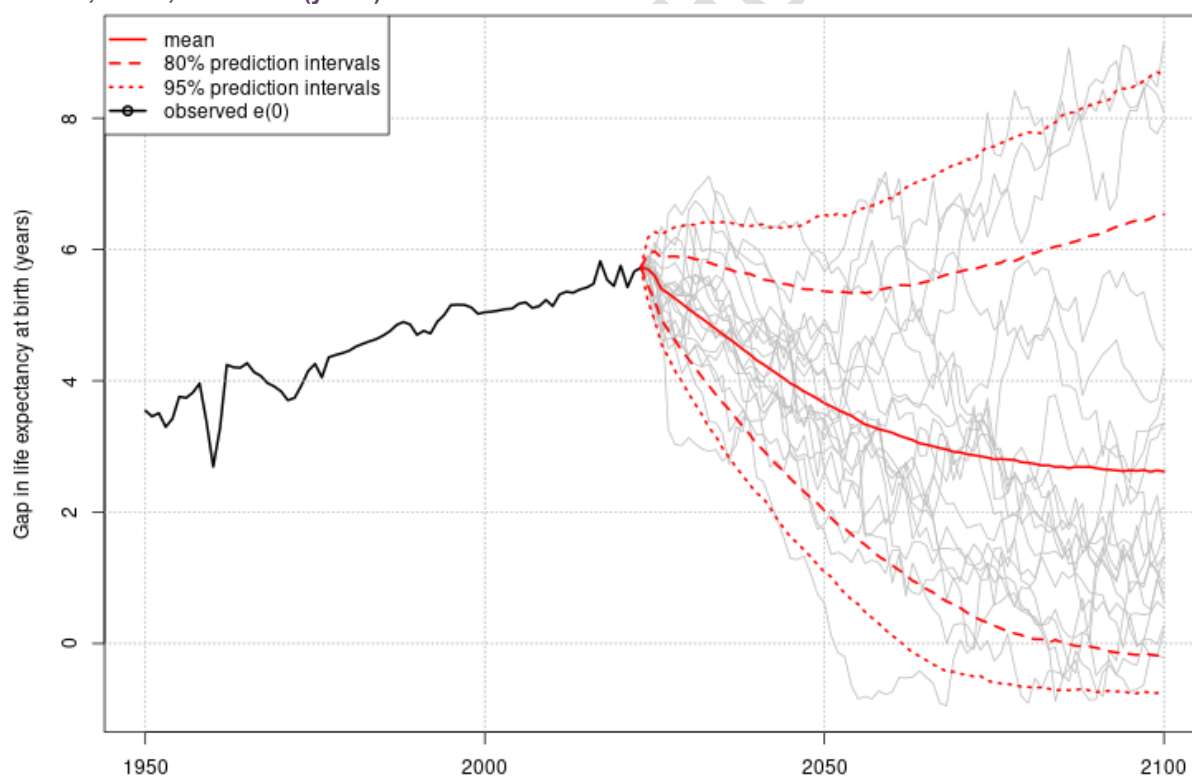
The second model used to project future mortality trends addresses the gap between female and male life expectancies at birth. The results obtained using the model of the sex gap in life expectancy were combined with those from the model of female life expectancy in order to derive projections of male life expectancy. In other words, the projected values of male life expectancy were obtained by subtracting the projected gap from the projected value of female life expectancy. The application of this approach considered the correlation between female and male life expectancies, and the existence of outlying data points during periods of crisis or conflict (Raftery and others, 2014b).

The gap in life expectancy at birth between females and males was modelled using an autoregressive model, with female life expectancy serving as a covariate. A large body of literature exists on biological, behavioural and socioeconomic factors underlying the gap in life expectancy between women and men (Oksuzyan and others, 2008; Rogers and others, 2010; Trovato and Heyen, 2006; Trovato and Lalu, 1996, 1998). Recent trends provide evidence of a narrowing sex gap in almost all high-income countries (Glei and Horiuchi, 2007; Meslé, 2004; Oksuzyan and others, 2008; Pampel, 2005). The pattern of decline in the sex gap at high levels of life expectancy, which has been observed for high-income countries and some emerging economies, was assumed to apply in the future to other countries as well. This trend is not implausible given the diffusion of effective public health and safety measures and medical interventions

(Vallin, 2006; Bongaarts, 2009). In effect, the projection model used by the United Nations implies, on the basis of past experience in countries from across the world, that the future sex gap is expected to widen when life expectancy is low but will tend to narrow once female life expectancy reaches about 75 years. In the current implementation of the model, this narrowing is assumed to continue until the female life expectancy attains a threshold value of 86 years. This specification brought about some convergence in the male and female values of life expectancy at birth within the projection interval for some countries. For projected levels of female life expectancy at or above the highest values observed to date (about 86 years), the sex gap was modelled as a constant with normally distributed distortions because little information on the determinants of changes in the gap exists at these high ages and beyond.

A large number of future trajectories for the gap in life expectancy were simulated to systematically produce joint probabilistic projections of female and male life expectancies. To construct projections of male life expectancy at birth, the autoregressive model of the gender gap in life expectancy was used to generate 10,000 trajectories of the gap for each country (figure II.8), representing uncertainty in the projected future gap. Each simulated value of the sex gap was then subtracted from its paired value of female life expectancy to generate the corresponding projected value of male life expectancy. Graphs of the sex gap trajectories for all countries are available online⁵⁸.

Figure II.7 Estimates and projected probabilistic trajectories of gap between female and male life expectancy at birth, China, 1950-2100 (years)



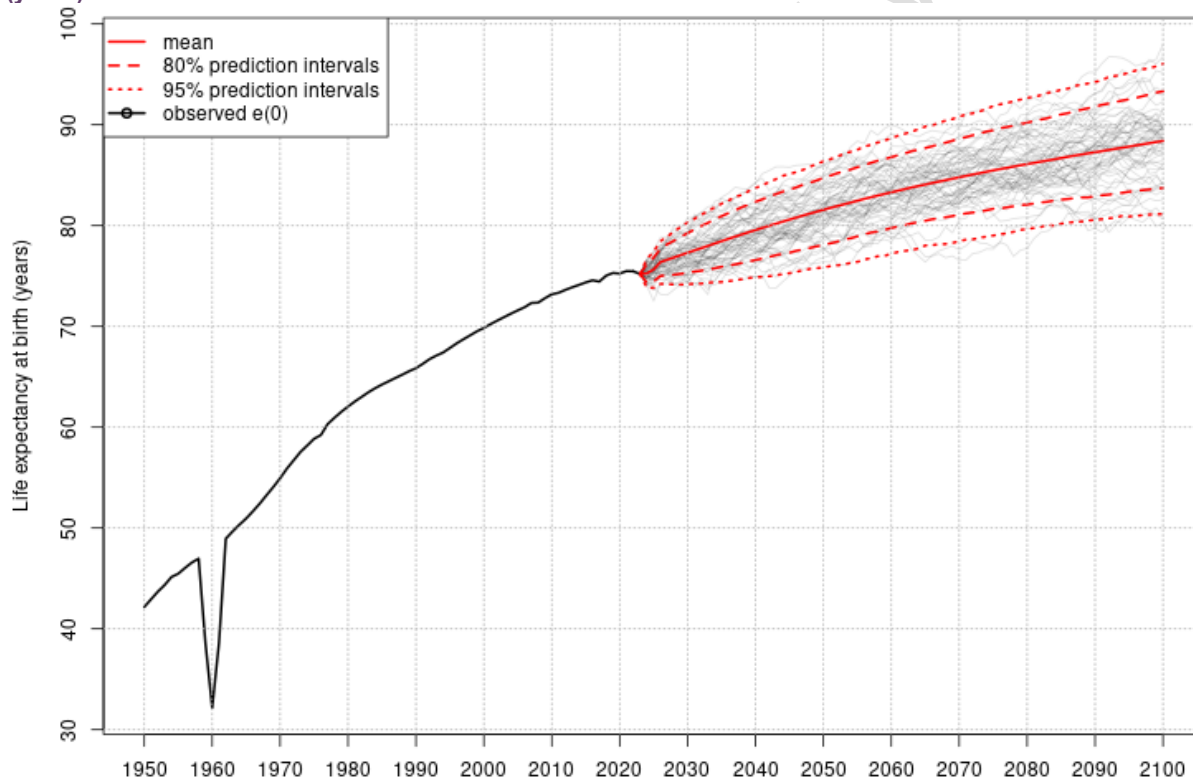
NOTE: For clarity, only 60 trajectories of the 10,000 calculated are shown here for 2024 to 2100. The mean projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively.

⁵⁸ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of female-male gap in life expectancy at birth: mean, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Graphs/Probabilistic/EX/FMGAP/156>.

