Mapping geographical inequalities in access to drinking water and sanitation facilities in low-income and middle-income countries, 2000–17


This version is available from Sussex Research Online: http://sro.sussex.ac.uk/id/eprint/93179/

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:
Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

http://sro.sussex.ac.uk
Mapping geographical inequalities in access to drinking water and sanitation facilities in low-income and middle-income countries, 2000–17

Local Burden of Disease WaSH Collaborators

Summary

Background Universal access to safe drinking water and sanitation facilities is an essential human right, recognised in the Sustainable Development Goals as crucial for preventing disease and improving human wellbeing. Comprehensive, high-resolution estimates are important to inform progress towards achieving this goal. We aimed to produce high-resolution geospatial estimates of access to drinking water and sanitation facilities.

Methods We used a Bayesian geostatistical model and data from 600 sources across more than 88 low-income and middle-income countries (LMICs) to estimate access to drinking water and sanitation facilities on continuous continent-wide surfaces from 2000 to 2017, and aggregated results to policy-relevant administrative units. We estimated mutually exclusive and collectively exhaustive subcategories of facilities for drinking water (piped water on or off premises, other improved facilities, unimproved, and surface water) and sanitation facilities (septic or sewer sanitation, other improved, unimproved, and open defecation) with use of ordinal regression. We also estimated the number of diarrhoeal deaths in children younger than 5 years attributed to unsafe facilities and estimated deaths that were averted by increased access to safe facilities in 2017, and analysed geographical inequality in access within LMICs.

Findings Across LMICs, access to both piped water and improved water overall increased between 2000 and 2017, with progress varying spatially. For piped water, the safest water facility type, access increased from 40·0% (95% uncertainty interval [UI] 39·4–40·7) to 50·3% (50·0–50·5), but was lowest in sub-Saharan Africa, where access to piped water was mostly concentrated in urban centres. Access to both sewer or septic sanitation and improved sanitation overall also increased across all LMICs during the study period. For sewer or septic sanitation, access was 46·3% (95% UI 46·1–46·5) in 2017, compared with 28·7% (28·5–29·0) in 2000. Although some units improved access to the safest drinking water or sanitation facilities since 2000, a large absolute number of people continued to not have access in several units with high access to such facilities (>80%) in 2017. More than 253000 people did not have access to sewer or septic sanitation facilities in the city of Harare, Zimbabwe, despite 88·6% (95% UI 87·2–89·7) access overall. Many units were able to transition from the least safe facilities in 2000 to safe facilities by 2017; for units in which populations primarily practised open defecation in 2000, 686 (95% UI 664–711) of the 1830 (1797–1863) units transitioned to the use of improved sanitation. Geographical disparities in access to improved water across units decreased in 76·1% (95% UI 71·6–80·7) of countries from 2000 to 2017, and in 53·9% (50·6–59·6) of countries for access to improved sanitation, but remained evident subnationally in most countries in 2017.

Interpretation Our estimates, combined with geospatial trends in diarrhoeal burden, identify where efforts to increase access to safe drinking water and sanitation facilities are most needed. By highlighting areas with successful approaches or in need of targeted interventions, our estimates can enable precision public health to effectively progress towards universal access to safe water and sanitation.

Funding Bill & Melinda Gates Foundation.

Copyright © 2020 The Author(s). Published by Elsevier Ltd. This is an Open Access article under the CC BY 4.0 license.
Research in context

Evidence before this study
In light of the health risks associated with unsafe drinking water and sanitation, as well as broader considerations of human development, the Sustainable Development Goals (SDGs) included the target of universal access to safe facilities by 2030. The WHO and United Nations Children’s Fund (WHO–UNICEF) Joint Monitoring Programme estimates access to water and sanitation nationally and by urban and rural areas, while the Global Burden of Diseases, Injuries, and Risk Factors (GBD) study quantifies the health risks posed by unsafe water and sanitation nationally and for subnational regions in select countries. Although these and other efforts provide valuable insights, they mask local and cross-boundary variation and ultimately result in an incomplete picture of areas in greatest need of intervention. The limited availability of accurate and wide-ranging estimates monitoring local geographical inequalities presents a barrier to achieving universal access to safe water and sanitation facilities. Studies have used model-based geostatistics to map various health and sociodemographic factors, highlighting the potential to apply these methods for mapping access to water and sanitation across low-income and middle-income countries (LMICs).

