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World Population Prospects

United Nations

Methodology of the United Nations Population Estimates and Projections

2015 REVISION

ESA/P/WP.242

Department of Economic and Social Affairs
Population Division

World Population Prospects
The 2015 Revision

Methodology of the United Nations Population Estimates and Projections

United Nations
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The Department of Economic and Social Affairs of the United Nations Secretariat is a vital interface between global policies in the economic, social and environmental spheres and national action. The Department works in three main interlinked areas: (i) it compiles, generates and analyses a wide range of economic, social and environmental data and information on which States Members of the United Nations draw to review common problems and take stock of policy options; (ii) it facilitates the negotiations of Member States in many intergovernmental bodies on joint courses of action to address ongoing or emerging global challenges; and (iii) it advises interested Governments on the ways and means of translating policy frameworks developed in United Nations conferences and summits into programmes at the country level and, through technical assistance, helps build national capacities.

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Notes

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PREFACE

This report provides a detailed overview of the methodology used to produce the *2015 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 *2015 Revision* is the twenty-fourth round of global population estimates and projections produced by the Population Division since 1951.

The 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 variants used in generating the different sets of population projections as well as information on the recently developed probabilistic projection methods, which depict the uncertainty of future demographic trends, with results presented for all countries and areas of the world up to the year 2100. The Population Division has continued to refine the methods used for these probabilistic projections. It should be stressed, however, that making projections to 2100 is subject to a high degree of uncertainty, especially at the country level. In that regard, users are invited to focus not only on the outcomes of the medium variant, which for each country corresponds to the median of several thousand projected trajectories of each demographic component, but also on the associated prediction intervals, which provide an assessment of the uncertainty inherent in such projections. Detailed information on the uncertainty bounds for different components at the country level is available on the website of the Population Division, *www.unpopulation.org*.

The *2015 Revision* of the World Population Prospects was prepared by a team led by Barney Cohen[1] and François Pelletier, including Kirill Andreev, Lina Bassarsky, Victor Gaigbe-Togbe, Patrick Gerland, Danan Gu, John Kanakos, Vladimira Kantarova, Neena Koshy, Nan Li, Igor Ribeiro, Cheryl Sawyer, and Thomas Spoorenberg.

[1] Deceased 19 September 2015.

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EXPLANATORY NOTES

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

Two dots (..) indicate that data are not available or are not reported separately.
A hyphen (-) indicates that the item is not applicable.
An em dash (—) indicates that the value is zero (magnitude zero)
0 and/or 0.0 indicates that the magnitude is not zero, but less than half of the unit employed
A minus sign (-) before a figure indicates a decrease.
A full stop (.) is used to indicate decimals.
Years given refer to 1 July.
Use of a hyphen (-) between years, for example, 1995-2000, signifies the full period involved, from 1 July of the first year to 30 June of the second year.
Numbers and percentages in tables do not necessarily add to totals because of rounding.

References to countries, territories and areas:

The designations employed and the material in this publication 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 or area or its authorities, or concerning the delimitation of its frontiers or boundaries.

The designation “more developed” and “less developed” regions are intended for statistical purposes and do not express a judgment about the stage reached by a particular country, territory or area in the development process. The term “country” as used in this publication also refers, as appropriate, to territories or areas.

More developed regions comprise all regions of Europe plus Northern America, Australia/New Zealand and Japan. Less developed regions comprise all regions of Africa, Asia (excluding Japan), and Latin America and the Caribbean as well as Melanesia, Micronesia and Polynesia. Countries or areas in the more developed regions are designated as “developed countries”. Countries or areas in the less developed regions are designated as “developing countries”.

The group of least developed countries, as defined by the United Nations General Assembly in its resolutions (most recently, 68/18) included 48 countries in 2015: 34 in Africa, 9 in Asia, 4 in Oceania and one in Latin America and the Caribbean. Those 48 countries are: Afghanistan, Angola, Bangladesh, Benin, Bhutan, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Comoros, Democratic Republic of the Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gambia, Guinea, Guinea-Bissau, Haiti, Kiribati, Lao People's Democratic Republic, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Myanmar, Nepal, Niger, Rwanda, São Tomé and Príncipe, Senegal, Sierra Leone, Solomon Islands, Somalia, South Sudan, Sudan, Timor-Leste, Togo, Tuvalu, Uganda, United Republic of Tanzania, Vanuatu, Yemen and Zambia. These countries are also included in the less developed regions.

The group denominated “other less developed countries” comprises all countries in the less developed regions minus the least developed countries.

The country classification by income level is based on 2014 GNI per capita from the World Bank.

The term “sub-Saharan Africa” is used to designate the countries of Africa excluding those of Northern Africa.

Countries and areas are grouped geographically into six major areas designated as: Africa; Asia; Europe; Latin America and the Caribbean; Northern America, and Oceania. These major areas are further divided into 21 geographical regions.

The names and composition of geographical areas follow those presented in “Standard country or area codes for statistical use” (ST/ESA/STAT/SER.M/49/Rev.3), available at http://unstats.un.org/unsd/methods/m49/m49.htm.

The following abbreviations have been used:

AIDS	Acquired immunodeficiency syndrome
DESA	Department of Economic and Social Affairs
DHS	Demographic and Health Surveys
GHS	General Household Survey
HIV	Human immunodeficiency virus
IGME	Inter-agency Group for Child Mortality Estimation
MICS	Multiple Indicator Cluster Survey
MIS	Malaria Indicator Survey
MDGs	Millennium Development Goals
TFR	Total fertility rate
UNAIDS	Joint United Nations Programme on HIV/AIDS
WFS	World Fertility Survey
WHO	World Health Organization

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 in some cases a reassessment of the past; and (b) the formulation of detailed assumptions about the future paths of fertility, mortality and international migration, again for every country or area of the world.

The population estimates and projections contained in this revision cover a 150-year time horizon, which can be subdivided into past estimates (1950-2015) and future projections (2015-2100). The past estimates were produced by starting with a base population by age and sex for 1 July 1950 and advancing the population through successive 5-year time intervals using the cohort-component method, based on age-specific estimates of the components of population change (fertility, mortality, and international migration). Population counts by age and sex from periodic censuses were used as benchmarks. The relevant estimates of demographic components for 1950-2015 were taken directly from national statistical sources, or were estimated by staff of the Population Division when only partial or poor-quality data were available. Necessary adjustments were made for deficiencies in age reporting, under-enumeration, or underreporting of vital events.

The year 2015, separating the past estimates from the projections, is called the base year of the projections. The projection period of this revision covers 85 years and ends in 2100.

Population projections prepared by the United Nations Population Division historically have been produced for a number of different variants to highlight, for instance, the effect of changes in the assumptions about the future trajectories of fertility on the future size and structure of the population. More recently a probabilistic approach was added to the projection of certain components, such as total fertility and life expectancy at birth by sex. Population estimates and projections were carried out for a total of 233 countries or areas. Detailed results have been published for 201 countries or areas with 90,000 inhabitants or more in 2015; for the remaining 32 countries or areas that fell below that threshold, only total population and growth rates have been made available.

In order to ensure the consistency and comparability of estimates and projections within countries over time and across countries, certain steps were undertaken. Newly available demographic information was subjected to quality analyses and was also evaluated by analysing the impact of its incorporation on recent trends in fertility, mortality, or migration, and by comparing the simulated outcome with existing estimates of the population structure by age and sex at successive time intervals. With respect to the projection period, statistical techniques or general guidelines were used to determine the paths that fertility, mortality and international migration are expected to follow in the future. In some cases, deviations from these guidelines or default median probabilistic trajectories were required. This was mainly the case for the projection of net international migration and life expectancy at birth for selected countries and for some countries where the prevalence of HIV/AIDS was still relatively high in recent years.

This report first describes the way that the estimates were revised during the preparation of the *2015 Revision*. It then examines the approaches and assumptions used to project fertility, mortality and international migration up to the year 2100. The report also contains an overview of the variants used in generating the different sets of population projections as well as information on the probabilistic projection methods.

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I. THE PREPARATION OF POPULATION ESTIMATES

A. GENERAL ANALYTICAL STRATEGY AND DATA AVAILABILITY BY DEMOGRAPHIC COMPONENT

With each revision of World Population Prospects (WPP), the Population Division of the United Nations carries out a re-estimation of historical demographic trends for countries and territories of the world. These demographic estimates are based on the most recently available data sources, such as censuses, demographic surveys, registries of vital events, population registers and various other sources (e.g., refugee statistics). With each new data collection, the time series of fertility, mortality and migration, as well as population trends by age and sex, can be extended and, if necessary, corrected retrospectively. For countries with highly deficient demographic data, or many years without a census or demographic survey, the availability of new data can often lead to a reassessment of historical demographic trends.

For most countries in the more developed regions, the availability of detailed information on fertility and mortality trends over time and of periodic censuses of the population has greatly facilitated the task of producing reliable estimates of past population dynamics. Yet, even for these countries, the data on international migration flows was often deemed inadequate. In that regard, consistency between population counts and the components of population change was sometimes achieved by assigning to net international migration the residual population estimate obtained by comparing the actual intercensal population growth rate with independent estimates of natural increase based on estimates of fertility and mortality. Within this exercise, adjustments to population counts were also made if deemed to be warranted.

For most countries in the less developed regions, the estimation of past trends is usually more complex. In these countries, demographic information may be limited or lacking, and the available data are often unreliable. In numerous cases, therefore, consistency can only be achieved by making use of models in conjunction with methods of indirect estimation (Moultrie et al., 2013; United Nations, 1983, 2002). In extreme cases, when countries had no data referring to the past one or two decades, estimates were derived by inferring levels and trends from those experienced by countries in the same region with a socio-economic profile similar to the country in question. Since the 1970s the emphasis put on surveys and census-taking in the developing countries has considerably improved the availability of demographic information.

A listing of the data sources used and the methods applied in revising past estimates of demographic indicators (i.e., those referring to 1950-2015) is available online[2].

Following the UN Principles and Recommendations on Population and Housing Censuses (United Nations, 2008), most countries conduct a census about once per decade. Altogether more than 1,600 censuses have been conducted worldwide since the 1950s, providing a wealth of data for analysis and monitoring. When countries have conducted several censuses, the results can be analysed not only for each census independently but also by following cohorts as they age through time and are counted in successive censuses (Gerland, 2014; Heilig et al., 2009; Spoorenberg and Schwekendiek, 2012).

At the global level, population data from censuses or official estimates based on censuses, population registers and surveys referring to 2010 or later were available for 172 countries or areas, representing 74 per cent of the 233 countries or areas included in this analysis, and 83 per cent of the world's population. For 54 countries, the most recent population data available were from the period 2000-2009. For the remaining 7 countries, the year of the most recent data available ranged from 1975 in Somalia, to 1984 in the Democratic Republic of Congo and Eritrea, and to 1998 in Pakistan.

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[2] Data sources and related meta-information for the *2015 Revision* of the *World Population Prospects* are available for each country from the following web page: http://esa.un.org/unpd/wpp/DataSources/

Aside from relying on census information concerning the distribution of the population by age and sex, in order to estimate the population as of 1 July 2015, the base year of the projections, trends in fertility, mortality and international migration up to this date had to be established. Ideally, this was done on the basis of complete, sex-specific, annual time series of age-specific fertility rates, life tables and age-specific rates of net international migration. In practice, however, the amount of information available was usually less comprehensive. For developing countries, estimates of recent fertility and child mortality were often derived from surveys, especially for countries lacking a civil registration system or one without sufficient coverage of all vital events. For countries with a reliable civil registration system, as is the case in most developed countries and in some developing countries, data on both fertility and mortality by age and sex are theoretically available on a continuous basis. However, owing either to delays in data processing or to difficulties in estimating the appropriate denominators for the calculation of age-specific fertility or mortality rates, fertility schedules and life tables were only available for selected years. In preparing the revised estimates of the base-year population, such information was taken into account together with trends in other indicators, such as changes in the overall number of births. Depending on the availability of recent information in a given country, estimates for the period 2010-2015 or for the year 2015 are, in many cases, based on a short-term projection forward from earlier time periods with available data.

To provide some assessment of the timeliness of the information on which the *2015 Revision* is based, tables I.1a, b and c present information on the availability of recent fertility or mortality data in 201 countries or areas with 90,000 inhabitants or more in 2015. As table I.1a indicates, this revision incorporates, in most case, relatively recent direct or indirect information on fertility: out of the 201 countries or areas, 177 had information on fertility that referred to 2010 or later. This implies that information on recent levels of fertility was available for 96.5 per cent of the world's population. Similarly, for child mortality, measured by the probability of dying between birth and age five, the availability of information is mostly up to date. Information on child mortality from 2010 or later was available for 165 countries or areas, encompassing 92 per cent of the world's population (table I.1b).