As in the 2022 revision (United Nations, 2022), the 2024 revision includes historical data for periods prior to 1950 for several countries in the dataset used to estimate the coefficients of the sex-gap model. The minimum and maximum bounds of the gap were set at -1 and 18, respectively⁵⁹. The sample of gender gap trajectories was then used to calculate 10,000 male life expectancy projections for each country. All the computation for the probabilistic projections of male life expectancy at birth were performed using the open source “bayesLife” R package (Ševčíková and others, 2024e).

The median of these projections was used as the standard mortality projection for the 2024 revision. To evaluate the uncertainty of future trends in male life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (figure II.8). Additional tables⁶⁰ and graphs⁶¹ for all countries are available online.

Figure II.8 Estimates and projected probabilistic trajectories of male life expectancy at birth, China, 1950-2100 (years)



NOTE: For clarity, only 60 trajectories of the 10,000 calculated are shown here for 2024 to 2100. The mean projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively.

The relationship between the probabilistic projections of male and female life expectancy at birth for selected projection periods can be summarized through scatter plots showing a subsample of 500

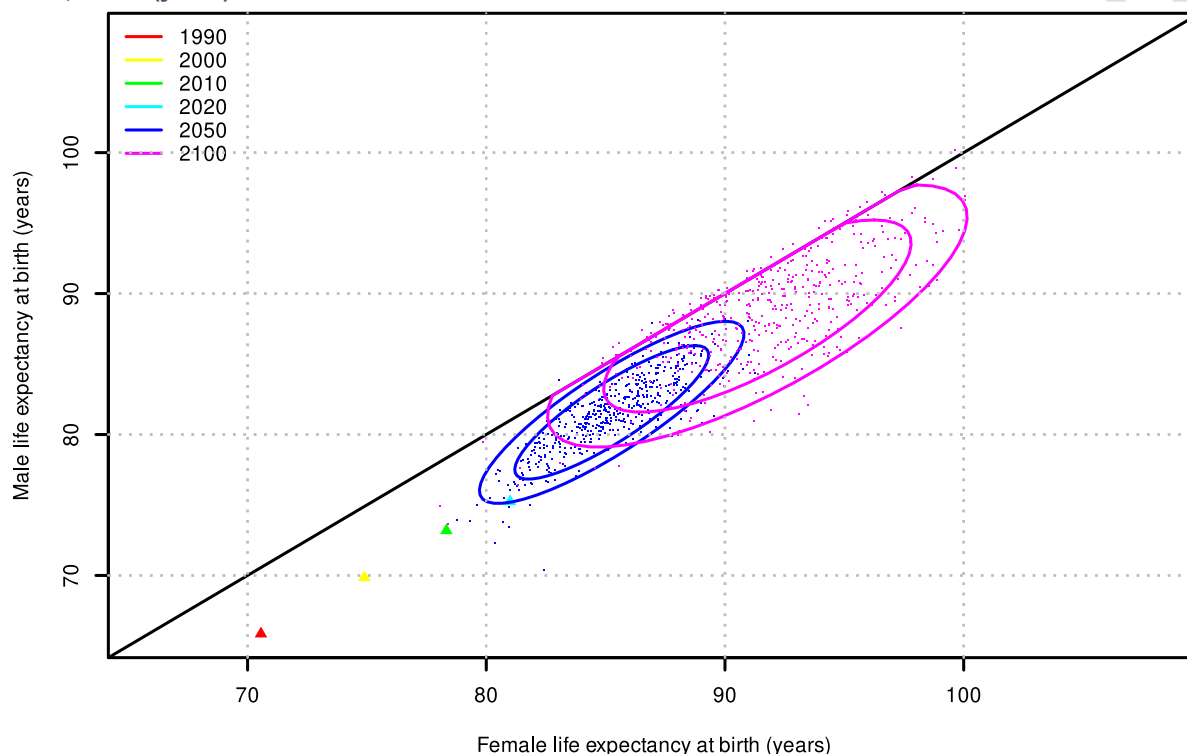
⁵⁹ Maximum female life expectancy for male projections handled by the first equation (parameter M in Equation (1) in Raftery and others (2014b)) is 84 for the data used for estimation with 3 degrees of freedom to deal with the heavy tail of the t-distribution due to more outliers with the use of annual time series instead of 5-year period averages used before the 2022 revision.

⁶⁰ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online tables of probabilistic projections of male life expectancy at birth: mean, median, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Download/Probabilistic/Input/>.

⁶¹ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of probabilistic projections of male life expectancy at birth: mean, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Graphs/Probabilistic/EX/Male/156>.

probabilistic trajectories of life expectancy at birth for males and females (figure II.9). The 80 and 95 per cent prediction intervals are shown as ellipses. The diagonal line represents equal male and female life expectancies. Graphs of the distribution of life expectancy by sex for all countries are available online.⁶²

Figure II.9 Comparison of probabilistic projections of female and male life expectancies at birth, selected periods, China (years)



NOTE: The figure shows the relationship between probabilistic projections of male and female life expectancies at birth for 1990, 2000, 2010, 2020, 2050, and 2100, computed based on estimates from the 2024 Revision of the *World Population Prospects*. For ease of viewing, only 500 of the 10,000 projected trajectories are shown here for each sex.

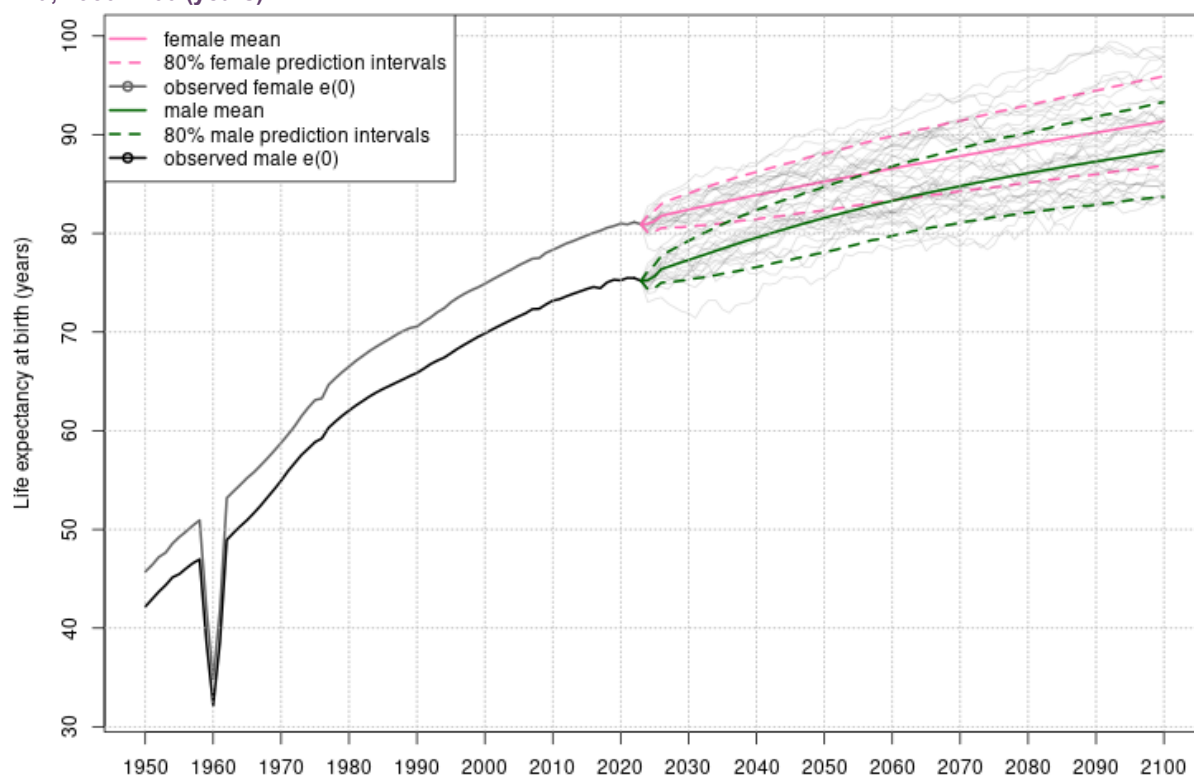
Summary plots are also available for all countries showing the mean and 80 per cent prediction intervals of female and male trajectories of life expectancy at birth (figure II.10),⁶³ and results for both sexes combined are also computed by aggregating deaths by age and sex and person-years of exposure at the trajectory level, and recomputing mortality rates and life tables for the 2,000 sample of life expectancy at birth trajectories used for each sex for the probabilistic population projections.⁶⁴

⁶² United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of Comparison between probabilistic projections of male and female life expectancies at birth for selected projection periods: 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Graphs/Probabilistic/EX/FMCOMP/156>.