Added value of this study
To our knowledge, this study presents the first high-resolution subnational estimates of access to safe drinking water and sanitation facilities across more than 88 LMICs and across all indicators of access from 2000 to 2017. Our Bayesian geostatistical models and extensive geolocated dataset account for spatial and temporal trends, and our suite of highly resolved spatial covariates leverage the relationships between access to water and sanitation and other variables for improved estimation. Additionally, this is the first application of ordinal regression methods on water and sanitation data at large spatial scales, allowing us to appropriately account for the mutually exclusive and collectively exhaustive (ie, accounting for 100% of the population) relationships between the relevant indicators of access. We report increasing access to safe facilities over time, but trends varied regionally, and many people continued to have no access to safe drinking water and sanitation facilities in 2017 across the LMICs studied. We estimate that 143 300 (95% uncertainty interval 126 100–163 000) deaths of children younger than 5 years were attributable to unsafe water in sub-Saharan Africa in 2017, yet increases in access to safe water averted more than 18 100 (15 700–21 200) child deaths in the region in that year. Averted child deaths were concentrated in select units that had great progress in access, while child diarrhoeal mortality increased in other units, probably due in part to decreases in access to piped water. Although geographical inequality decreased in most LMICs from 2000, in some cases the lowest level of access remained unchanged, effectively leaving behind some units, even as progress was made nationally.

Implications of all the available evidence
Despite considerable progress since 2000, geographical inequalities remain an obstacle to reaching the SDG target of universal access to safely managed facilities. Our estimates highlight where the most substantial improvements were achieved over time, identifying areas with successful strategies for adaptation elsewhere. Our identification of areas in which access to safe facilities is low, combined with high-resolution estimates of high diarrhoeal burden and child malnutrition prevalence, calls attention to communities with high susceptibility to the spread of infectious diseases. Although access to safe facilities is increasing in many countries, subnational inequalities point to the need for targeted interventions, particularly to reach communities with the lowest access and to increase access to the safest facility types. Our findings can inform local level monitoring of progress towards the SDG target, and provide a resource for decision makers to target areas most in need of additional resources.

The community has prioritised access by including safe water and sanitation targets in both the Millennium Development Goals and more recently in the Sustainable Development Goals (SDGs), in which the UN called for access to be universal (ie, 100% access) and equitable. Despite substantial expansion of access during the Millennium Development Goals era, it has been previously estimated that less than 75% of the population in many countries in sub-Saharan Africa and south and southeast Asia had access to improved facilities in 2017.

Previous estimates of access have been reported primarily at the national level, as well as at the subnational level across Africa and for a subset of other countries. The WHO and United Nations Children’s Fund (WHO–UNICEF) Joint Monitoring Programme (JMP) has analysed inequality of access by wealth quintile and urban-rural status, as well as within subnational regions for select locations. These analyses, however, do not provide comprehensive estimates over space and time across low-income and middle-income countries (LMICs) at fine spatial scales. Understanding variation in water and sanitation access in second administrative-level units (eg, districts, counties; henceforth termed units) is imperative to identifying low-access areas at heightened risk of disease transmission, and areas that have successfully achieved high levels of access. Previous studies have used model-based geostatistics to map health indicators such as under-5 mortality, diarrhoea incidence and prevalence, and child growth failure, along with sociodemographic factors such as educational attainment, and interventions such as insecticide-treated bednet coverage and childhood...
vaccines.12 We aimed to extend these methods to estimate access to safe drinking water and sanitation facilities at fine spatial resolutions.

Methods
Overview
To produce a comprehensive baseline of comparable estimates, we leveraged the indicators used by the JMP24 and the Global Burden of Disease (GBD) study7 with a Bayesian geostatistical model. With use of data from 600 unique datasets, we produced estimates of the relative (proportion) and absolute (number of people) access to water and sanitation facilities across continuous geographical surfaces and aggregated resulting predictions to national and subnational levels (reported as second administrative-level units) in more than 88 LMICs from 2000 to 2017. We modelled access by facility-type indicators and for specific facilities with an ordinal modelling framework. We report regional results according to the GBD 2017 geographical hierarchy.7 We highlight specific types of transitions made in access to facility types and report the number of child diarrhoeal deaths attributed to unsafe facilities and averted by increased access to safe facilities. Finally, we present an analysis of variation in subnational geographical inequality in access.