TABLE I.1a. DISTRIBUTION OF COUNTRIES OR AREAS, AND THEIR POPULATIONS, ACCORDING TO THE MOST RECENT DATA USED FOR THE ESTIMATION OF FERTILITY

Topic and reference date	*Africa*	*Asia*	*Europe and Northern America*	*Latin America and the Caribbean*	*Oceania*	*Total*
			Number of countries or areas			
No Information	—	—	—	—	—	—
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	—	—	—	—
2000-2004	—	1	1	1	—	3
2005-2009	8	5	—	5	3	21
2010 or later	49	45	41	32	10	177
TOTAL	57	51	42	38	13	201
			Population (millions)			
No Information	—	—	—	—	—	—
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	—	—	—	—
2000-2004	—	1	0	0	—	1.5
2005-2009	130	110	—	9	9	258
2010 or later	1 056	4 282	1 096	625	30	7 089
TOTAL	1 186	4 393	1 096	634	39	7 348
			Percentage of the population			
No Information	—	—	—	—	—	—
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	—	—	—	—
2000-2004	—	0.0	0.0	0.0	—	0.0
2005-2009	11.0	2.5	—	1.4	23.3	3.5
2010 or later	89.0	97.5	100.0	98.6	76.7	96.5
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

TABLE I.1b. DISTRIBUTION OF COUNTRIES OR AREAS, AND THEIR POPULATIONS, ACCORDING TO THE MOST RECENT DATA USED FOR THE ESTIMATION OF CHILD MORTALITY (UNDER AGE 5)

Topic and reference date	*Africa*	*Asia*	*Europe and Northern America*	*Latin America and the Caribbean*	*Oceania*	*Total*
			Number of countries or areas			
No Information	1	—	—	—	—	1
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	1	—	—	1
2000-2004	—	1	—	—	—	1
2005-2009	16	9	—	4	4	33
2010 or later	40	41	41	34	9	165
TOTAL	57	51	42	38	13	201
			Population (millions)			
No Information	1	—	—	—	—	1
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	0	—	—	—
2000-2004	—	30	—	—	—	30
2005-2009	417	128	—	8	9	563
2010 or later	768	4 235	1 096	626	30	6 755
TOTAL	1 186	4 393	1 096	634	39	7 348
			Percentage of the population			
No Information	0.0	—	—	—	—	0.0
Before 1990	—	—	—	—	—	—
1990-1994	—	—	—	—	—	—
1995-1999	—	—	0.0	—	—	—
2000-2004	—	0.7	—	—	—	0.4
2005-2009	35.2	2.9	—	1.3	23.5	7.7
2010 or later	64.8	96.4	100.0	98.7	76.5	91.9
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

In contrast with the availability of information on fertility and child mortality, information on adult mortality is more sparse and more likely to be outdated (table I.1c). Data on adult mortality referring to 2010 or later were available for just 101 countries or areas, encompassing 54 per cent of the world's population, and data from 2005-2009 were available for an additional 26 countries or areas. Empirical data on age-specific mortality were unavailable or considered inadequate for the estimation of adult mortality in a quarter of all countries or areas, representing about 13 per cent of the world's population. Information was especially lacking or of insufficient quality among the countries of Africa. Consequently, life expectancy at birth was often derived by using recent information about infant and child mortality together with model life tables. In addition, official estimates of adult mortality were sometimes considered, but not necessarily used because their quality was deemed inadequate. Thus, table I.1c reflects the data that was actually used in this revision, not the universe of potentially available data. Furthermore, the demographic impact of the AIDS epidemic has been explicitly incorporated using a multi-state epidemiological model in countries with high levels of HIV prevalence (for further details, see p. 28). For selected countries, empirical adult mortality estimates were considered "post-facto" to validate modelled estimates, but were not used as actual inputs.

It is important to consider the implications of data availability on the quality of the population estimates and projections. One way of assessing the probable overall impact of the uncertainty involved in making estimates when empirical data are non-existent, inadequate or outdated is to calculate the proportion of the population to which the less reliable or outdated information refers. With regard to information on fertility and child mortality, the population of countries or areas that lacked data entirely or whose most recent estimates referred to periods before 2005 amounted to about 1.5 million and 31 million people, respectively, which is quite small in percentage terms. However, the populations lacking similarly recent estimates of adult mortality totalled more than a billion persons, or 16 per cent of the global population. Thus, the most serious weakness faced in producing the 2015 base-year estimates of the population by age and sex for each country was the lack of recent information on mortality, especially on adult mortality.

TABLE I.1c. DISTRIBUTION OF COUNTRIES OR AREAS, AND THEIR POPULATIONS, ACCORDING TO THE MOST RECENT DATA USED FOR THE ESTIMATION OF ADULT MORTALITY

Topic and reference date	*Africa*	*Asia*	*Europe and Northern America*	*Latin America and the Caribbean*	*Oceania*	*Total*
			Number of countries or areas			
No Information	33	7	—	5	5	50
Before 1990	—	—	—	1	—	1
1990-1994	1	6	—	2	1	10
1995-1999	1	2	1	—	1	5
2000-2004	5	2	—	—	1	8
2005-2009	8	10	—	6	2	26
2010 or later	9	24	41	24	3	101
TOTAL	57	51	42	38	13	201
			Population (millions)			
No Information	666	305	—	1	1	973
Before 1990	—	—	—	1	—	1
1990-1994	12	144	—	4	0	160
1995-1999	11	8	0	—	8	27
2000-2004	30	1 403	—	—	0	1 433
2005-2009	285	506	—	19	1	811
2010 or later	182	2 027	1 096	610	29	3 944
TOTAL	1 186	4 393	1 096	634	39	7 348
			Percentage of the population			
No Information	56.1	6.9	—	0.1	2.0	13.2
Before 1990	—	—	—	0.1	—	0.0
1990-1994	1.0	3.3	—	0.7	0.4	2.2
1995-1999	0.9	0.2	0.0	—	19.5	0.4
2000-2004	2.5	31.9	—	—	0.7	19.5
2005-2009	24.0	11.5	—	2.9	3.8	11.0
2010 or later	15.4	46.1	100.0	96.2	73.6	53.7
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0

A final consideration in the revision of past estimates of population dynamics concerns the sources of information regarding international migration. In preparing this revision, 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, and to data about refugee stocks and flows prepared by the Office of the United Nations High Commissioner for Refugees. Even by combining these various data sources, it was difficult to produce comprehensive and consistent estimates of net migration over time. Therefore, in several cases, net international migration was estimated as the residual not accounted for by natural increase between successive census enumerations. The paucity of reliable and comprehensive data on international migration is an important limitation to producing more accurate population estimates.

B. Major analytical steps used to estimate populations by age and sex, fertility, mortality, and migration between 1950 and 2015

One of the major tasks in revising the estimates and projections of each country of the world is to obtain and evaluate the most recent information available on each of the three major components of population change: fertility, mortality and international migration. In addition, newly available census information or other data providing information on the age distribution of the population should also be evaluated. However, this process of updating and revising population estimates typically entails not only the separate evaluation of the quality of the different estimates available, but also - and more importantly - the search for consistency among them. The key task is therefore to ensure that for each country past trends of fertility, mortality and international migration are consistent with changes in the size of the population and its distribution by age and sex. The overall analytical approach used in the *2015 Revision* consisted of four major steps:

1. *Data collection, evaluation and estimation*: Analysts collect available data from censuses, surveys, vital and population registers, analytical reports and other sources for a given country[3]. These data are reviewed and used to estimate populations by age and sex, fertility, mortality and net international migration components. However, for many countries of the less developed regions, empirical demographic information may be limited or lacking and the available data can be unreliable. In these cases, models and indirect measures of fertility and mortality estimation have also been used to derive estimates. Typically, analysts assemble a collection of estimates from various sources for each component. In many cases, estimates derived from different sources or based on different modelling techniques can vary significantly, and all available empirical data sources and estimation methods should be compared. Various techniques have been used to identify the most likely time-series of fertility, mortality and international migration data.

   An example of this process of data collection, comparison and re-evaluation is shown in figure I.1, which plots various series of total fertility estimates for Nigeria available in preparing the *2010*, *2012* and *2015 Revisions*. As can be observed in figure I.1, as new information became available, the more recent trends of fertility were updated across revisions. The data shown in blue and purple represent all empirical evidence considered in deriving total fertility estimates for the period 1970-1975 to 2010-2015 in Nigeria that were available at the time of the *2010 Revision*. Multiple data sources were considered, and one or multiple estimation methods were used to derive fertility estimates from each source. These methods included: (a) direct estimates based on maternity-history data adjusted for underreporting from the 1981-1982 Nigeria World Fertility Survey (WFS), 1990, 1999, 2003 and 2008 Demographic and Health Surveys (DHS), (b) recent births in the preceding 12 months (or 36 months) by age of mother, from these surveys and from the 1971-1973 National Fertility, Family Planning and Knowledge, Attitudes and Practices survey, 1991 census, 2000 Nigeria Sentinel Survey, 2007 Multiple Indicator Cluster Survey (MICS 3); (c) adjusted fertility using Brass P/F ratio (United Nations, 1983) and data on children ever born from these sources; and, (d) cohort-completed fertility[4] from these surveys and censuses, and the 1995 MICS and 1999 MICS2 surveys.

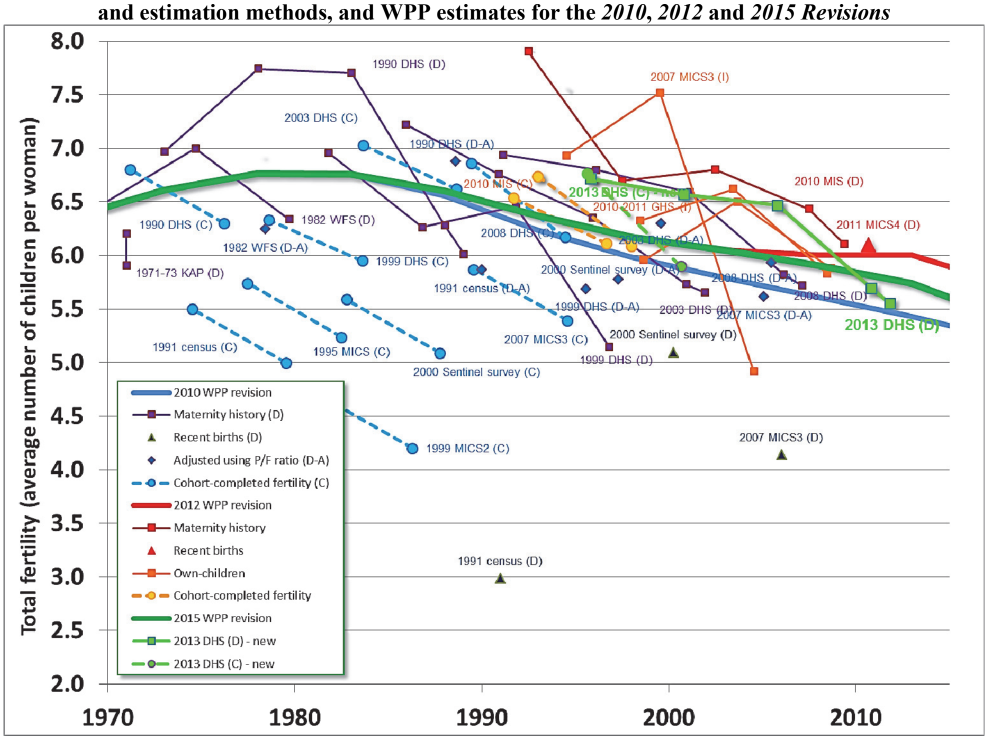
   In the *2012 Revision*, results from several new surveys became available and were considered in addition to those previously used. Specifically, the 2010 Malaria Indicator Survey (MIS) provided maternity-history data covering the retrospective period 1990-2010, the 2011

[3] Traditionally, the data are provided by the UN Statistics Division (Demographic Yearbook), Regional Commissions (e.g., ECLAC), other UN agencies (e.g., WHO, UNICEF, UNAIDS) and by international databases (e.g., Human Mortality Database, Human Fertility Database), as well as microdata archives (e.g., DHS, MICS, IPUMS-International). Ideally, each new dataset for a country would include a census population by single or abridged age groups and sex, a recent life table, age-specific fertility rates, and net-migration by age and sex.

[4] Using Ryder's (1964, 1983) correspondence between period and cohort measures, the mean number of children ever born (CEB) to a cohort is used to approximate the period total fertility rate at the time this cohort was at its mean age at childbearing. See Feeney (1995, 1996) for further details about time translation of mean CEB for women age 40 and over.

Multiple Indicator Cluster Survey (MICS4) provided fertility for the 12-months preceding the survey, and microdata available for the MICS4 survey as well as the previous 2007 Multiple Indicator Cluster Survey (MICS3) and 2010-2011 General Household Survey (GHS) enabled the computation of indirect fertility estimates using the own-children method. These additional estimates, shown in red and orange in figure I.1, were the basis for increasing estimated fertility levels in the *2012 Revision*. When the *2015 Revision* was prepared, new data had become available from the 2013 DHS providing retrospective fertility information for the previous 25 years, and it was deemed necessary to revise downward the estimates of fertility for more recent periods (green line). These modifications in the more recent fertility levels also had implications for the projected fertility trends and associated projected populations.