⁶³ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of Comparison between probabilistic projections of male and female life expectancies at birth for selected projection periods: 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Graphs/Probabilistic/EX/FMCOMP/156>.

⁶⁴ United Nations, Department of Economic and Social Affairs, Population Division (2024). *World Population Prospects 2024*. New York: United Nations. Online plots of probabilistic projections of both sexes life expectancy at birth: mean, 80 and 95 per cent prediction intervals; see <https://population.un.org/wpp/Graphs/Probabilistic/EX/BothSexes/156>.

Figure II.10 Estimates and projected probabilistic trajectories of female and male life expectancy at birth, China, 1950-2100 (years)



NOTE: For clarity, for each sex only 60 trajectories of the 10,000 calculated are shown here for 2024 to 2100. The mean projection is the solid pink line for female, and the 80 per cent prediction intervals are shown as dashed pink lines respectively. Projections of male life expectancy at birth are indicated by green lines.

6. Special considerations for countries affected by HIV and AIDS

The 2024 revision took the same approach as the 2019 and 2022 revisions to project the life expectancy at birth of countries affected by the HIV and AIDS epidemic. For the 60 countries or areas having ever experienced an adult HIV prevalence of one per cent or more among males or females during the period 1980 and 2023, the levels of life expectancy at birth were projected using the existing Bayesian probabilistic life expectancy projection methods (Ševčíková and others, 2024e) extended to account for past and expected levels and trends in HIV prevalence and adult antiretroviral therapy (ART) coverage (Godwin and Raftery, 2017). The latest epidemiological data for these countries referred to the period 1980-2023 (UNAIDS, 2023). The projection assumptions for the future course of the HIV and AIDS epidemic were similar to those in previous revisions; the 2024 revision assumed that the HIV prevalence rate observed in 2023 would decline by 2100 to about one-tenth of its value, following an exponential decay function. ART coverage was projected to reach 90 per cent in 2050 if it was below 85 per cent in 2019 or to reach 95 per cent if it was above 85 per cent in 2023; it remained constant thereafter until 2100. All computations for the probabilistic projections of life expectancy at birth for HIV and AIDS countries were performed using the open source “bayerLifeHIV” R package (Ševčíková and others, 2024b).

7. Adjustments for future mortality improvements for selected countries or areas

The approach to project life expectancy described above worked well for most countries that have experienced normal or typical improvements in survival since the 1950s. However, some countries stood out because of much faster or much slower improvements than those experienced by other countries. Countries that experienced much faster gains in life expectancy since the 1950s, or over segments of the estimation period, tend to be those where life expectancy remains relatively low. In some of these countries, a relatively rapid decline in child mortality in the latter part of the estimation period contributed to an unreasonably optimistic projection of life expectancy at birth. Conversely, for several countries that experienced periods of stagnating mortality during the estimation period, the standard model described above produced unreasonably pessimistic projections of life expectancy. In both cases, adjustments were made such that the four parameters of the double logistic function responsible for future gains for each country were informed by the experiences of the leading countries in their respective regions.

The countries to which the adjustments were applied are listed in table II.2 together with the respective values used as priors for each adjusted parameter.⁶⁵ In cases of too optimistic projections of life expectancy, this approach was used to temper unreasonably high values over the long term, thus avoiding implausible outcomes or crossovers in the long-term projections (i.e., countries that were lagging in the recent observation period becoming leaders by 2100). In cases of too-pessimistic projections of life expectancy, this approach was used to provide further guidance on the trajectory of long-term potential gains, assuming that, in the long run, these countries would gradually catch up with more advanced countries in their region.

Table II.2 Countries for which adjustments were made to the default mortality projection trajectory in the 2024 revision

<i>A. Countries with projected life expectancies that were deemed too high</i>		Upper bound for country-specific priors of the double-logistic parameters			
<i>Country or area</i>	Δ_{c3}	Δ_{c4}	k^c	z^c	
1. Afghanistan	11.84	18.83	0.7263	0.1188	
2. Angola	12.17	19.06	0.4958	0.1159	
3. Benin	13.31	20.28	0.4408	0.1193	
4. Brazil	13.30	18.23	0.4799	0.1182	
5. Burkina Faso	13.57	20.32	0.4408	0.1195	
6. Burundi	13.71	20.12	0.4434	0.1197	
7. Cambodia	12.77	19.47	0.6369	0.1179	
8. Chad	12.17	19.21	0.3422	0.1159	
9. Côte d'Ivoire	13.21	20.39	0.4408	0.1193	
10. Democratic Republic of the Congo	12.76	20.03	0.4416	0.1195	
11. Dominican Republic	11.98	18.31	0.7983	0.1128	
12. Ecuador	12.90	18.35	0.6734	0.1174	
13. Eswatini	12.35	19.22	0.4196	0.1184	
14. Falkland Islands (Malvinas)	14.18	17.71	0.6827	0.1220	
15. French Polynesia	13.69	18.65	0.3861	0.1222	
16. Gambia	14.06	21.08	0.6225	0.1217	
17. Guadeloupe	13.99	21.01	0.3861	0.1216	
18. Guatemala	12.43	18.46	0.5354	0.1152	
19. Guinea	13.31	20.12	0.3761	0.1193	

⁶⁵ Following the formal notation of Raftery and others (2013), country-specific priors were specified for the first set of countries for the upper bound of the Δ_{c3} , Δ_{c4} , k^c and z^c double-logistic parameters while for the second set of countries, the lower bound were used for these parameters. In general, the upper quartile of the distribution of these parameters for the best performers in each region was used to inform other countries.

<i>A. Countries with projected life expectancies that were deemed too high</i>	Upper bound for country-specific priors of the double-logistic parameters			
<i>Country or area</i>	Δ_{c3}	Δ_{c4}	k^c	z^c
20. Guinea-Bissau	13.57	19.99	0.4408	0.1195
21. Haiti	13.29	19.63	0.5342	0.1174
22. Kiribati	12.68	18.60	0.4454	0.1164
23. Kosovo (under UNSC res. 1244)	13.79	20.20	0.7357	0.1184
24. Lao People's Democratic Republic	12.20	18.77	0.5731	0.1140
25. Liberia	13.21	20.07	0.3761	0.1193
26. Madagascar	15.28	22.09	0.5005	0.1260
27. Malawi	13.98	20.04	0.5758	0.1219
28. Maldives	13.46	18.26	0.8917	0.1198
29. Mali	12.58	19.50	0.5245	0.1157
30. Martinique	13.99	21.01	0.3861	0.1201
31. Monaco	13.92	21.41	0.7461	0.1213
32. Morocco	11.71	17.49	0.7451	0.1172
33. Mozambique	13.74	20.06	0.4846	0.1196
34. Namibia	13.23	20.00	0.4889	0.1187
35. New Caledonia	13.69	21.01	0.3861	0.1204
36. Nicaragua	12.94	20.67	0.7670	0.1196
37. Niger	12.51	18.79	0.4120	0.1157
38. Nigeria	13.52	20.12	0.3497	0.1195
39. Oman	13.35	19.49	0.8575	0.1178
40. Papua New Guinea	13.20	17.79	0.3948	0.1147
41. Peru	12.29	17.04	0.5358	0.1182
42. Qatar	14.17	20.47	0.3773	0.1216
43. Réunion	13.99	21.01	0.3861	0.1220
44. Saint Barthélemy	13.99	17.79	0.3861	0.1190
45. Senegal	13.28	20.12	0.6375	0.1196
46. Sierra Leone	13.54	20.07	0.4215	0.1197
47. South Sudan	11.44	18.04	0.2722	0.1181
48. State of Palestine	13.28	20.50	0.5168	0.1205
49. Tajikistan	13.62	20.86	0.4336	0.1205
50. Timor-Leste	12.77	19.47	0.5783	0.1179
51. Tokelau	13.89	18.74	0.5125	0.1174
52. Türkiye	13.50	19.03	0.6862	0.1197
53. United Arab Emirates	14.04	20.47	0.3773	0.1211
54. Wallis and Futuna Islands	13.69	18.74	0.3861	0.1174
55. Western Sahara	12.93	19.64	0.7207	0.1153
56. Yemen	12.63	17.56	0.9359	0.1120

<i>B. Countries with projected life expectancies that were deemed too low</i>	Lower bound for country-specific priors of the double-logistic parameters			
<i>Country or area</i>	Δ_{c3}	Δ_{c4}	k^c	z^c
1. Belize	10.82	16.77	0.7702	0.0977
2. Cameroon	10.21	16.37	0.5265	0.0926
3. Faroe Islands	10.78	16.92	1.4943	0.0966
4. Fiji	10.30	15.42	0.7764	0.0828
5. Hungary	10.27	15.31	1.7031	0.1082