Figure I.1. Total fertility estimates for Nigeria, 1970-2015, based on various data sources and estimation methods, and WPP estimates for the *2010*, *2012* and *2015 Revisions*



NOTE: This figure illustrates the "cloud" of empirical estimates of the total fertility rate derived from different data sources in Nigeria. The thick solid lines – in blue, red and green - represent the assessments from the *2010, 2012 and 2015 Revisions*, respectively. Overall, as new information became available, the more recent estimates of fertility were revised. With the incorporation of the results of the 2013 DHS, the fertility levels in Nigeria were estimated to be lower in the *2015 Revision*, as compared to the *2012 Revision*, throughout the more recent years.

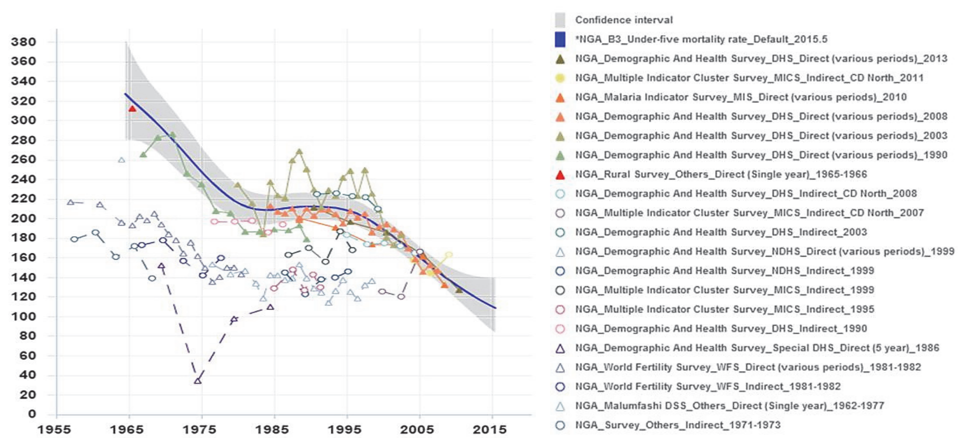
In a similar manner, analysts may re-evaluate intercensal demographic trends for each component of demographic change for the estimation period of 1950-2015. This process has required the consolidation of empirical evidence ideally back to 1950 or even earlier. In many instances, some of this information was missing or only available through retrospective sources. As was demonstrated in figure I.1, different data sources as well as different analytical methods can produce substantially different estimates of underlying rates, and frequent non-sampling errors can bias series in systematic ways. To address these various challenges, trends by age and sex (or overall summary indices like $_5q_0$ and $_{35}q_{15}$ or $_{45}q_{15}$[5] when time series of age-specific mortality rate were unavailable) were generated either through expert-based opinion reviewing and weighting each observation analytically, or, in more

[5] $_5q_0$ refers to under-five mortality, that is, the probability of dying between birth and age 5. $_{35}q_{15}$ *and* $_{45}q_{15}$ are the probabilities of dying between age 15 and 50 and 15 and age 60, respectively, conditional on survival to age 15. These are commonly used summary indices of adult mortality.

recent years, using automated statistical methods (for example, pooled analysis using Loess (local regression) or cubic splines with analytical weights (Obermeyer et al., 2010; Rajaratnam et al., 2010; Wang et al., 2012), or by using a bias-adjusted data model to control for systematic biases between different types of data (Alkema and New, 2013; Alkema et al., 2012)).

The overall analytical approach used to measure under-five mortality in the *2015 Revision* followed that of the United Nations Inter-agency Group for Child Mortality Estimation (IGME) (Hill et al., 2012; You et al., 2015), which fitted a robust trend through the various data sources. Further details about the methodology for estimating child mortality and detailed set of series included in the analysis are publicly available for all countries at http://www.childmortality.org. As an example, figure I.2 provides an overview of the underlying empirical estimates for Nigeria, which were used to derive child mortality ($_5q_0$) estimates for both sexes combined. Note that the various series represented by dashed lines were excluded from the analysis due to their lack of reliability or national representativity.

Figure I.2. Estimates of under-five mortality for Nigeria, 1955-2015, derived by using various data sources and estimation methods, with IGME fitted trend



Source: www.childmortality.org

To estimate sex-specific under-five mortality, the analysis and modelling of time trends used the sex ratio of mortality for $_1q_0$ and $_5q_0$ (Alkema et al., 2014) due to the smaller number of observations available for sex-disaggregated mortality. Estimated sex differentials were applied to the mortality for both sexes combined to obtain $_1q_0$ and $_5q_0$ by sex, with $_4q_1$ derived as a residual[6].

For adult ages, age and sex-specific mortality rates (or summary indices of adult mortality such as $_{35}q_{15}$ or $_{45}q_{15}$) were analysed using a variety of data sources and estimation methods based on data availability and reliability (Hill, Choi and Timaeus, 2005; Masquelier, 2012; Moultrie et al., 2013; Obermeyer et al., 2010; Rogers and Crimmins, 2011; United Nations, 1983, 2002). For example, figure I.3 shows estimates of female adult mortality in Senegal based on various data sources and estimation methods. These various sets of estimates can be roughly categorized into four types: (a) model-based, (b) direct estimates (e.g., household deaths, survival from sibling histories), (c) indirect estimates (e.g., paternal and maternal orphanhood methods) and (d) small areas. If all estimation methods and data sources were internally consistent, all estimates should agree but as seen through the plots in figure I.3, the reality is quite complex and estimates are often biased.

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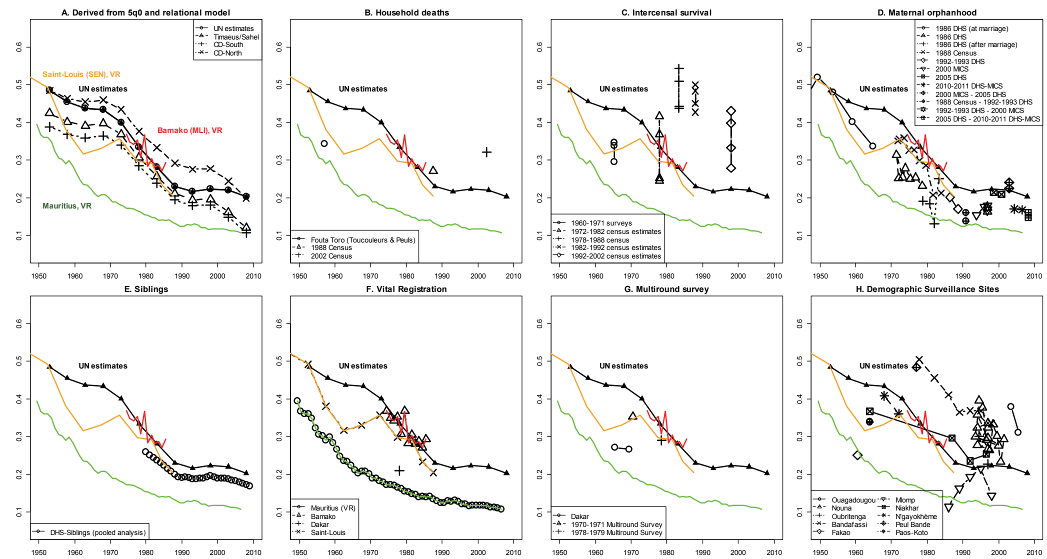
[6] Child mortality is computed as $_4q_1 = 1 - \frac{l_5}{l_1} = 1 - \frac{(1 - {_5q_0})}{(1 - {_1q_0})}$.

Figure I.3. Estimates of female adult mortality for Senegal derived by using various data sources and estimation methods



NOTE: Estimates of female adult mortality ($_{45}q_{15}$) for Senegal were derived using the implied relationship between child mortality and adult mortality of the North model of the Coale-Demeny Model Life Tables in the 1950s, but were assumed to converge over time towards the South model of Coale and Demeny by the 1990s (panel A). In addition, recent data on household deaths from the 1988 and 2002 censuses (panel B) and the 1978-1979 Multiround Survey (panel G) were also considered, together with estimates from data on parental orphanhood from these censuses and surveys (panel D) and estimates from DHS siblings survival (panel E). Intercensal survivorship from successive census age distributions (smoothed and unsmoothed) for periods 1976-1988 and 1988-2002 (panel C) was reviewed but excluded from the analysis due to lack of reliability. Data from urban vital registration (panel F) and West African rural demographic surveillance sites (Panel H) were also considered.

2. *Further evaluation and adjustments*: After the initial compilation and trend line determination, the data were evaluated for geographical completeness and demographic plausibility. Post-enumeration surveys were used if available to evaluate the quality of census data. If necessary, adjusted data were obtained from national statistical offices or adjustments were applied by analysts of the United Nations Population Division using standard demographic techniques, such as for under-enumeration of young children or age-heaping using smoothing.

   In the case of mortality, for countries with nationally representative but incomplete death registration, adult death registration data were typically evaluated (and adjusted if necessary) using death distribution methods[7] for various combinations of age groups, and with smoothed or unsmoothed census age distributions. When available, the relationship between $_5q_0$ and $_{45}q_{15}$ (or other similar summary indices) by sex was used for the purposes of additional validation against reference mortality datasets such as the Human Mortality Database (Gerland, 2014).

   Mortality rates at older ages (e.g., 85 and over) often required additional smoothing or adjustment using the Kannisto model of old-age mortality (Thatcher, Kannisto, and Vaupel, 1998) fitted on data from age 75 onward. Old age mortality rates were adjusted[8] if necessary to insure consistency (a) by age (monotonic increase), (b) by sex over time (monotonic decline) and (c) between sex by period (male greater or equal to female).

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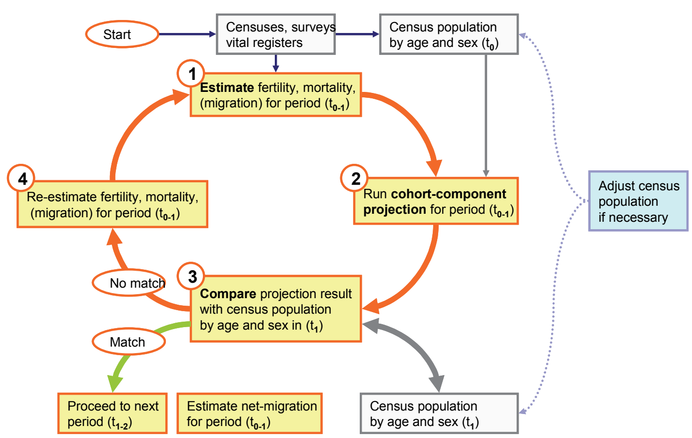
[7] Generalized growth balance (GGB) method, the synthetic extinct generations (SEG) method (i.e., Bennett-Horiuchi unadjusted and adjusted for census coverage change) and a hybrid of the two approaches (GGB/SEG).

[8] Especially for earlier periods with more deficient old age mortality data (e.g., 1950-1980 in some countries), mortality rates at age 75 and over were adjusted using the average rate of mortality increase by age based on the historical experience of the Human Mortality Database (University of California, Berkeley (USA), and Max Planck Institute for Demographic Research (Germany). Available at www.mortality.org for countries at similar levels of mortality.

For countries where no, or only minimal, demographic information was available, demographic models were used to estimate fertility, mortality and migration. Estimates contained in previous *World Population Prospects* were carefully reviewed and, if necessary, were revised based on the new data.

3. *Consistency checking and cross-validation*: The previous steps provided initial sets of independent estimates for each demographic component (population, fertility, mortality, and migration). However, the methods used focus on only one demographic component (such as fertility or mortality) without taking into account the interaction with the other demographic components. A further check on the estimates occurs when the separate estimates for fertility, mortality and migration are integrated into a cohort-component projection framework where these demographic rates are simultaneously applied to a base population in order to compute subsequent populations by age and sex. Typically, population "projection" uses vital rates and migration to project populations by age and sex from a baseline year, denoted t_0, forward in time. In its simplest form, the population in year t+n, $t_0 \leq t \leq t+n$, equals the population in year t plus the intervening births and net migration, minus the intervening deaths (Preston, Heuveline and Guillot, 2001; Whelpton, 1936). This is known as the demographic balancing relationship.

Figure I.4. Process used to ensure intercensal consistency between demographic components and populations

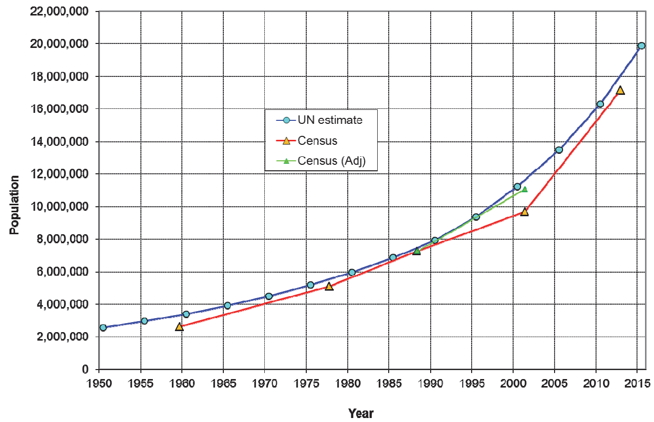


NOTE: The diagram above illustrates how individual estimates of fertility, mortality and net-migration were subjected to tests of internal consistency using a cohort-component projection framework for the period between t_0 and t_1. This procedure has been applied in each new revision of the *World Population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

The estimates obtained from steps 1 and 2 were subjected to a series of checks whereby the relationship between the enumerated populations and their estimated intercensal demographic components (fertility, mortality, migration) was tested for internal consistency. For countries where several censuses were available, intercensal consistency was analysed by projecting the population between census years using the initial estimates for fertility, mortality and migration obtained in steps 1 and 2. If the population by age and sex of the subsequent censuses could not be matched by the projection, adjustments for one or more demographic components were made (figure I.4). In some cases the initial starting population itself was revised appropriately after back-surviving cohorts from one or multiple censuses with more plausible results. Projection consistency was achieved through an iterative step-by-step "project-and-adjust" process from one census to the next, and considered altogether to insure optimal overall intercensal cohort consistency.

The validation with enumerated census populations can be conducted on the overall total as seen in figure I.5 for Niger plotting the total population by year as enumerated in each census (red line with yellow triangles), adjusted for net-omissions by age and sex using post-enumeration surveys (green line with triangles), and based on the United Nations estimated reconstruction using an initial 1950 base population and subsequent trends in fertility, mortality and international migration.

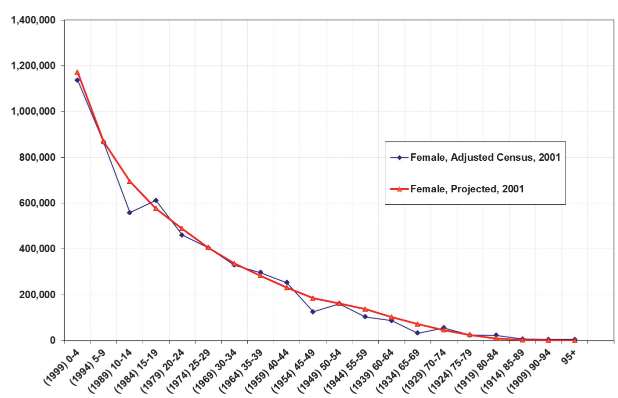
Figure I.5. Total population, Niger: comparison of United Nations estimates and the enumerated and adjusted populations from various censuses



NOTE: The UN estimates for Niger are consistent with data from the 1977, 1988 and 2001 censuses (after adjustment for under-enumeration), with the provisional totals from the 2012 census, and with estimates of the associated trends in fertility, mortality and international migration.

Further validation was conducted by comparing the population distribution by age and sex enumerated in each census with the reconstructed estimates produced by the United Nations Population Division. Figure I.6 provides a comparison of the female population for Niger plotted by 5-year age groups (and selected birth cohorts in parentheses) as enumerated in 2001 census (line with diamonds), and the United Nations reconstructed estimate (line with triangles) using an initial 1950 base population and subsequent trends in fertility, mortality and net international migration.

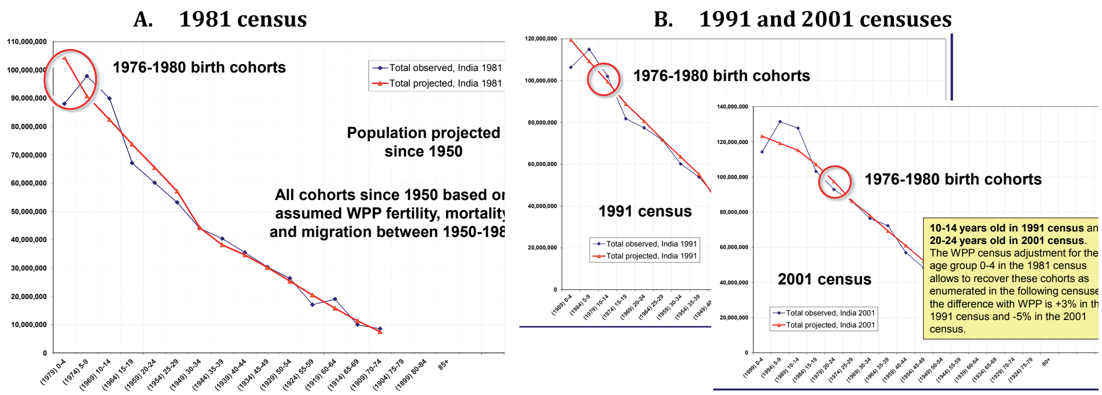
Figure I.6. Comparison of United Nations estimates of female population size and adjusted 2001 census data by age group for Niger



NOTE: This figure illustrates the degree of fit between the official adjusted population from the 2001 census and the United Nations estimate for 2001 based on a projection starting in 1950. Particular care was taken to ensure that the projected population matched closely the census population in the first two age groups (0-4 and 5-9). The closeness of the match suggests that the adjusted UN fertility estimates are probably accurate for the 10 years prior to the 2001 census. Moreover, the figure suggests that the UN fertility and mortality estimates for the past 50 years are fairly consistent with the census cohorts. The differences at ages 10-14 and 45-49 are probably due to age-reporting errors in the census affecting those age groups.

When multiple successive censuses are available, like in the case of India for example, it is possible to track cohorts over time. This information can be used to assess the degree to which an apparent under-enumeration of children under the age of five reflected a real reduction in the size of the birth cohort or whether it was the result of age misreporting or date omission problems (Gerland, 2014). As seen in figure I.7, the size of the 1976-1980 birth cohorts in India as enumerated in 1981 census (panel A) was compared with the number of 10-14 year olds in the 1991 as well as the number of 20-24 year olds in the 2001 census (panel B). Based on the UN adjusted estimates for the age group 0-4 (as compared to the 1981 census), the subsequent "projected" sizes of these adjusted cohorts are fairly close to the enumerated populations in corresponding age groups in the 1991 and 2001 censuses. This suggests that the systematic under-enumeration of children under the age of 5, together with some over-reporting of children age 5-9 and 10-14, is a reporting artefact that disappears once children reach older ages.

Figure I.7. Comparison of 1976-1980 birth cohorts enumerated in the 1981, 1991 and 2001 censuses of India and *2012 Revision* estimates based on a 1950 population reconstruction



NOTE: India 1976-1980 birth cohorts (circled) enumerated in 1981, 1991 and 2001 censuses (line with diamond) compared to projected cohorts based on WPP reconstruction (line with triangles) using an initial 1950 base population and subsequent trends in fertility, mortality and international migration.

4. *Checking consistency across countries*: Once all the 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. "Outliers" and "crossovers" were identified and, if deemed necessary, further checks were applied to validate the preliminary estimates. An important component of the work at this stage was ensuring the consistency of information on net international migration, which for each 5-year period must sum to zero at the world level.

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II. THE PREPARATION OF POPULATION PROJECTIONS

The Population Division has employed the cohort-component projection method for producing individual country projections since the *1963 Revision*. This method, the most common projection method used by demographers, provides an accounting framework for the three demographic components of change — fertility, mortality and international migration — and applies it to the population in question. Technically, it is not a complete projection method on its own, as it requires that the components of change — fertility, mortality and migration — be projected in advance. Rather, it is an application of matrix algebra that enables demographers to calculate the effect of assumed future patterns of fertility, mortality, and migration on a population at some given point in the future (see Preston et al., 2001).

In the *2015 Revision*, the future population of each country was projected from 1 July 2015 (by comparison, a projection base year of 2010 was used for the *2012 Revision*). Because population data for that date were not available for all countries or areas of the world, the 2015 estimate was derived from the most recent population and demographic data available, as described in part I. To project the population until 2100, various assumptions were made regarding future trends in fertility, mortality and international migration. Because the future is uncertain, a number of different projection variants were produced to convey the sensitivity of the projections to changes in the underlying assumptions. The following paragraphs summarize the assumptions used for each variant.

A. Fertility assumptions: convergence toward low fertility

The fertility assumptions are described in terms of the following groups of countries:

- *High-fertility countries*: Countries that until 2015 had no fertility reduction or only an incipient decline;
- *Medium-fertility countries*: Countries where fertility has been declining but whose estimated level is above 2.1 children per woman in 2010-2015;
- *Low-fertility countries*: Countries with total fertility at or below 2.1 children per woman in 2010-2015.

1. Medium-fertility assumption

The *2015 Revision* of the *World Population Prospects* used the same probabilistic method for projecting total fertility as the *2012 Revision* with two notable enhancements. First, the new revision of the model has incorporated the latest information from the 2010 round of censuses as well as from newly-available surveys. Second, the approach used to project the age pattern of fertility was revised, leading to a uniform method that is used for all countries of the world.

a. Overall approach

There is a general consensus that the historical evolution of fertility includes three broad phases (see figure II.1 and further details below): (i) a high-fertility, pre-transition phase, (ii) a fertility transition phase, and, (iii) a low-fertility, post-transition phase. During the third, or post-transition, phase, it is assumed that fertility will fluctuate around or below 2.1 children per woman. The past fertility trends for all countries and areas were re-evaluated and re-estimated for the *2015 Revision* using the most recent empirical evidence from censuses, surveys, registers and other sources, taking into account all information available and conducting internal checks for consistency by tracking changes in cohort size between successive censuses.

The probabilistic method used in the *2015 Revision* builds on models of fertility change developed in earlier revisions. In several past revisions of the *World Population Prospects*, it was assumed that countries in the transition from high to low fertility would ultimately approach a fertility floor of 1.85 children per woman, regardless of their current position in the fertility transition. The transition from the current level of fertility to the fertility floor was expressed by three models of fertility change over time. These fertility projection models were formalized starting in the *2004*

Revision using a double-logistic function, defined by six deterministic parameters (United Nations, 2010). For countries that had already reached a fertility level below 2.1 children per woman, a much simpler model of fertility change was used. In general, it was assumed that fertility would recover at a uniform pace from very low levels of fertility, eventually converging to a fertility level of 1.85 children per woman, just as in the high and medium fertility countries.

The assumption of a fixed ultimate fertility level at a value of 1.85 is no longer used as part of the United Nations population projections. Rather, the probabilistic method used in the 2015 *Revision* for projecting total fertility consisted of two separate steps, as described below.

In the first step, models were constructed to describe the sequence of change from high to low fertility (phase II of the fertility transition, see figure II.1). For countries undergoing a fertility transition, the pace of the fertility decline was characterized by a systematic decline combined with various random distortions. The pace of the systematic decline in total fertility was 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 (BHM), which resulted in country-specific *distributions* for the parameters of the decline. These distributions were informed by historical trends within the country, as well as by the variability of historical fertility trends across all countries that have already experienced a fertility decline. This approach made it possible not only to take into account the historical experience of each country, but also to gauge the degree of uncertainty about the pace of future fertility decline based upon the past experience of other countries when they were at similar levels of fertility. Within this model, the pace of decline and the limit to which fertility was able to 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 (namely, the world's experience according to the information for all countries) was used to inform the statistical distributions of the parameters of the double-logistic function. This approach is particularly important for countries at the beginning of their fertility transition, for which limited information exists regarding the speed of fertility decline. In such cases, future potential trajectories of fertility were informed mainly by the world's experience, including the variability of such experience, amongst countries at similar levels of fertility in the past. The Bayesian statistical approach is suitable for estimating the parameters of a double-logistic model even when the number of empirical observations for a country is very limited.

The second component of the projection model concerns countries that have completed the demographic transition and reached Phase III of low fertility (see figure II.1). For these countries, a time series model was used to project fertility on the assumption that fertility in the long run would approach and fluctuate around country-specific ultimate levels based on a Bayesian hierarchical model (Raftery et al., 2014). The time series model used the empirical evidence from low-fertility countries that have experienced fertility increases from a sub-replacement level following a historic fertility decline. Thus, future long-run fertility levels in the *2015 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. This approach not only enables a better accounting of the historical experience of each country but also reflects the variability in historical fertility trends of all low-fertility countries and the uncertainty about the pace of a potential fertility recovery and long-run fertility levels. The world mean parameter for the country-specific asymptotes was restricted to be no greater than a fertility level of 2.1 children per woman[9].