<i>B. Countries with projected life expectancies that were deemed too low</i>		Lower bound for country-specific priors of the double-logistic parameters			
6.	Japan	9.74	16.63	0.8898	0.0885
7.	Jersey	10.50	16.92	0.4822	0.1027
8.	Kenya	10.63	16.59	0.9291	0.0932
9.	Kyrgyzstan	10.21	16.29	0.3328	0.0950
10.	Lesotho	10.37	16.28	0.6396	0.0919
11.	Libya	10.30	15.86	1.3160	0.0882
12.	Liechtenstein	9.84	15.78	0.6849	0.0855
13.	Mauritania	10.53	16.85	0.5441	0.0929
14.	Mauritius	11.45	19.83	1.9428	0.1037
15.	Nauru	10.65	16.61	0.4173	0.0945
16.	Netherlands	10.86	16.41	0.8318	0.1039
17.	Pakistan	11.50	16.63	0.9606	0.1025
18.	Philippines	11.23	17.37	1.3651	0.1081
19.	Romania	10.37	16.25	0.8037	0.0927
20.	Serbia	11.03	16.82	1.3829	0.0976
21.	Sri Lanka	10.48	16.78	0.9270	0.0933
22.	United States Virgin Islands	10.92	17.61	1.6797	0.0975
23.	Viet Nam	11.23	17.37	1.3651	0.1081
24.	Zimbabwe	10.52	16.31	0.3399	0.0930

8. *Special considerations in the context of the COVID-19 pandemic for 2020-2023*

The impacts of the COVID-19 pandemic, which caused reductions in life expectancies across much of the world in 2020 and 2021, and in some countries up to 2023, necessitated a modified approach to the short-term projections of life expectancy. For all countries, it was assumed that life expectancy at birth returned to the pre-pandemic trajectory in 2024, based on the annual time series of life expectancies at birth up to 2019, and empirical estimates for the period 2020-2023 were censored from the model fitting.

9. *Special considerations in the context of locations experiencing mortality crises in 2023*

In another five countries (China, Libya, State of Palestine, Syrian Arab Republic, and Türkiye), recent trends and levels of life expectancy at birth for one or both sexes have been negatively affected by crises, including political upheaval, armed conflict, public health issues, and environmental disasters. In this context, the baseline level of life expectancy at birth used for 2023 implied too pessimistic values as a starting point for the projected trajectories of life expectancy at birth, and would assume that the situation in 2023 persists for too many projection years. For these countries, the values of life expectancy at birth projected for 2024 and 2025 were adjusted by blending the most recently observed trend up to 2023 with the unadjusted model prediction for 2026 onward using spline interpolation reflecting a gradual recovery in 2024 and 2025 toward the model prediction of a continuous progress in life expectancy, respectively. All probabilistic trajectories were proportionately adjusted based on this approach for the median trajectory of each country.⁶⁶

⁶⁶ The adjustment for a country and time period corresponds to the ratio between the unadjusted median life expectancy at birth and adjusted median life expectancy at birth. It is applied to each life expectancy at birth probabilistic trajectory for the corresponding country and period.

D. PROJECTING AGE PATTERNS OF MORTALITY

Once the path of future life expectancy was determined, mortality rates by single year of age and sex were calculated, consistent with the projected life expectancy at birth for each year. The specific approach employed to project sex- and age-specific mortality for each country depended on the type and quality of the empirical information used to estimate the age pattern of mortality in recent periods:

a) Model life tables (MLT)

For eight countries or areas, projected sex-specific mortality rates were obtained from an underlying model life table that matched projected life expectancy at birth. Model patterns were selected from the set of model life tables extended to a maximum life expectancy at birth of 100 years (Li and Gerland, 2011)⁶⁷. The Coale-Demeny North family of model life tables was used for Gibraltar and Isle of Man. The Coale-Demeny West family was used for Falkland Island (Malvinas), Guernsey, Holy See, Jersey, and Liechtenstein. The UN Far Eastern family was used for the Wallis and Futuna Islands.

b) Modified Lee-Carter method (LC)

For 25 countries with high-quality information on mortality age patterns⁶⁸, sex- and age-specific mortality rates were projected by extrapolating country-specific historical trends using the modified Lee-Carter method constrained to the projected life expectancy at birth (Li and others, 2013). This method selects appropriate increases in the level parameter (k_t) for each year of the projection with the age pattern (a_x) based on the average of 2015 through 2019 and smoothed over age. The age pattern of mortality improvement (b_x) gradually changes with the level of mortality, reflecting a deceleration of mortality decline at younger ages and an acceleration at older ages.

c) Pattern of mortality decline method (PMD)

The remaining 204 countries or areas had some recent and reliable empirical information on mortality age patterns, but without the quality or time coverage needed for the modified Lee-Carter method to yield stable results (Gu and others, 2017). For these countries, projected sex- and age-specific mortality rates were obtained from a model of the typical age-specific patterns of mortality improvement given the level of life expectancy at birth. This model was calibrated to the range of country experiences represented in the HMD (Andreev and others, 2013)⁶⁹. For each country, the model was fit to the mortality pattern of a recent year or years that was not impacted by COVID-19 or other crisis mortality, smoothed over age as warranted.

To impose some structure on the projected mortality patterns over the long-term projection horizon, those obtained from the PMD model were blended gradually towards a model life table age pattern of mortality matched to the projected life expectancy at birth. The Coale-Demeny West family of model life tables was used for 142 countries, the Coale-Demeny North family for 50 countries, and the UN Far Eastern family for 12 countries.

⁶⁷ The last available entry in the revised system of model life tables of 100.0 years of life expectancy, for both males and females, is not meant to represent a ceiling for human longevity.

⁶⁸ Including Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Slovenia, Spain, Sweden, Switzerland, United Kingdom, and United States of America.

⁶⁹ Available demographic data have permitted reliable estimation of the patterns of mortality improvement only up to 75-80 years of e_0 for males, and 80-85 years for females. For extrapolating patterns of mortality improvement into higher levels of life expectancy at birth, smoothed linear trends were extrapolated for levels of life expectancy at birth up to 105-110 years of age.

Where necessary, projected mortality age patterns were constrained below age 60 to avoid implausible crossover between male and female mortality patterns, especially at very high levels of projected life expectancies. An open source implementation of these three projection methods is available through the “MortCast” R package (Ševčíková and others, 2024c; Ševčíková and others, 2016).

E. INTERNATIONAL MIGRATION IN THE MEDIUM SCENARIO

1. Projecting total net migration

International migration is the component of population change that is the most difficult to project. Data regarding past trends are often sparse or incomplete. Moreover, the movement of people across international borders, which is often a response to rapidly changing economic, social, political and environmental factors, is an erratic process. In some instances, both the volume and direction of international migration have changed significantly within a short period of time. Some countries that have historically been primarily countries of origin have become countries of destination for international migrants, and vice versa. Any long-range assumption regarding future trends in international migration is virtually guaranteed to prove incorrect. Given that migration flows to and from most countries tend to be small relative to the size of the total population, these errors are not expected to substantially influence the population projections. However, for countries in which international migration has been or will become a dominant factor in demographic change, the assumption applied in the projection can be highly consequential.

For the first time, the medium variant of net international migration in the *2024 revision* was projected using probabilistic methods developed by Azose and Raftery (2015; 2016), and adapted to use annual time series using an updated version of “bayesMig” (Azose and others, 2024), an open-source and portable software implementation based on the R statistical language, and the full dataset used for the *2024 revision* (United Nations, 2024b). A Bayesian hierarchical approach was used to model future trajectories of the crude net migration rate around the world based on historical experience across countries and to account for uncertainties and correlations across countries and over time. Because the variability in count data grows roughly in proportion to population size, the initial modelling focuses on rates as an easier way to obtain more stable variance and share experiences between countries on a common scale. In the final step, the net migration rates were converted back into net migration counts for population projections.

The overall analytical approach follows these ten steps:

1. Using the annual estimates of crude net migration rates from 1950 to 2023 for all countries from the *2024 revision*, a Bayesian hierarchical first-order autoregressive, or AR(1), the model was fitted to crude net migration rate data for all countries to estimate the parameters of the Azose and Raftery (2015) migration model via bayesMig (Azose and others, 2024).⁷⁰
2. By default, the estimation period used for model fitting referred to 1950 to 2023, but the application of autoregressive statistical methods in this context faced two types of challenges for some countries: (1) the country-specific overall rate of change and long-term mean net migration rate are influenced

⁷⁰ Actually, ten Markov chain Monte Carlo (MCMC) simulations were run in parallel to find the various combinations of parameters with 50,000 iterations performed for each simulation with a thinning of 1 out of 10 trajectories, and the first 20,000 for each simulation were discarded as burn-in trials so that the effect of initial values on the final results is minimized.

by the reference period used to fit the model, which might need to be adjusted depending on the country's historical context (e.g., conflicts, political, and economic changes), and (2) the short-term and long-term projections are highly influenced by the most recent situation (e.g., countries experiencing large in/out flows of migrants or refugees in 2023). Expert knowledge was incorporated to inform prior distributions and provide further guidance to the model fitting with respect to the reference period used for a specific set of locations (Table II.3.A).

- To address the challenges with the set of countries experiencing recent large movements of net international migrants or refugees, expert knowledge was used to define the expected target years when the situation in these locations is expected to return to some baseline level (Table II.3.B), and for a subset of those that experienced large in/outflow of recent refugees the extent that about 2/3 of these recent refugees are expected to return to their country of origin by the target year⁷¹. For each of these cases, some linearly interpolated values were estimated between the 2023 baseline and the expected median value for the user-defined target year. All probabilistic trajectories were adjusted proportionately based on the expected values for the median trajectory of each country.⁷²

Table II.3 Countries for which adjustments were made to the default migration projection trajectory in the 2024 Revision

<i>A. Countries with user-defined reference periods</i>			
<i>Country or area</i>	<i>Reference period</i>	<i>Country or area</i>	<i>Reference period</i>
1. Armenia	1995-2019	22. Jordan	1970-2012
2. Azerbaijan	1995-2022	23. Kosovo	2000-2023
3. Brazil	1962-1977	24. Latvia	1950-2021
4. Chad	1950-2022	25. Lithuania	1950-2021
5. Colombia	1985-2023	26. Malta	1990-2015
6. Croatia	2000-2023	27. Micronesia	1970-2023
7. Cuba	1981-2023	28. Montenegro	1950-2021
8. Czechia	1995-2021	29. Nigeria	1990-2023
9. Dem. People's Republic of Korea	1993-2023	30. Norway	1950-2021
10. Ecuador	1950-1982	31. Pakistan	1985-2021
11. Egypt	1950-2022	32. Panama	1990-2023
12. Estonia	2000-2021	33. Poland	2000-2021
13. Finland	1990-2021	34. Portugal	1970-2023
14. Germany	1950-2021	35. Republic of Moldova	1950-2021
15. Greece	1990-2020	36. Russian Federation	1980-2021
16. Guatemala	1950-1964	37. Serbia	2000-2021
17. Honduras	2005-2023	38. Seychelles	1950-2010
18. Hungary	2000-2021	39. Slovakia	1995-2021
19. India	1991-2023	40. Sudan	1950-2022
20. Indonesia	1990-2023	41. Ukraine	2000-2021
21. Japan	1996-2023	42. Western Sahara	1982-2023

⁷¹ As noted by Devictor (2019; 2017), the median duration of exile at the end-2018 stands at 5 years, i.e. half of the refugees worldwide have spent 5 years or less in exile. The median has fluctuated widely since the end of the Cold War, in 1991, between 4 and 14 years. Recent statistical analysis for 35 countries with ongoing refugee crises by Susmann and Raftery (2024) also validates the projection assumption that two thirds of refugees will return to their country of origin within 5 years.

⁷² The adjustment for a country and time period corresponds to the ratio between the unadjusted median crude net migration rate and expected interpolated rates. It is applied to each net migration rate probabilistic trajectory for the corresponding country and period.

B. Countries with user-defined target year to return to baseline net migration level

Country or area	Target year	Return of refugees	Country or area	Target year	Return of refugees
1. Azerbaijan	2024		15. Latvia	2026	2/3
2. Armenia	2024		16. Lithuania	2026	2/3
3. Brazil	2040		17. Malta	2026	
4. Chad	2027	2/3	18. Montenegro	2026	2/3
5. Croatia	2024		19. Norway	2026	
6. Czechia	2026	2/3	20. Poland	2026	2/3
7. Ecuador	2030		21. Republic of Moldova	2026	2/3
8. Egypt	2027	2/3	22. Russian Federation	2026	2/3
9. Estonia	2026	2/3	23. Serbia	2026	2/3
10. Finland	2027		24. Seychelles	2030	
11. Germany	2026	2/3	25. Slovakia	2026	2/3
12. Greece	2025		26. South Sudan	2024	
13. Hungary	2026	2/3	27. Sudan	2027	2/3
14. Jordan	2026	2/3	28. Ukraine	2026	2/3

C. Countries with user-defined net migration rates for selected projection period

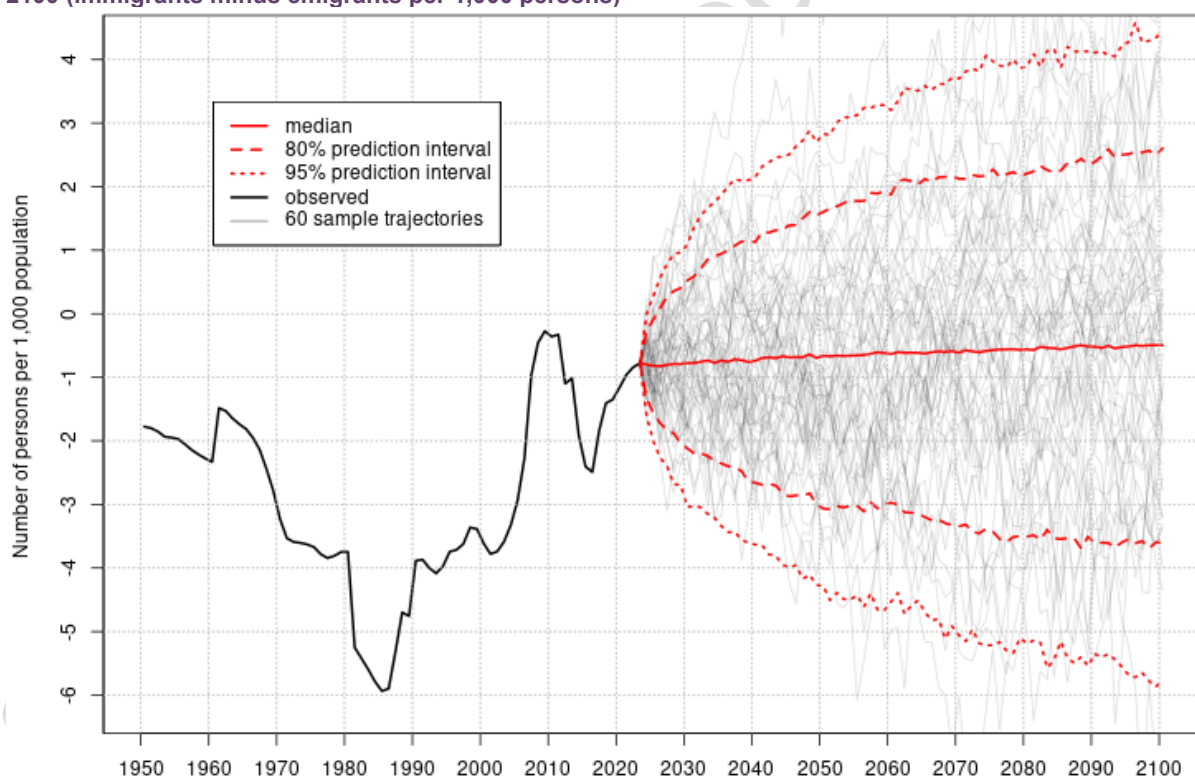
Country or area	Projection period	User-defined net migration rate per 1000	Country or area	Projection period	User-defined net migration rate per 1000
1. Argentina	2035-2100	0.01	17. Mauritius	2030-2100	-1.50
2. Bahrain	2030-2100	0.50	18. Mexico	2024-2100	-0.80
3. Cambodia	2030-2100	-1.50	19. Nepal	2028-2100	-1.00
4. Colombia	2050-2100	-0.01	20. Nicaragua	2037-2100	-1.20
5. Costa Rica	2026-2100	0.20	21. Oman	2030-2100	0.50
6. Cuba	2050-2100	-1.00	22. Panama	2040-2100	0.40
7. Curacao	2030-2100	2.00	23. Peru	2030-2100	-0.14
8. Democratic Republic of the Congo	2024-2100	-0.25	24. Philippines	2040-2100	-1.00
9. Dominican Republic	2050-2100	-1.60	25. Qatar	2030-2100	0.50
10. Ecuador	2050-2100	-0.12	26. Saint Vincent and the Grenadines	2040-2100	-2.00
11. French Guiana	2030-2100	1.00	27. Saudi Arabia	2030-2100	0.50
12. Haiti	2050-2100	-1.00	28. Solomon Islands	2040-2100	-1.50
13. Honduras	2050-2100	-0.07	29. Trinidad and Tobago	2030-2100	-0.50
14. Iran (Islamic Republic of)	2030-2100	-0.40	30. Turkmenistan	2030-2100	-0.40
15. Kuwait	2030-2100	0.50	31. United Arab Emirates	2030-2100	0.50
16. Martinique	2040-2100	-2.00	32. Uruguay	2024-2100	-0.40