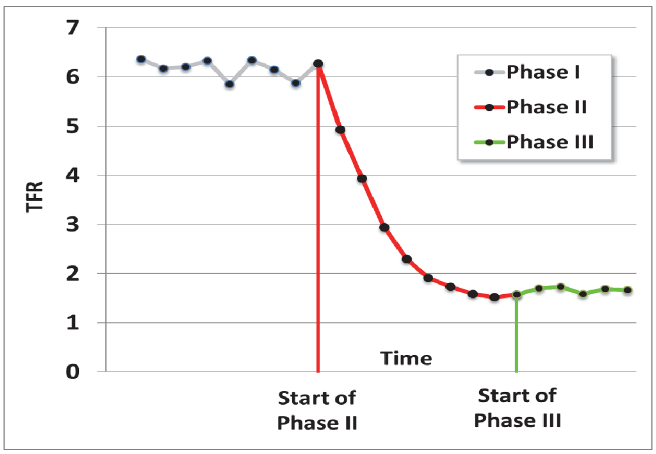
While the long-term assumption of a fertility increase is supported by the experience of many low-fertility countries in Europe and East Asia (Bongaarts and Sobotka, 2012; Caltabiano, Castiglioni, and Rosina, 2009; Goldstein, Sobotka and Jasilioniene, 2009; Myrskylä, Goldstein and Cheng, 2013; Myrskyla, Kohler and Billari, 2009; Sobotka, 2011), this new approach additionally draws upon the specific experience of each country. With this method, countries that have experienced extended

[9] 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.

periods of low fertility with no empirical indication of an increase in fertility were projected to continue at low fertility levels in the near future. This assumption is supported by research on the "low fertility trap hypothesis" for some low-fertility countries of Europe (Lutz, 2007; Lutz, Skirbekk and Testa, 2006) and East Asia (Basten, 2013; Frejka, Jones and Sardon, 2010; Jones, Straughan and Chan, 2008).

The two modelling processes described above are represented in figure II.1. During the observation period, the start of Phase II was determined by examining the maximum total fertility. The start of Phase II was deemed to occur before 1950 for countries where this maximum is less than 5.5, and in the period of the local maximum for all other countries. The end of Phase II during the observation period was defined as the midpoint of the time periods when the first two successive increases were observed, once the level of total fertility was below 2 children per woman. If no such increase was observed; a country was treated as still being in Phase II.

Figure II.1. Schematic phases of the fertility transition



Phase I: High-fertility, pre-transition phase. Not modelled.

Phase II. Fertility transition phase, modelled by double-logistic function using a Bayesian hierarchical model.

Phase III. Low-fertility, post-transition phase, modelled with a first-order auto-regressive time series model, AR(1), in a Bayesian hierarchical framework.

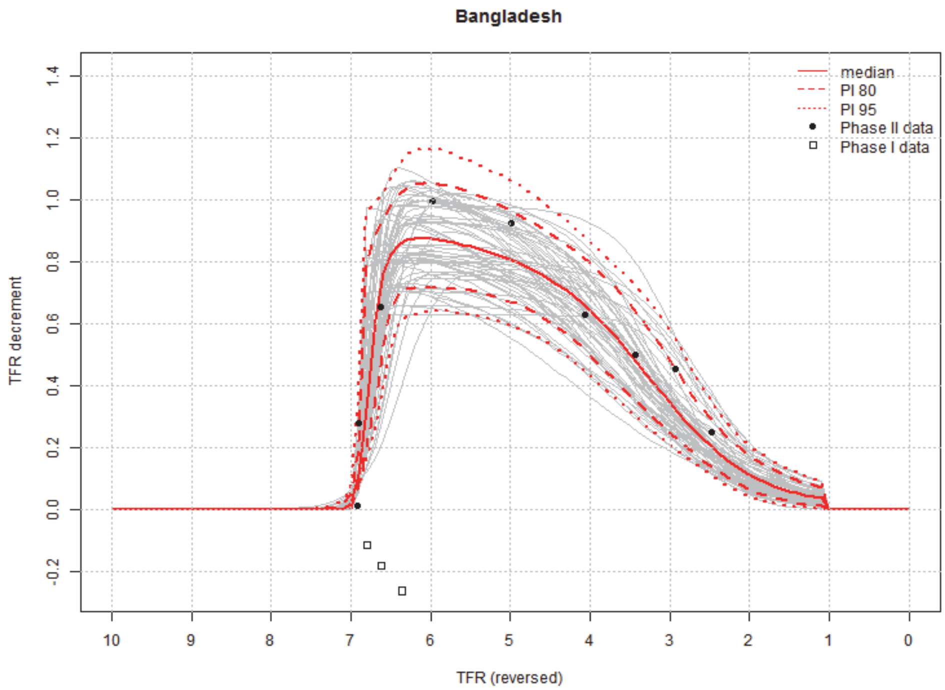
To construct projections for all countries still in Phase II, the Bayesian hierarchical model was used to generate 600,000[10] double-logistic curves for all countries that have experienced a fertility decline (see example in figure II.2), representing the uncertainty in the double-logistic decline function of those countries[11]. This sample of double-logistic curves was then used to calculate 600,000 total fertility projections for all countries that had not reached Phase III by 2010-2015. 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.

For a trajectory that has fallen to a level around or below replacement-level fertility, and where there is evidence of a fertility increase over two successive time periods, future changes were calculated using a time series model of fertility recovery informed by the experience of countries that have followed similar patterns in the past.

Ever since the *2010 Revision*, the assumption of a long-run fertility level of 1.85 children per woman has not been used. Rather, in recent revisions the projected level of total fertility has been allowed to fall *below* that threshold, reflecting uncertainty with regard to the historic minimum level of fertility (at the end of Phase II) before the start of a recovery (in Phase III). The pace of fertility change, as well as the level and timing when Phase II stops and Phase III starts, varies for each of the 600,000 projected fertility trajectories for a country that has not reached Phase III by 2010-2015. 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 2010-2015, the time series model for that phase is used directly.

[10] Actually ten simulations are run in parallel with 62,000 iterations performed for each simulation, and the first 2,000 are discarded.
[11] Graphs of this double-logistic curve are available online at: http://esa.un.org/unpd/wpp/Graphs/Probabilistic/FERT/CHG/

Figure II.2. Total fertility decrements and prediction intervals of estimated double-logistic curve for Bangladesh (systematic decline part)



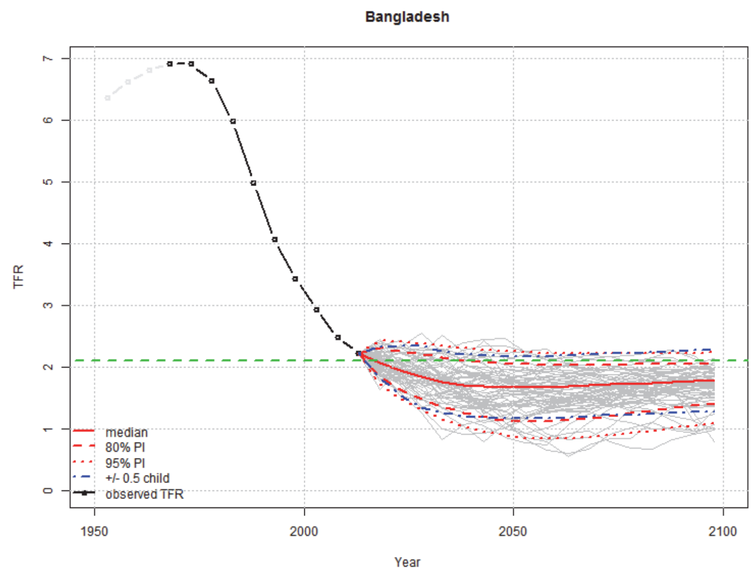
NOTE: Observed five-year decrements by level of total fertility are shown as black dots. For clarity, only 60 trajectories of the 600,000 calculated are shown here. The median projection is the solid red line, while the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines, respectively.

By systematically sampling one in ten of the 600,000 simulated trajectories produced by this process, the end result was 60,000 projected trajectories of total fertility for each country. The median of these 60,000 trajectories is used as the medium fertility variant projection in the *World Population Prospects*. To express the uncertainty surrounding future trends in fertility, 80 and 95 per cent prediction intervals were also calculated (see figure II.3 for Bangladesh; additional tables[12] and graphs[13] are available online for all countries). For countries that had not reached Phase III by 2010-2015, the projected median trajectory reflects the uncertainty as to when the fertility transition will end and at which level.

[12] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online tables of stochastic projections of total fertility: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/

[13] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of projections of total fertility: median, 80% and 95% prediction intervals, high and low WPP fertility variants; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/FERT/TOT/

Figure II.3. Probabilistic trajectories of projected total fertility (2015-2100) for Bangladesh



NOTE: For clarity, only 60 trajectories of the 60,000 calculated are shown here. The median projection is the solid red line, while the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines, respectively. The high- and low-fertility variants of the *2015 Revision* correspond to +/- 0.5 child around the median trajectory, shown here as blue dashed lines. The replacement-level of 2.1 children per woman is plotted as green horizontal dashed line only for reference.

b. Caveat about medium-high fertility countries experiencing slower declines than expected

The *2015 Revision* has drawn on new empirical evidence on fertility levels and trends that became available since the publication of the *2012 Revision*. The empirical evidence from available surveys and the 2010 round of censuses has provided the basis for a reassessment of fertility levels and trends experienced within the last decade. In a number of countries, particularly in Africa, new data sources have provided evidence of slower-than-expected fertility declines or even a stalled decline; in some cases, increases of total fertility have also been identified. Such patterns have been observed across different revisions and require extra attention.

The fertility projections for sub-Saharan Africa follow the general path from high to low fertility observed in other regions. More specifically, the trajectories are informed by the fertility changes observed since 1950 in countries of Asia and Latin America and the Caribbean, as well as in other African countries that were more advanced in the process of fertility transition. However, this assumption may be overly optimistic in the face of some recent empirical evidence (Bongaarts and Casterline, 2013). The assumption implies that, in the long run, all sub-Saharan African countries will follow the same general path from high to low fertility that was experienced in other regions, albeit at a slower pace and potentially driven by a different combination of factors (with regard to patterns of female education, union formation, length of birth intervals, ideal number of children, adoption of modern contraceptive methods and so on).

The fertility projections produced in the *2015 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. Should massive efforts to scale up family planning information, supplies and services be realized, then the median fertility projections may be too high. On the other hand, 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.

c. *Long-term ultimate fertility level once countries reach low fertility*

Empirical evidence suggests that 38 countries or areas with total fertility levels below 2.1 children per woman at some point between 1950 and 2015 have experienced slight increases in fertility after they had reached their lowest level. The *2015 Revision* did not impose any long term convergence toward a level of 2.1 children per woman. Future long-run fertility levels were determined for each country individually, informed by statistical distributions incorporating the empirical experience of all low-fertility countries that had experienced an increase of fertility in at least two consecutive periods. Further details about the methodology are contained in Alkema et al. (2011) and Raftery et al. (2014).

d. *Projection of the age pattern of fertility*[14]

Once the path of future total fertility was determined, age-specific fertility rates by five-year age group consistent with the total fertility for each quinquennium were calculated. In the *2015 Revision* a new standard approach was used to project age-specific patterns of fertility for all countries. Beginning from the most recent observation of the age pattern of fertility in the base period of projection, the projected age patterns of fertility are based on past national trends combined with a trend leading toward a global model age pattern of fertility[15] (Ševčíková et al., 2015). The projection method was implemented on the proportionate age-specific fertility rates (PASFR) with seven age groups from 15-19 to 45-49.

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

(a) A first preliminary projection, assuming that the PASFRs converge to the global model pattern; and

(b) A second preliminary projection, assuming that the observed national trend in PASFRs continues into the indefinite future.

The method is applied to all the trajectories that make up the probabilistic projection of the total fertility rate for all countries, based on the historical data used in the *2015 Revision*.

It was assumed that the transition from the most recent age pattern of fertility to the global model age pattern of fertility is dependent on the timing when the total fertility rate (TFR) enters Phase III, i.e. when the fertility transition is completed and a given country trajectory reaches its lowest level of fertility. For countries in Phase III, a time series model to project the TFR was used, based on an assumption that in the long run fertility would approach and fluctuate around country-specific ultimate fertility levels determined by a Bayesian hierarchical model (Raftery et al., 2014).

2. High-fertility assumption

The *2015 Revision* retains a number of standard variants that are used to illustrate the effects of certain fertility assumptions when applied to all countries simultaneously. Under the high variant, fertility is projected to remain 0.5 children above the fertility in the medium variant over most of the projection period. To insure a smoother transition between the baseline period (2010-2015) and the high variant, fertility in the high variant is initially +0.25 child in the first projection period (2015-2020), +0.4 child in the second projection period (2020-2025), and +0.5 child thereafter. By 2025-2030, fertility in the high variant is therefore half a child higher than that of the medium variant. That is, countries reaching a total fertility rate of 2.1 children per woman in the medium variant have a total fertility rate of 2.6 children per woman in the high variant.

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[14] This section is based on Ševčíková et al., 2015. For more details, please refer to the working paper: https://www.csss.washington.edu/Papers/2015/wp150.pdf

[15] The global model pattern in this revision is based on an unweighted average of PASFRs for selected low fertility countries that have already reached their Phase III, and represent later childbearing patterns with mean age at childbearing close to or above 30 years in 2010–2015: Austria, Czech Republic, Denmark, France, Germany, Japan, Netherlands, Norway, and Republic of Korea.