4. Using the results from the model fitting from step 1, and the additional constraints from steps 2 and 3, bayesMig (Azose and others, 2024) was used to create projections of net migration rates, and generate 2,000 trajectories from 2024 to 2100 for each country.
5. Upon review of the median projection results for the net migration rates for each country, for a subset of locations, the default level for the long-run projection up to 2100 was considered to deviate too much from prior expectations and expert knowledge about country history and context. For each of

these cases, user-defined target values were defined and used as constraints for the user-defined projection period (Table II.3.C). All probabilistic trajectories were proportionately adjusted based on these expected values for the median trajectory of each country.⁷³

6. Additional constraints were also imposed on the cumulative migration rates over different time periods to prevent migrations from growing indefinitely, and to generate unrealistic population growth (Azose and others, 2016). The following upper bound constraints were imposed as maxima of cumulative migration for each of the 2,000 trajectories of several countries of the Gulf region where temporary labour migrants comprise a large share of the population: 26.8 per 1,000 for Bahrain, 67.5 per 1,000 for Kuwait, 56.9 per 1,000 for Oman, 70 per 1000 for Qatar, 16.1 per 1,000 for Saudi Arabia and 73 per 1,000 for the United Arab Emirates. These limits were set based on past fluctuations experienced by these countries and the unconstrained 95th percentiles.
7. Based on the additional constraints from steps 5 and 6, a new set of projections of net migration rates was generated using bayesMig to consider these set of constraints in addition to those from steps 2-3, and 2,000 trajectories were exported for each country (Figure II.11).

Figure II.11 Estimates and projected probabilistic trajectories of crude net migration rate, Mexico, 1950-2100 (immigrants minus emigrants per 1,000 persons)

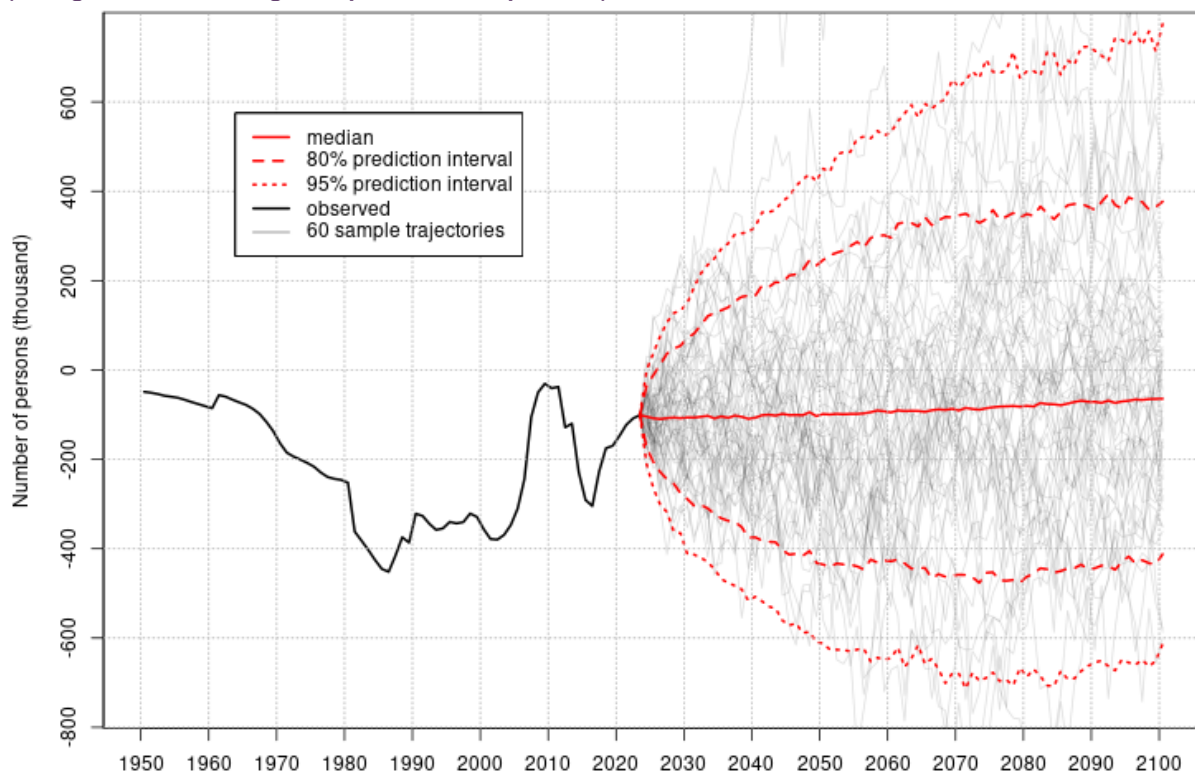


Note: For ease of viewing, only 60 trajectories of the 2,000 simulated trajectories are shown here for 2024 to 2100. The median trajectory is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines, respectively.

⁷³ The adjustment for a country and time period corresponds to the ratio between the unadjusted median crude net migration rate and expected target rates. It is applied to each net migration rate probabilistic trajectory for the corresponding country and period.

8. Using these 2,000 trajectories of net migration rates, an initial set of net migration counts was computed using bayesPop (Ševčíková and others, 2024d) to generate probabilistic population projections based on the population, fertility and mortality data by age and sex from the *2024 revision*, and the 2,000 trajectories of total fertility rates, life expectancy at birth by sex, and net migration rates (from step 6) combined with model-based assumptions about the expected distribution of migrants by sex and age (see II.E.2). While this initial step was necessary to convert net migration rates into counts using the underlying average projected populations, no further constraint was applied to ensure zero worldwide net migration annually for each of the 2,000 trajectories.
9. As with estimates, net migration balancing was carried out for projections as a final step to ensure that, at the global level, the sum of all net international migration flows equalled zero for each year of the projection period. To ensure that for each of the 2,000 trajectories the sum annually of net migration counts across all countries is zero, an extra step was implemented to “balance” total net migration counts. Using the set of 2,000 trajectories of unbalanced net migration counts for each country from step 8 (and underlying population counts), the trajectories were adjusted annually by redistributing any overflow migrants to all countries in proportion to their projected populations. This balancing step was performed in three sequential steps: (1) balancing of non-labor countries only, (2) balancing of labour countries only (Bahrain, Bangladesh, Egypt, India, Indonesia, Kuwait, Oman, Pakistan, Philippines, Qatar, Saudi Arabia, United Arab Emirates), and (3) balancing all countries. Before the balancing steps, the following upper bound limits on the annual number of net migrants were imposed as maxima for each of the 2,000 trajectories of several countries of the Gulf region where temporary labour migrants comprise a large share of the population: 58,000 for Bahrain, 330,000 for Kuwait, 451,000 for Oman, 295,000 for Qatar, 543,000 for Saudi Arabia, and 1,135,000 for the United Arab Emirates.
10. The 2,000 adjusted and balanced trajectories of total net migration counts (from step 9) for each country (for example see Figure II.12 for Mexico) were exported and used as inputs to the final run of the probabilistic population projections (see section II.G). They were also used to generate the median projected values for each country that were used for the medium deterministic scenario of the *2024 revision* (after applying an additional rebalancing step as described in step 9 because the annual sum of all the country medians is initially unbalanced).

Figure II.12 Estimates and projected probabilistic trajectories of net migration counts, Mexico, 1950-2100 (immigrants minus emigrants per thousand persons)



Note: For ease of viewing, only 60 trajectories of the 2,000 simulated trajectories are shown here for 2024 to 2100. The median trajectory is the solid red line, and the 80 and 95 per cent prediction intervals (PI) are shown as dashed and dotted red lines respectively.

2. Projecting net migration by sex and age

The projected distribution of international migrants by sex and age was established on the basis of what was known about the recent sex- and age-patterns of net international migration for each country. In the previous revision in 2022, for most countries the model patterns described in section I.E (including the family, male labour, female labour, and population distribution) were applied to project the sex- and age-patterns of net international migration over the full projection horizon for most countries. However, these model patterns were unsuitable to represent the patterns observed in some countries for which net migration is positive in some age groups and negative in others. In these instances, custom patterns were implemented based on the average estimated distribution over the last decade of the estimation period.

For the 2024 revision, a new approach was implemented to project net international migration patterns by age and sex. The approach entails first dividing the total net international migration into counts of immigration and emigration, respectively, and then applying a Rogers-Castro model to further apportion those counts by age and sex. A full description of the methodology is available in Raymer et al. (2023). Key model parameters include the migration rate, defined as the proportion of the population in each year that migrates (immigrants + emigrants), the peak ages of immigration and emigration, respectively, the proportion female among immigrants and emigrants, and a flag indicating whether migration patterns are

characterized as “low dependency”, with relatively few children or older persons outside of the traditional working ages migrating.