3. Low-fertility assumption

Under the low variant, fertility is projected to remain 0.5 children below the fertility in the medium variant over most of the projection period. To insure a smoother transition between the baseline period (2010-2015) and the low variant, fertility in the low variant is initially -0.25 child in the first projection period (2015-2020), -0.4 child in the second projection period (2020-2025), and -0.5 child thereafter. By 2025-2030, fertility in the low variant is therefore half a child lower than that of the medium variant. That is, countries reaching a total fertility rate of 2.1 children per woman in the medium variant have a total fertility rate of 1.6 children per woman in the low variant.

4. Constant-fertility assumption

As the name implies, under the constant-fertility variant, fertility in all countries remains constant at the level estimated for 2010-2015.

5. Instant-replacement assumption

Under the instant-replacement variant, for each country fertility is set to the level necessary to ensure a net reproduction rate of 1 starting in 2015-2020. Fertility varies over the remainder of the projection period in such a way that the net reproduction rate always remains equal to one thus ensuring, over the long-run, the replacement of the population[16].

B. MORTALITY ASSUMPTIONS: INCREASING LIFE EXPECTANCY FOR MOST COUNTRIES

1. Normal-mortality assumption

Assumptions are made in terms of life expectancy at birth by sex. As in previous revisions, life expectancy was generally assumed to rise over the projection period. In contrast with the assumptions made about future fertility trends, only one variant of future mortality trends (median path) was used for each country for the standard projection variants (e.g., high, medium and low fertility variants).

The *2015 Revision* of the *World Population Prospects* used probabilistic methods for projecting life expectancy at birth with only slight modifications to the approach used in the *2012 Revision*; these refer mainly to the gap in female-male in life expectancy and to the adjustments that were made.

a. ***Overall approach***

The probabilistic method used in the *2015 Revision* for projecting life expectancy at birth was done in two separate steps, as described below:

The first step focuses on progress made in female life expectancy at birth, and models the sequence of change from high to low mortality (Raftery et al., 2013). The transition from high to low mortality can be decomposed into two phases, each of which can be approximated by a logistic function. The first phase consists of initial slow growth in life expectancy and the diffusion of progress against mortality (e.g., small survival improvements at low levels of life expectancy associated with diffusion of hygiene and improved nutrition), followed by a period of accelerated improvements, especially for infants and children (e.g., larger gains associated with greater social and economic development, mass immunization, etc.). The second phase begins once the easiest gains, mainly against infectious diseases, have been achieved. The second phase is characterized by continuing gains against non-communicable diseases, but these improvements occur at a slower pace because of the greater challenges in preventing premature deaths at older ages (Fogel, 2004; Riley,

[16] Mortality levels are also taken into account while measuring the replacement level.

2001). The age at which the averted deaths from infectious and non-communicable diseases generally occur also has an impact on the gains in the life expectancy at birth.

For all countries undergoing mortality transition, the pace of improvement in life expectancy at birth is decomposed into a systematic decline and random distortion terms. The pace of the 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 using a Bayesian hierarchical model, which results in country-specific distributions for the parameters of the gains 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 world's experience is used to inform the statistical distributions of the parameters of the double-logistic.

Under these conditions, the pace of improvement and the asymptotic limit in 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 of maximum female life expectancy over the past 150 years has been highly linear, increasing at about 2.4 years per decade over most of that period (Oeppen and Vaupel, 2002; Vaupel and Kistowski, 2005), and at a slightly slower pace (about 2.26 years of gains per decade) after the vanguard countries started to exceed 75 years of female life expectancy at birth in the 1960s (Vallin and Mesle, 2009). By assuming that the asymptotic average rate of increase in life expectancy is nonnegative, life expectancy is assumed to continually increase (on average), and no limit is imposed on life expectancy in the foreseeable future. However, after analysis of the projected gains in life expectancy that were derived by applying the estimates of life expectancy to the original model developed by Raftery et al (2013), the decision was taken to modify the value of the (z) parameter to temper the pace of future gains somewhat[17]. The original parameter yielded life expectancy levels that were fairly high and annual gains in life expectancy at birth that were almost constant even after reaching very high levels of life expectancy. For this reason, further guidance on the future rate of progress was taken from the increase in maximum female life span among a set of countries with high life expectancies and the most reliable data on mortality at very old ages. Maximum female lifespan in these countries has been increasing linearly at least since the 1970s at a pace of about 1.25 years per decade for countries like Sweden and Norway (Wilmoth, Deegan, Lundstrom and Horiuchi, 2000; Wilmoth and Ouellette, 2012; Wilmoth and Robine, 2003). This more moderate pace was used to inform the asymptotic average rate of increase in female life expectancy used in the *2015 Revision*.

To construct projections of female life expectancy at birth for all countries without generalized HIV/AIDS epidemic, the Bayesian hierarchical model was used to generate 1,450,000[18] double-logistic curves for each country (see example in figure II.4), representing the uncertainty in the double-logistic gain function (graphs of this double-logistic curve are available online[19]). For each trajectory, at any given time, the double-logistic function gives the expected improvement in life expectancy based on its current level. A distortion term, representing deviations of increments from the double-logistic curve observed in past experience, was also added to the expected gain in life expectancy.

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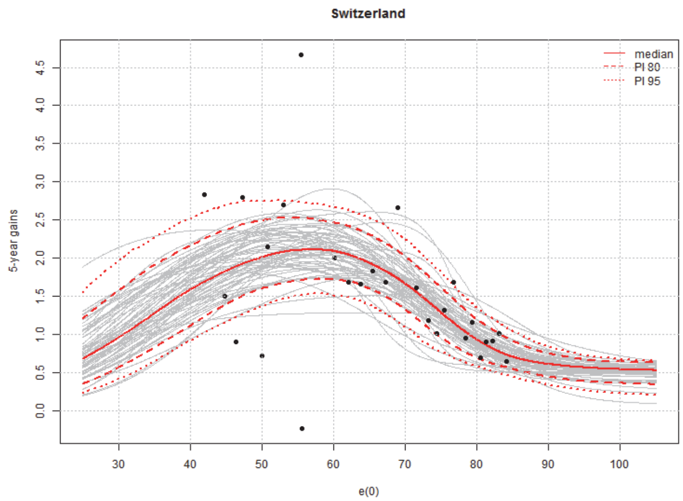
[17] Following Raftery et al. (2013) formal notation, to set the posterior median to an annual gain of 0.125 year (or 5-year gain of 0.625 in this context), the upper bound value of 0.653 was used for the world prior (z) and country-specific prior (z^c) in the estimation of the double-logistic parameters.

[18] Actually, ten simulations were run in parallel with 155,000 iterations performed for each simulation, and the first 10,000 were discarded.

[19] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of female gains in life expectancy at birth curves (based on Double-Logistic function) from the Bayesian Hierarchical Model (BHM): median, 80 and 95 per cent prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/CHGFEM/

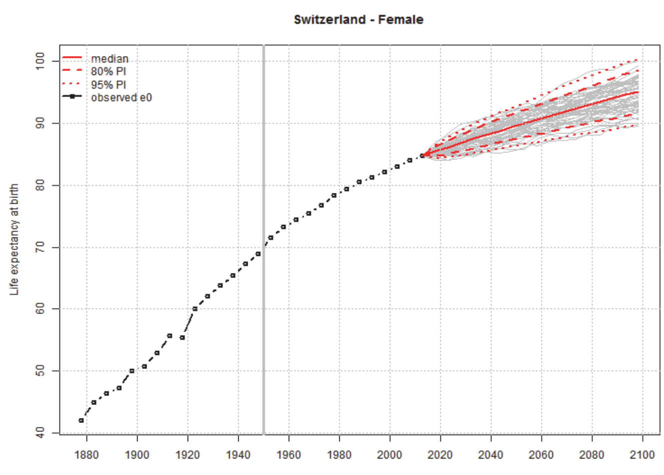
Figure II.4. Female gains in life expectancy at birth and prediction intervals of estimated double-logistic curve for Switzerland (systematic decline part)



NOTE: The observed five-year gains by level of life expectancy at birth (e(0)) are shown by black dots. For clarity, only 60 trajectories of the 1,450,000 calculated are shown here. The median projection is the solid red line, and the 80% and 95% prediction intervals are shown as dashed and dotted red lines respectively. In addition to estimates of female life expectancy at birth for the period 1950-2015 (based on the *2015 Revision*), historical data for pre-1950 periods are included.

A systematic sampling of 1/14 of the 1,450,000 double-logistic curves was then used to calculate over 100,000 life expectancy projections for each country. The median of these 100,000 trajectories is used as the standard mortality projection in the *World Population Prospects*. To evaluate the uncertainty of future trends in female life expectancy at birth, 80 and 95 per cent prediction intervals have also been calculated (see figure II.5 for Switzerland, additional tables[20] and graphs[21] are available online for all countries).

Figure II.5. Probabilistic trajectories of projected female life expectancy at birth (2015-2100) for Switzerland



NOTE: For clarity, only 60 trajectories of the 100,000 calculated are shown here. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively. In addition to estimates of female life expectancy at birth for the period 1950-2015 (based on the *2015 Revision*), historical data (i.e, before 1950 as marked by vertical grey line) were included.

[20] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online tables of probabilistic projections of female life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/

[21] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of probabilistic projections of female life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/Female/

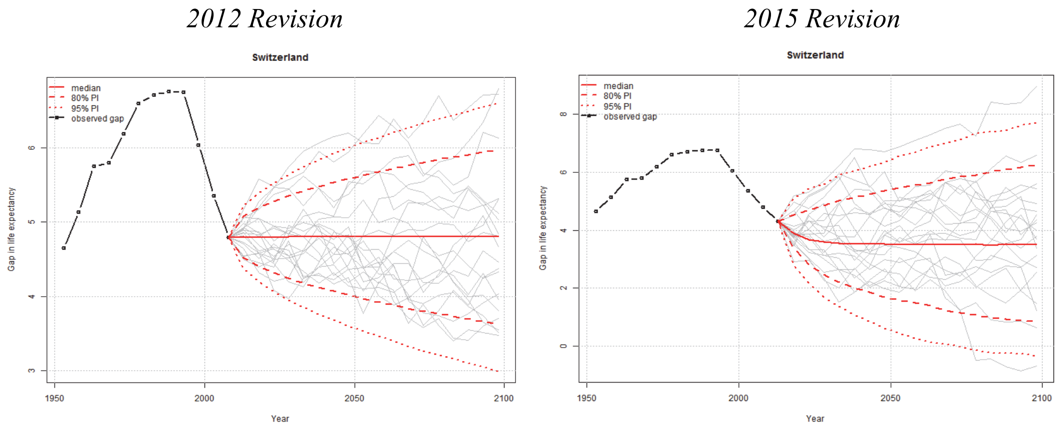
The second step of the mortality projection process models the gap between female and male life expectancy at birth in order to derive projections of male life expectancy. Probabilistic projections of female life expectancy at birth (obtained through step one) were used in conjunction with stochastic projections of the gender gap to produce probabilistic projections of male life expectancy at birth, taking into account the correlation between female and male life expectancies, and the existence of outlying data points during periods of crisis or conflict (Raftery, Lalic and Gerland, 2012). The gap in life expectancy at birth between females and males is modelled using an autoregressive model with female life expectancy used as a covariate. A large body of literature exists on biological, behavioural and socioeconomic factors underlying the gap in life expectancy between females and males (Oksuzyan et al., 2008; Rogers et al., 2010; Trovato and Heyen, 2006; Trovato and Lalu, 1996, 1998), and the recent narrowing of the gap in high-income countries (Glei and Horiuchi, 2007; Meslé, 2004; Oksuzyan et al., 2008; Pampel, 2005). The pattern of decline in the gap in life expectancy observed for high-income countries and for some emerging economies is assumed to apply in the future to other countries as well as through the diffusion of effective public health and safety measures and medical interventions (Bongaarts, 2009; Vallin, 2006). Practically this means that based on past experience across the world, the future gender gap is expected to widen when life expectancy is low, but on average once female life expectancy reaches about 75 years, the gap stops widening and starts narrowing. The narrowing of the gap continues until a threshold level of female life expectancy is reached. This threshold value, set at 83 years in the *2012 Revision,* was increased to 86 years in the *2015 Revision* in order to permit slightly more convergence in the sex differential of mortality.

Therefore, once the projected female life expectancy reaches or exceeds the highest observed levels of female life expectancy (about 86 years for the *2015 Revision*), the gap is modelled as a random walk with normally distributed changes and no drift because little information on the determinants of changes in the gap exist at these high ages and beyond. To systematically produce joint probabilistic projections of female and male life expectancy, a large number of future trajectories for the gap in life expectancy have been simulated. For each simulated value of the gap, the simulated male life expectancy projection is obtained by subtracting it from a simulated value of female life expectancy projection.

To construct projections of male life expectancy at birth, the gender gap autoregressive model was then used in conjunction with probabilistic projections of female life expectancy at birth to generate 100,000 gender gap trajectories for each country (see example in figure II.6), representing the uncertainty in the future gap between female and male life expectancy projections (graphs of the gender gap trajectories are available online[22]). As indicated above, in the *2015 Revision*, it was deemed necessary to increase the threshold to 86 years in order to permit slightly more convergence in the sex differential of mortality. As seen in the case of Switzerland in figure II.6, the female-male gap in life expectancy at birth in the *2012 Revision* remained constant basically from the onset of the projection, with a sex gap of just under five years, while in the *2015 Revision* it was permitted to converge slightly more before plateauing at under four years.