The appropriate values of these parameters can vary appreciably across countries depending on the primary direction and drivers of international migration. To implement this method for all countries over the full projection period, the `optim()` package for R was used to identify the optimal values of the migration rate and peak ages that most closely replicated the observed patterns computed for the most recent estimation period among the countries for which residual methods were used. The proportions of females among immigrants and emigrants were computed for each country based on migration transitions by origin, destination, and sex estimated by Abel and Cohen (2022). Thirteen countries were flagged as “low dependency” owing to the relatively low levels of net migration of children and older persons over the last five years of the estimation period.⁷⁴ Lastly, for several countries of the Gulf region where temporary labour migrants comprise a large share of the current *de facto* population, including Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates, an effort was made to model the return flow of those migrants, taking into account their ageing.

F. THIRTEEN PROJECTION SCENARIOS

In projecting future levels of fertility and mortality, probabilistic methods were used to reflect the uncertainty of the projections based on the historical variability of changes in each variable. The method considers the past experience of each country while also reflecting uncertainty about future changes based on the past experience of other countries under similar conditions. The medium scenario projection corresponds to the mean fertility and mortality and median net migration of several thousand distinct trajectories of each demographic component derived using the probabilistic model of the variability in changes over time. Prediction intervals reflect the spread in the distribution of outcomes across the projected trajectories and thus provide an assessment of the uncertainty inherent in the medium scenario projection.

In addition to the medium scenario and 80 and 95 per cent prediction intervals available from the probabilistic population projections, the 2024 revision includes thirteen deterministic projection scenarios that illustrate the impact of differing assumptions from the medium scenario (table II.4). Eight of these scenarios differ only with respect to the level of fertility; that is, they share the same assumptions with respect to the sex ratio at birth, mortality, and international migration. The eight fertility scenarios include five scenarios seen before in previous revisions—medium, low, high, constant-fertility and instant-replacement-fertility—as well as three new scenarios that consider alternative trajectories for fertility among adolescents. A comparison of the results from these eight scenarios allows for an assessment of the effects of different fertility assumptions on other demographic parameters.

Under the high scenario, fertility is projected to remain at 0.5 births above the fertility in the medium scenario over the entire projection period except for the initial years. To create a smooth transition between levels observed for the baseline period (2023) and future levels within the high scenario, fertility for the high scenario was assumed to be 0.25 births higher in the first five years of the projection (2024-2028) compared to the baseline, 0.4 births higher in the second five years of the projection (2029-2033), and 0.5 births higher thereafter. Thus, starting in 2034, fertility in the high scenario was assumed to be 0.5 births higher than that of the medium scenario. In other words, a country with a total fertility rate of 2.1 births per

⁷⁴ Bahrain, Bangladesh, Cambodia, Cayman Islands, Kuwait, Maldives, Malta, Oman, Qatar, Saudi Arabia, Seychelles, Singapore and the United Arab Emirates.

woman in some time period under the medium scenario would have a total fertility of 2.6 births per woman in the high scenario.

Under the low scenario, fertility is projected to remain at 0.5 births below the fertility in the medium scenario over most of the projection period. To ensure a smoother transition between the baseline period (2023) and the low scenario, fertility in the low scenario is initially 0.25 births lower in the first five years of the projection (2024-2028), 0.4 births lower in the second five years of the projection (2029-2033), and 0.5 births lower thereafter. By 2034, fertility in the low scenario is therefore half a child lower than that of the medium scenario. That is, countries reaching a total fertility rate of 2.1 births per woman in the medium scenario have a total fertility rate of 1.6 births per woman in the low scenario.

As the name implies, under the constant-fertility scenario, fertility in all countries will remain constant at the level projected for 2024. Meanwhile, mortality and migration assumptions are the same as those in the medium fertility scenario.

Under the instant-replacement scenario, for each country, fertility is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2024 (after taking into account the survival up to reproductive ages). Fertility varies over the remainder of the projection period such that the net reproduction rate always remains equal to one, ensuring the replacement of the population over the long run.⁷⁵ Mortality and migration assumptions are the same as those in the medium fertility scenario.

For the *2024 revision*, three new scenarios were introduced to consider the potential impact of changes in fertility rates among adolescent women and girls:

- The first scenario imagines that fertility rates at ages below 18 years will immediately fall to zero in 2024 and remain at zero throughout the remainder of the century.
- The second scenario considers that fertility rates at ages below 20 years decline by 20 per cent annually, beginning in 2024, until the adolescent birth rate falls below 10 births per thousand women aged 15 to 19 years.
- A third scenario imagines the same accelerated fertility decline as in the second scenario, but also that half of the reduction in fertility among women and girls younger than 20 years is recovered once those cohorts have aged 10 years (i.e., half of the reduced fertility among women aged 17 is recovered 10 years later among women aged 27).

In addition to the eight fertility scenarios, a constant-mortality scenario, a zero-migration scenario, an instant replacement zero-migration scenario, and a “no change” scenario, that is, both fertility and mortality are kept constant, have been computed. The constant-mortality scenario and the zero-migration scenario both use the medium-fertility assumption, whereas the instant replacement zero-migration scenario uses the instant replacement fertility assumption. The constant-mortality and no change scenarios have the same international migration assumption as the medium scenario. Consequently, the results of the constant-mortality scenario can be compared with those of the medium scenario to assess the effect of changing mortality has on population size and composition. Similarly, the zero-migration scenario differs from the medium scenario only with respect to the underlying assumption regarding international migration. Therefore, the zero-migration scenario allows for an assessment of the effect that non-zero net migration

⁷⁵ Mortality levels are also taken into account while measuring the replacement level.

has on various population sizes and compositions. When compared to the medium scenario, the no change scenario sheds light on the effects that changing fertility and mortality have on the results obtained.

A final scenario, called “momentum” illustrates the impact of age structure on long-term population change (United Nations, 2017a). This scenario combines elements of three scenarios: the instant-replacement-fertility scenario, the constant-mortality scenario, and the zero-migration scenario.

Table II.4 Projection scenarios in terms of assumptions for fertility, mortality and international migration

Projection scenarios	Assumptions		
	Fertility	Mortality	International migration
Medium	Medium*	Medium*	Medium*
High fertility	High	Medium	Medium
Low fertility	Low	Medium	Medium
Constant-fertility	Constant as of 2024	Medium	Medium
Instant-replacement-fertility	Instant-replacement as of 2024	Medium	Medium
No fertility below age 18 years	Age-specific fertility below age 18 = 0 as of 2024	Medium	Medium
Accelerated decline of adolescent birth rate (ABR)	Age-specific fertility below age 20 declines by 20 per cent per year until ABR is below 10 births per 1000 women aged 15-19	Medium	Medium
Accelerated decline of ABR with recovery	Accelerated ABR decline with recovery of half of reduced fertility once cohorts have aged 10 years	Medium	Medium
Constant-mortality	Medium	Constant as of 2024	Medium
No change	Constant as of 2024	Constant as of 2024	Medium
Zero-migration	Medium	Medium	Zero from 2024
Instant replacement zero-migration	Instant-replacement as of 2024	Medium	Zero from 2024
Momentum	Instant-replacement as of 2024	Constant as of 2024	Zero from 2024

* Based on the mean probabilistic projections for fertility and mortality, and median probabilistic projections for net migration.

In comparison to one another, deterministic scenarios permit a decomposition of the projected future populations according to the contributions of the four demographic determinants of change: fertility, mortality, migration, and momentum.

- The difference between the population projected with the “zero-migration” scenario and that in the medium variant results in a change in the future population owing to net international migration.
- The difference between the “instant-replacement zero-migration” scenario and the “zero-migration” scenario indicates the change in population due to changes in fertility.
- The difference between the “momentum” scenario and the “instant-replacement zero-migration” scenario gives the change in population due to changes in mortality.
- Finally, the difference between the “momentum” scenario and the population at the beginning of the projection period is the change in population due to the momentum intrinsic to the population age structure.

The *Summary of Results*, which accompanies the 2024 revision of the *World Population Prospects*, includes several examples and illustrations of this decomposition of the demographic components of population change (United Nations, 2024a).

G. POPULATION PROJECTION METHOD

Population projection was carried out using the same CCMPP engine as for the estimates, described in section I.A of this report.

Two types of population projections were included in the *2024 revision*: a deterministic version and a probabilistic version.