[22] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of female-male gap in life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/FMGAP/

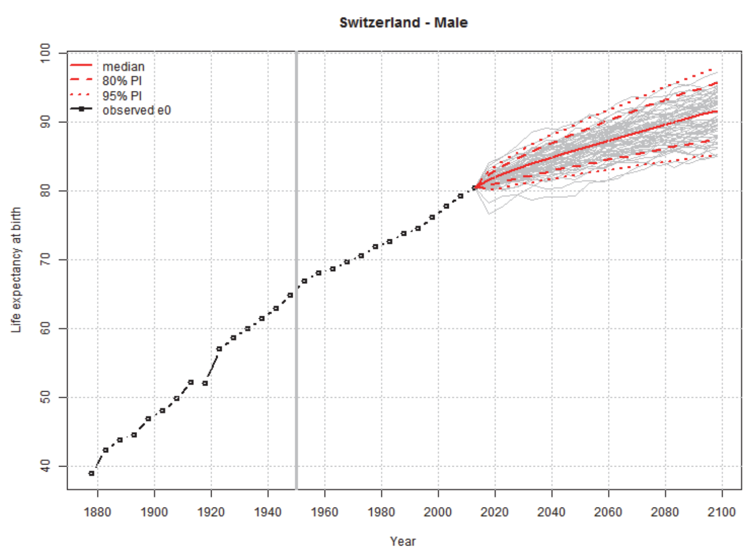
Figure II.6. Female-male gap in life expectancy at birth and prediction intervals for Switzerland, *2012 and 2015 Revisions*



NOTE: The observed gap between female and male life expectancy at birth are shown by black dots and solid line. For clarity, only 60 trajectories of the 100,000 calculated are shown here. The median 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 sample of gender gap trajectories was then used to calculate over 100,000 male life expectancy projections for each country. The median of these projections was used as the standard mortality projection in the *World Population Prospects*. To evaluate future trends in male life expectancy at birth, 80 and 95 per cent prediction intervals were also calculated (see figure II.7 for Switzerland, additional tables[23] and graphs[24] are available online for all countries).

Figure II.7. Probabilistic trajectories of projected male life expectancy at birth (2015-2100) for Switzerland



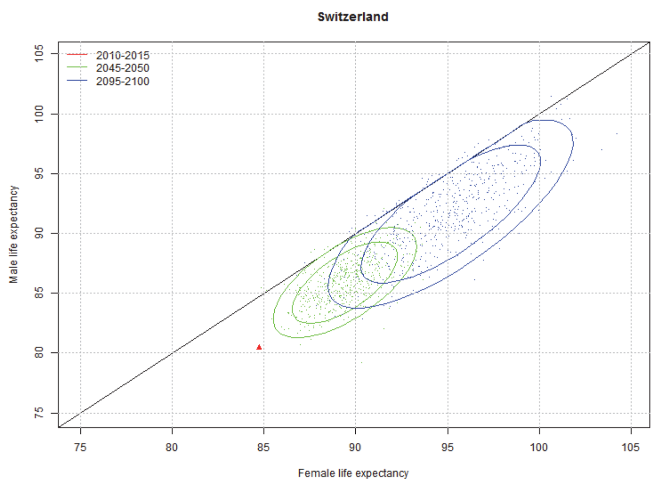
NOTE: For clarity, only 60 trajectories of the 100,000 calculated are shown here. The median projection is the solid red line, and the 80 and 95 per cent prediction intervals are shown as dashed and dotted red lines respectively. In addition to estimates of life expectancy at birth for the period 1950-2015 (based on the *2015 Revision*), historical data (i.e, before 1950 as marked by vertical grey line) were included.

[23] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online tables of probabilistic projections of male life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Download/Probabilistic/Input/

[24] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of probabilistic projections of male life expectancy at birth: median, 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/Male/

The relationship between probabilistic projections of male and female life expectancies at birth for selected projection periods (e.g., 2015–2020, 2050–2055 and 2095–2100) can be summarized through scatter plots showing a subsample of 500 probabilistic trajectories of life expectancy at birth for both male and female (see example in figure II.8). The 80 and 95 per cent prediction intervals are shown as ellipses respectively. The relationship if both male and female life expectancies are equal is displayed with a diagonal line. Graphs of the joint distributions of life expectancy by sex are available online.[25]

Figure II.8. Comparison of probabilistic projections of female and male life expectancies at birth for selected periods for Switzerland



NOTE: The chart shows the relationship between probabilistic projections of male and female life expectancies at birth for 2010-2015, 2045-2050 and 2095-2100 that has been carried out with estimates from the *2015 Revision* of the *World Population Prospects*. For clarity, only 500 projected trajectories of the 100,000 calculated are shown here for each sex.

b. Adjustments

The approach to life expectancy projection described above worked well for the majority of countries that have experienced normal mortality improvements since the 1950s. But several countries stood out either because of much faster or much slower improvements than typically experienced by other countries. Countries that have experienced much faster gains in life expectancy since the 1950s, or over segments of the estimation period, are often countries that still have relatively low life expectancy even though they may have made substantially faster progress than that historically observed in other countries. A relatively fast decline in child mortality may have contributed to a strong increase in the projected life expectancy based on the current model application in some of these countries. On the other hand, several countries that have experienced periods of stagnating mortality in the observation period have tended to under-perform in the projection of life expectancy while using the standard approach. In both cases, adjustments were made such that the four parameters of the double logistic function responsible for future gains beyond around 60 years of life expectancy for each country have been informed by the experience of the leading countries in its respective region[26]. In the first case, this approach was used to temper over-optimistic large gains for some countries in the distant future that would lead to implausible crossovers in long-term projections (i.e., countries that are lagging today becoming leaders by 2100). In the second case, this approach

[25] United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Population Prospects: The 2015 Revision*. New York. Online plots of Comparison between probabilistic projections of male and female life expectancies at birth for selected projection periods: 80% and 95% prediction intervals; see http://esa.un.org/unpd/wpp/Graphs/Probabilistic/EX/FMCOMP/

[26] Following Raftery et al. (2013) formal notation, 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 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.

was used to provide further guidance on the trajectory of long term potential gains for countries that have experienced mortality stagnation or worsening (i.e., it is assumed that, in the long run, these countries will gradually catch up with the more advanced countries in their region). The countries to which adjustments were applied are listed in table II.1. Aside from reasons highlighted above, within each of these lists, there are also cases where adjustments were made on the basis that unlikely cross-overs were taking place with the application of the original model.

TABLE II.1. COUNTRIES FOR WHICH ADJUSTMENTS WERE MADE TO THE DEFAULT PROJECTION TRAJECTORY

	Country or area		*Country or area*
A. Countries with projected life expectancies that were deemed too high			
1	Algeria	20	Madagascar
2	Bangladesh	21	Mongolia
3	Bhutan	22	Morocco
4	Bolivia (Plurinational State of)	23	Nepal
5	Brazil	24	Nicaragua
6	Cambodia	25	Niger
7	Chile	26	Oman
8	China, Hong Kong SAR	27	Panama
9	Democratic Republic of the Congo	28	Republic of Korea
10	Dominican Republic	29	Republic of Moldova
11	El Salvador	30	Samoa
12	Eritrea	31	Sierra Leone
13	Guatemala	32	Singapore
14	Iran (Islamic Republic of)	33	South Sudan
15	Ireland	34	Tajikistan
16	Kyrgyzstan	35	Timor-Leste
17	Lao People's Democratic Republic	36	Tunisia
18	Lebanon	37	Turkey
19	Liberia	38	Vanuatu
B. Countries with projected life expectancies that were deemed too low			
1	Belize	8	Guyana
2	Benin	9	Micronesia (Fed. States of)
3	Chad	10	Montenegro
4	China	11	Nigeria
5	Comoros	12	Pakistan
6	Djibouti	13	Papua New Guinea
7	Ghana	14	Yemen

c. Projection of the age pattern of mortality

Once the path of future life expectancy was determined, mortality rates by five-year age group and sex consistent with the life expectancy at birth for each quinquennium were calculated. For countries with recent empirical information on the age patterns of mortality, mortality rates for the projection period were obtained by extrapolating the most recent set of mortality rates by the rates of change from: (a) country-specific historical trends using an extended Lee-Carter approach (Li, Lee, and Gerland, 2013)[27], or (b) typical age-specific patterns of mortality improvement by level of mortality estimated from individual country experiences included in the Human Mortality Database (Andreev, Gu, and Gerland, 2013)[28], or (c) from extended model life tables (Li and Gerland, 2011). In both instances, additional constraints were sometimes used at younger and/or older ages to ensure greater consistency in sex differentials, especially at very high levels of projected life expectancies.

In other words, under such procedures, the empirical or estimated age pattern of mortality is transformed as life expectancy changes over time. For countries lacking recent or reliable information on age patterns of mortality, mortality rates were directly obtained from an underlying model life table. A choice could be made among nine model life table systems, four proposed by Coale and Demeny (1966); Coale, Demeny and Vaughn (1983); and Coale and Guo (1989), and five model systems for developing countries produced by the United Nations (1982). These nine model life tables have been updated and extended by the Population Division in order to cover the whole age range up to 130 years, and a range of life expectancies from 20 to 100 years[29,30].

2. The impact of HIV/AIDS on mortality

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

As a consequence, instead of an overall mortality process that can be captured by standard age patterns of mortality and smooth trends of changing life expectancy, for countries highly affected by HIV/AIDS, two separate mortality processes must be modelled: the mortality due to the HIV/AIDS epidemic itself and the mortality that prevails among the non-infected population. The latter is often called the level of "background mortality".

The *2015 Revision* made explicit modelling assumptions to incorporate the demographic impact of the HIV/AIDS epidemic for 21 countries where HIV prevalence among persons aged 15 to 49 was ever equal to or greater than 2.4 per cent between 1980 and 2013 (table II.2). In countries most highly affected by the HIV/AIDS epidemic, mortality was projected by modelling explicitly the course of the epidemic and projecting the yearly incidence of HIV infection. The model developed by the UNAIDS Reference Group on Estimates, Modelling and Projections (Stanecki, Garnett, and Ghys, 2012; Stover, Brown, and Marston, 2012), and all epidemiological parameters (including treatment data)

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[27] In this case, the extended Lee-Carter approach is constrained to the projected median UN life expectancy at birth by selecting appropriate increases in the level parameter (k_t) for each of the projection periods with the age pattern (a_x) based on the most recent period or the average 1950-2010 period, and the age pattern of mortality improvement (b_x) gradually changes by level of mortality to reflect the fact that mortality decline is decelerating at younger ages and accelerating at old ages.

[28] Available demographic data have permitted reliable estimation of the patterns of mortality improvement only up to 75-80 years of e0 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.

[29] United Nations Population Division (2011). *Extended Model Life Tables Version 1.3*. New York: United Nations. Available online at: http://esa.un.org/unpd/wpp/Download/Other/MLT/

[30] It must be noted that the last available entry in the revised system of model life tables of 100.0 years of life expectancy, for both males and females, are not meant to represent a ceiling for human longevity.

used by UNAIDS were made available to the Population Division in 2014[31] and were used to derive the mortality impact of HIV/AIDS. The model was not used for all countries with prevalence above 2.4 percent to generate mortality estimates. In cases where sufficient empirical evidence on adult mortality was available, and HIV prevalence was below about 5-7 per cent, estimates of adult mortality by age and sex were derived from empirical observations in conjunction with estimates of under-five mortality (see online listing of data sources[32] for country-specific details).

TABLE II.2. HIV PREVALENCE RATE AMONG ADULTS AGED 15-49 IN THE COUNTRIES FOR WHICH EXPLICIT MODELLING OF HIV/AIDS WAS EMPLOYED IN THE *2015 REVISION*

Region/Country	*Adult HIV prevalence rate (%) in 2013*	*Maximum HIV rate (%) between 1980 and 2013*	*Region/Country*	*Adult HIV prevalence rate (%) in 2013*	*Maximum HIV rate (%) between 1980 and 2013*
Angola	2.4	2.4	Malawi	10.3	17.5
Botswana	21.9	27.7	Mozambique	10.8	..
Burundi	1.0	2.5	Namibia	14.3	17.0
Cameroon	4.3	5.3	Rwanda	2.9	6.3
Central African Rep.	3.8	9.0	South Africa	19.1	19.1
Congo	2.5	5.8	Swaziland	27.4	27.4
Equatorial Guinea[33]	5.3	5.3	Uganda	7.4	12.6
Ethiopia	1.2	4.1	UR of Tanzania	5.0	8.8
Gabon	3.9	6.0	Zambia	12.5	14.7
Kenya	6.0	10.8	Zimbabwe	15.0	28.7
Lesotho	22.9	22.9			

Source: UNAIDS (2014). Gap Report. Geneva, Switzerland, and 2013 set of UNAIDS/WHO estimates (unpublished tabulations made available in 2014).
http://www.unaids.org/sites/default/files/en/media/unaids/contentassets/documents/unaidspublication/2014/UNAIDS_Gap_report_en.pdf

The projection assumptions used in the *2015 Revision* assumed that the HIV prevalence rate observed in 2013 would decline by 2100 to about 1/10 of its value following an exponential decay function. The sex ratio of HIV incidence (female to male incidence for age 15-49) was assumed to follow a linear trend from its 2013 value to reach 1.1 in 2050 and to remain constant thereafter. Proportions of HIV-positive children and adults receiving treatment in each country were taken from estimates prepared by the World Health Organization and UNAIDS. For adults, coverage of treatment was projected to reach 90 per cent in 2050 if it was below 85 per cent in 2013 or to reach 95 per cent if it was above 85 per cent in 2013; it remained constant thereafter until 2100. A similar approach was used for the treatment of children while coverage of interventions to prevent mother-to-child transmission of HIV was assumed to reach 90 per cent in almost all countries by 2050, and remain constant thereafter until 2100.