- a) In the deterministic versions, the population was projected using the trajectories of fertility, mortality and net international migration described in the previous section. Computations for geographic aggregates and other country-groupings were carried out as described in section I.A of this report.
- b) The probabilistic version extends the deterministic medium scenario by incorporating uncertainty about future changes in fertility, mortality, and net international migration. For each country, 2,000 population projections were computed from 2024 to 2100, each one using a projected trajectory of total fertility rates, projected trajectory of life expectancy by sex, and net migration counts in the country sampled from the predictive distribution of these quantities. The various population and demographic indicators, including vital events and vital rates, were computed for each trajectory and summarized using 80 and 95 per cent prediction intervals. All computations were performed using the open source “bayesPop” R package, which in 2022 was updated to work with single years of age and one-year periods of time (Ševčíková and others, 2024d; Ševčíková and Raftery, 2016).

These probabilistic projections do not consider the uncertainty in the baseline population or mortality and migration rates, but as of the *2022 Revision*, they incorporate the uncertainty in past fertility estimates (Liu and Raftery, 2020; Liu and others, 2023).

Computations for geographic aggregates and other country groupings were first performed at the trajectory level, and the aggregated results of the 2,000 trajectories of population and vital events used to derive summary statistics.

Between-country correlations not captured by the Bayesian hierarchical projection model for total fertility are incorporated into the final projected trajectories for each country using the method described in Fosdick and Raftery (2014) through a set of time-invariant covariates, that is, whether the countries are contiguous, whether they were colonized by the same country after 1945, and whether they are located in the same continental region. For mortality, the modelling approach used (Raftery and others, 2013; Raftery and others, 2014b; Godwin and Raftery, 2017) does not require additional provisions for between-country correlations in life expectancy.

For net international migration, all trajectories are balanced for each year at the global level such that the sum of total net international migration across all countries is zero (see II.E.1).

ANNEX

A. Methodological note on extrapolation and graduation of model life table reference data

1) Extrapolation to life expectancies at birth up to 115 years

In 2010, in preparation for an extended projection horizon to the year 2100 in the *2012 revision* of the *World Population Prospects*, the United Nations Population Division extrapolated the set of Coale-Demeny and United Nations abridged model life tables to life expectancies at birth up to 100 years (Li and Gerland, 2011)⁷⁶.

Since then, with the adoption of Bayesian methods for projecting life expectancies at birth, it is necessary to extrapolate the model life table patterns even further to accommodate the more extreme values of that can arise with thousands of projected trajectories of e_0 over an 80-year horizon. Thus, in preparation for the *2022 revision* of the *World Population Prospects*, the Coale-Demeny and United Nations abridged Model Life Table patterns were extrapolated to life expectancies at birth up to 115 years⁷⁷.

Extrapolation was carried out for each model life table family by fitting a limited Lee-Carter forecast (using the `interp_lc_lim()` function of the DemoTools package for R) to the abridged set model life table patterns associated with life expectancies of 90, 92.5, 95, 97.5, and 100 years. The resulting set of extrapolated life tables have life expectancies at birth ranging from 102.5 years up to 115 years, in increments of 2.5 years. Taken together with the previous set of abridged model patterns to a life expectancy of 100 years, these life tables form smooth mortality surfaces by age, sex, and e_0 levels.

2) Graduation to single year of age

For the *2022 revision*, the Population Division transitioned from the historical practice of estimating population and demographic rates for five-year age groups and five-year periods of time to single-year age groups and one-year periods of time. This “one-by-one” framework necessitated model life table patterns that correspond to single years of age.

Each of the abridged model life tables described above was graduated to single years of age using the `lt_abridged2single()` function of the DemoTools package for R. This function, in turn, called the `pclm()` function of the `ungroup` package to return single-age mortality rates (${}_1m_x$) by splitting the ${}_n d_x$ life table deaths, offset by ${}_n L_x$ life table person-years of exposure. For ages 110 through 130, the ${}_1 m_x$ were modelled by fitting a Kannisto function to the ${}_1 m_x$ of the oldest 20 ages returned by the `pclm()` function. The resulting model life tables by single year of age have life expectancies at birth that are very close to, though not identical, to their abridged counterparts.

B. Converting cohort deaths to deaths by age and recovering population exposures

The CCMPP moves cohorts over age and through time in single-year increments. Members of a cohort aged x at time t advance to age $x+1$ at time $t+1$ according to the probabilities of surviving given by the life table survival ratios. Each time step of the CCMPP returns the number of deaths by cohort ${}_t DC_x$ computed using the starting population by sex and age at time t , and the life table survival ratios (S_x) computed based on the sex- and age-specific mortality rates (${}_t M_x$) for the period spanning t to $t+1$. A series of cohort separation factors (CS_x), computed based on the l_x and ${}_t L_x$ columns of the life table, are then used to convert the deaths by cohort back to deaths by age that align with the way deaths are

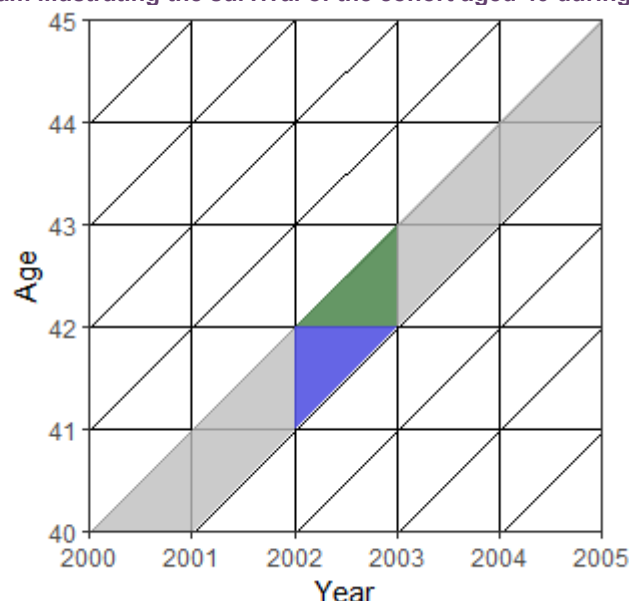
⁷⁶ <https://www.un.org/development/desa/pd/data/model-life-tables>

⁷⁷ The tools used for graduation to single year of age presently do not permit extensions beyond 115 years of life expectancy at birth. In general, the `pclm` model cannot converge at such low levels of mortality.

recorded by age and period in vital registers. This section describes the calculations performed during the WPP workflow to apply those separation factors to derive deaths by age and recover the population exposures corresponding to the estimated vital rates.

In demography, the relationships between age, period, and cohort are often represented using a Lexis diagram (figure A.1), with time on the horizontal axis and age on the vertical axis. To illustrate an example, the shaded area in figure A.1 highlights the space through which the cohort that celebrated their 40th birthdays in the year 2000 survived through the ensuing five years. Deaths that occurred to this cohort during the year 2002 are represented by the spaces shaded in blue and green. These are the cohort deaths that are computed in the CCMPP based on the life table survival ratios estimated for 2002.

Figure A.1 Lexis diagram illustrating the survival of the cohort aged 40 during 2000 from 2000 to 2005



To compute deaths by age for 2002, one must split the cohort deaths into two groups: deaths that occurred to members aged 41 years (blue triangle) and deaths that occurred to members aged 42 years (green triangle). Because mortality risks tend to increase with age, the share of cohort deaths located in the green triangle is typically larger than that in the blue triangle. That share varies over location, time, sex and age. It is determined by the survival probabilities described by the life table.

The computation of the cohort separation factors used in the *World Population Prospects* is carried over from those implemented in the legacy-Abacus programme, developed by Thomas Buettner and colleagues, that underpinned the *World Population Prospects* through the 2019 revision (United Nations, 2019b). For each age x :

$$CS_x = ({}_1L_x - l_{x+1}) / ({}_1L_x - {}_nL_{x+1})$$

Then, deaths by age and period (${}_1DA_x$) are estimated for ages 1 to 129 years (the last age before the open age group 130+):

$${}_1DA_x = {}_1DC_x * (1 - CS_x) + ({}_1DC_{x+1} * CS_{x+1})$$

For age 0:

$${}_1DA_x = {}_1DC_0 + ({}_1DC_1 * CS_0)$$

And for the open age group 130+:

$$DA_{130} = DC_{130} + (1 - CS_{129})$$

Once deaths by age and sex have been estimated for each period, population exposures measured in person-years (${}_1E_x$) are recovered such that, together with deaths by age and sex (${}_1DA_x$), they reproduce the period mortality rates (${}_1M_x$) used to compute the original life table input to the CCMPP:

$${}_1E_x = {}_1DA_x / {}_1M_x$$

Beginning with the 2022 revision of the *World Population Prospects*, the population exposures by sex and single year of age for the estimates and medium variant projection have been published on the website of the Population Division in a dedicated CSV file.

advance unedited version

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