3. Constant-mortality assumption

Under the constant-mortality assumption, mortality over the projection period is maintained constant for each country at the level estimated for 2010-2015.

[31] A special release of *Spectrum* (UNPOP100, December 2014), specifically extended to handle higher life expectancy projections up to age 100 was used for the *2015 Revision*. Different versions of *Spectrum* are available at: http://spectrumbeta.futuresinstitute.org/

[32] Data sources and related meta-information for the *2015 Revision* of the *World Population Prospects* are available for each country from the following web page: http://esa.un.org/unpd/wpp/DataSources/

[33] The estimated values for Equatorial Guinea were not published in the Gap Report (UNAIDS, 2014).

C. International migration assumptions

International migration is the component of population change that is most difficult to project. Data on 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 a very volatile process. Not only has international migration shown drastic changes in absolute numbers, but the direction of the flows has changed as well. As a result, some countries that historically have been primarily countries of origin have become countries of destination, and vice versa. Therefore, formulating assumptions about future trends in international migration is extremely challenging. Where migration flows have historically been small and have had little net impact on the demography of a country, adopting the assumption that migration will remain constant throughout most of the projection period is usually acceptable. In situations where migration flows are a dominant factor in demographic change, more attention is needed.

When a person moves from one country to another, that person is an emigrant when leaving the country of origin and becomes an immigrant when entering the country of destination. Because immigration and emigration flows affect countries differently, international migration is ideally studied as the flow of people moving between countries. In practice, data on international migration flows only exist for a small number of countries. Therefore, international migration in this revision, as in previous ones, has been incorporated as net migration. Net migration—the difference between the number of immigrants and the number of emigrants for a particular country and period of time—shows the net effect of international migration on the respective population. It does not provide an indication about the number of immigrants and emigrants involved. In an extreme case, immigration and emigration for a country could be significant, but if the number of immigrants were equal to the number of emigrants, net migration would amount to zero.

In preparing assumptions about future trends in international migration, several pieces of information were taken into account: (*1*) information on net international migration or its components (immigration and emigration) as recorded by countries; (*2*) data on labour migration flows; (*3*) estimates of undocumented or irregular migration; (*4*) and data on refugee movements in recent periods.

The basic approach for formulating future net international migration assumptions is straightforward for most countries. For any given country, a distinction was made between international migration flows and the movement of refugees. For international migration, it was assumed that recent levels, if stable, would continue until 2045-2050. The government's views on international migration as well as estimates of undocumented and irregular migration flows affecting a country were also considered. Regarding the movements of refugees, it was assumed in general that refuges return to their country of origin within one or two projection periods, i.e., within 5 to 10 years. If a country experienced both international migration and refugee movements, the two processes were added in order to capture the overall net migration during a particular period in the future.

Usually, migration assumptions are expressed in terms of the net number of international migrants. The distribution of migrants by sex was established on the basis of what was known about the participation of men and women in different types of flows for any given country (*i.e.*, labour migration, family reunification, etc.). Given the lack of suitable information on the age distribution of migrant flows, models were generally used to distribute the overall net number of male and female migrants by age group according to the dominant type of migration flow assumed (for example, labour migration or family migration). The age and sex profiles of the net migration flows were then used as input for the cohort-component projection model (Castro and Rogers, 1983; United Nations, 1989, pp. 65-70). In the rare instances when the age and sex distribution of international migrants was known, those distributions were used to determine the most suitable model or, in some cases, those data were used directly as input. The distribution of net migrants by age and sex was generally kept constant over the projection period. However, if a country was known to attract temporary labour migrants, an effort was made to model the return flow of those labour migrants accounting for the ageing of the migrants involved. The same practice was applied to refugee flows.

International migration has become a nearly universal phenomenon affecting virtually all countries of the world. For the few countries that were known neither to admit international migrants nor to supply a sizeable number of migrants, net migration was assumed to be zero, or to become zero shortly after the start of the projection. However, the vast majority of countries were projected to experience non-zero net international migration during most of the projection period. Among these, almost twice as many were projected to be sending countries as receiving countries.

As a final step, it was necessary to ensure that the sum of all international migration added to zero at the global level for each 5-year estimation and projection period. This was achieved by an iterative process in which individual country estimates and projections were revisited and altered accordingly.

1. Normal migration assumption

Under the normal migration assumption, the future path of international migration is set on the basis of past international migration estimates and consideration of the policy stance of each country with regard to future international migration flows. Overall, projected levels of net migration were generally kept constant until 2045-2050, with the exception of circumstances noted above, such as large recent fluctuations in migration numbers, refugee flows, or temporary labour flows. After 2050, it is assumed that net migration would gradually decline and reach 50 per cent of the projected level of 2045-2050 by 2095-2100. This assumption is unlikely to be realized but represents a compromise between the difficulty of predicting the levels of immigration or emigration within each country of the world for such a far horizon, and the recognition that net migration is unlikely to reach zero in individual countries.

2. Zero-migration assumption

Under this assumption, for each country, international migration is set to zero starting in 2015-2020.

D. Eight projection variants

The *2015 Revision* included eight different projection variants (see table II.3). Five of those variants differed only with respect to the level of fertility, that is, they shared the assumptions made with respect to mortality and international migration. The five fertility variants are: low, medium, high, constant-fertility and instant-replacement fertility. A comparison of the results from these five variants allows an assessment of the effects that different fertility assumptions have on other demographic parameters. The high, low, constant-fertility and instant-replacement variants differ from the medium variant only in the projected level of total fertility. In the high variant, total fertility is projected to reach a fertility level that is 0.5 children above the total fertility in the medium variant. In the low variant, total fertility is projected to remain 0.5 children below the total fertility in the medium variant. In the constant-fertility variant, total fertility remains constant at the level estimated for 2010-2015. In the instant replacement variant, fertility for each country is set to the level necessary to ensure a net reproduction rate of 1.0 starting in 2015-2020. Fertility varies slightly over the projection period in such a way that the net reproduction rate always remains equal to one, thus ensuring the replacement of the population over the long run.

In addition to the five fertility variants, a constant-mortality variant, a zero-migration variant and a "no change" variant (i.e., both fertility and mortality are kept constant) have been prepared. The constant-mortality variant and the zero-migration variant both used the same fertility assumption (medium fertility). Furthermore, the constant-mortality variant has the same international migration assumption as the medium variant. Consequently, the results of the constant-mortality variant can be compared with those of the medium variant to assess the effect that changing mortality has on various population quantities. Similarly, the zero-migration variant differs from the medium variant only with respect to the underlying assumption regarding international migration. Therefore, the zero-migration variant allows an assessment of the effect that non-zero net migration has on various population quantities. Lastly, the "no change" variant has the same assumption about international migration as the medium variant but differs from the latter by having constant fertility and mortality. When compared to the medium variant, therefore, its results shed light on the effects that changing fertility and mortality have on the results obtained.

TABLE II.3. PROJECTION VARIANTS IN TERMS OF ASSUMPTIONS FOR FERTILITY, MORTALITY AND INTERNATIONAL MIGRATION

	Assumptions		
Projection variant	*Fertility*	*Mortality*	*International migration*
Low fertility	Low	Normal	Normal
Medium fertility	Medium	Normal	Normal
High fertility	High	Normal	Normal
Constant-fertility	Constant as of 2010-2015	Normal	Normal
Instant-replacement-fertility	Instant-replacement as of 2015-2020	Normal	Normal
Constant-mortality	Medium	Constant as of 2010-2015	Normal
No change	Constant as of 2010-2015	Constant as of 2010-2015	Normal
Zero-migration	Medium	Normal	Zero as of 2015-2020

E. INTERPOLATION PROCEDURES

The cohort-component method used in the *2015 Revision* requires a uniform age format for the estimation of the size and structure of a population and the measurement of vital events. For the purpose of global population estimates and projections, most empirical data are only available in five-year age groups. As a consequence, all results produced by the cohort-component method in the *2015 Revision* are also in five-year age groups and, for vital events, represent five-year periods. All vital rates are given as the average over the five-year period from mid-year (*t*) to mid-year (*t*+5) centred on 1 January year (*t*+3). For example, the estimate for life expectancy at birth for 2000-2005 refers to the period from mid-2000 to mid-2005 (i.e., 2000.5 to 2005.5 in decimal dates), with 1 January 2003 as the mid-point (i.e., 2003.0 using a decimal date). Special interpolation routines were then used to produce estimates and projections for single calendar years and for single-year age groups. It must be noted, however, that interpolation procedures cannot recover the true series of events or the true composition of an aggregated age group.

a. Interpolation of populations by age and sex

The basis for the calculation of interpolated population figures by single year of age and for calendar years ending with either 0 or 5 were the estimated and projected quinquennial population figures by five-year age groups for each sex. In a first step, the quinquennial population figures were interpolated into annual population figures by applying Beers' ordinary formula (Swanson and Siegel, 2004, p. 728). The second step of this interpolation was to generate the population by single year of age for each year by applying Sprague's fifth-difference osculatory formula (Swanson and Siegel, 2004, p. 727) for subdivision of groups into fifths. This interpolation procedure generated a smooth interpolated series of figures while maintaining the original values. It should be noted that for ages above 80 and for age under five, the stability and reliability of the interpolation procedure was not always satisfactory.

In order to maintain consistency along cohort lines, a third step has been added. This third step is to interpolate linearly the populations by single year of age for each calendar year between those ending with 0 or 5, along the cohort survival line. For example, the populations at ages 1, 2, 3, and 4, in years 1951, 1952, 1953, and 1954 respectively, are linear interpolations between the population aged 0 in 1950 and the population aged 5 in 1955. The last such linear interpolation is carried out between age 94 at time t and age 99 at time t+5. Because of the last age group being open-ended, a linear interpolation is not possible beyond age 94. As a last step, the interpolation results are prorated such that the sum of all age groups between ages 0 and 99, before and after the linear interpolation, is the same.

b. Interpolation of vital events and summary statistics

For the interpolation of vital events, their rates and other measures into annualized times series, the modified Beers formula was used (Swanson and Siegel, 2004, p. 729). This formula combines interpolation with some smoothing. The Beers modified method was preferred over the Beers "ordinary" formula as it avoided fluctuations at the beginning and the end of the series that were atypical for the variables concerned.

The time periods in the estimates and projections of this revision are anchored to mid-year. Each observation or projection period starts at 1 July of a particular year and ends at mid-year five years later. Therefore, the annualized interpolated indicators refer to the period between the mid-year points of two consecutive calendar years. In order to provide annualized variables that refer to calendar years, an adjustment was made that simply assumed that the arithmetic average between two such periods would be a good representation of the calendar year based indicator.

F. TABULATIONS

Once the individual country projections are prepared, the results are aggregated into the world, regions, major areas, development groups and other aggregates. For a list of the aggregation units see the explanatory notes at the beginning of the report.

The aggregation of populations by age and sex and vital events by age and sex is performed by simply adding the variables according to lists that assign individual countries to the aggregates. For synthetic variables, like life expectancy, total fertility, median age or net reproduction rates, proper population weighted averages are calculated.

G. SUMMARY OF METHODOLOGICAL CHANGES INTRODUCED IN THE *2015 REVISION*

The following summarizes the changes and adjustments that were made in the *2015 Revision* in relation to procedures followed in the *2012 Revision*.

- The *2015 Revision* used a more systematic approach to project age-specific patterns of fertility.
- The *2015 Revision* used updated parameters in the model that was used to project the gender gap in life expectancy; the threshold value of 83 years that was used in the *2012 Revision* was increased to 86 years in the *2015 Revision*.
- In the *2015 Revision*, it was assumed that net migration would gradually decline and reach 50 per cent of the projected level of 2045-2050 by 2095-2100, as compared to zero by 2095-2100 in the *2012 Revision.*
- In the *2015 Revision*, the impact of HIV/AIDS on mortality was modelled explicitly for 21 countries where HIV prevalence among persons aged 15 to 49 was at one time equal to or greater than 2.4 per cent between 1980 and 2013.

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