Study design
We generated estimates for two sets of four mutually exclusive and collectively exhaustive indicators of access— one set for drinking water and one for sanitation—with uncertainty intervals (UIs), from 2000 to 2017. Each set of four indicators collectively accounts for 100% of the population in the respective geographical area. We used an ordinal regression framework in which each indicator was modelled using an ensemble modelling framework for each country individually. We produced subnational-level estimates for 88 LMICs for water and 89 LMICs for sanitation, first estimating continent-wide surfaces at a resolution of approximately 5 × 5 km, and then aggregating to second and first administrative and national boundaries. We included low, low-middle, and middle development countries, as classified by their Socio-demographic Index quintile,13 an indicator based on education, fertility, and income (appendix p 94). Despite their relatively high Socio-demographic Index, China and Libya were included to maintain geographical continuity. Countries were excluded if sufficient data were not available for reliable estimation with use of our modelling paradigm. A complete list of the countries included is available in the appendix (p 94). This study complied with the Guidelines for Accurate and Transparent Health Estimates Reporting (appendix p 93).14 Further details on methods and software used are available in the appendix (pp 9–11).

Data
Data were collated from Demographic and Health Surveys, Multiple Indicator Cluster Surveys, and other household surveys and censuses across 88 countries for water and 89 for sanitation from 2000 to 2017 (inclusion criteria details in appendix p 6). We used data from 600 unique sources—501 for water and 457 for sanitation (some sources contained both water and sanitation data). For water, 60·2% of our data by weighted sample size comprised geopositioned points, and 69·3% of weighted sanitation data were points. All other data were areal data. Drinking water facilities were categorised as piped (piped on or off premises), other improved (protected wells and springs, bottled water, rainwater collection, bought water), unimproved (unprotected wells and springs), or surface water (figure 1). Sanitation facilities were categorised as sewer or septic (sewer or septic tanks), other improved (improved latrines, ventilated improved latrines, composting toilets), unimproved (flush toilets to open channels, unimproved latrines), or open defecation (figure 1), using standardised definitions from the JMP.13,24 The resulting schema yielded mutually exclusive and collectively exhaustive indicators for water and sanitation access.17

Statistical analysis
To account for the ordinal data structure of the indicators of access for water (piped, other improved, unimproved, and surface water) and sanitation (sewer or septic, other improved, unimproved, and open defecation), this analysis used an ordinal continuation-ratio modelling strategy.15 This approach allows for the simultaneous modelling of mutually exclusive categorical responses, as shown in similar geospatial analyses.10,11 We first modelled the proportion of the population with access to sewer or septic sanitation using a binomial model. We then modelled the proportion of the population with access to other improved sanitation conditioned on not having access to sewer or septic sanitation. Subsequently, we modelled the proportion with access to unimproved sanitation conditioned on not having access to sewer or septic sanitation or other improved sanitation. The estimates from the second and third conditional models were then combined with the estimates from the first to generate a full set of estimates for access for all four indicators. In this manner, the estimates and their associated uncertainty incorporate the mutually exclusive and collectively exhaustive data structure. The same approach was used for the set of four indicators of access to drinking water facilities.

For each model used in this strategy, we used an ensemble modelling approach. Applying a stacking ensemble modelling approach, the data were initially fit with seven gridded-raster covariates (appendix p 28) to three independent models using a generalised additive model, boosted regression trees, and lasso regression. This generalised stacking approach has been successfully used in similar geospatial analyses of health and social data to optimise predictive performance.16,17 Predictions were generated from each of these child models to create raster
To assess the effect of changes in water and sanitation access on diarrhoeal disease mortality in children younger than 5 years, we used a comparative risk assessment framework to construct counterfactuals and assess child deaths averted due to increased access. We used estimates of diarrhoeal mortality in children younger than 5 years available at the same spatial scales from the geospatial analysis described by Reiner and colleagues for this counterfactual analysis; as such, only countries with data available from Reiner and colleagues were included. We combined these mortality estimates with risk ratios estimated in GBD 2017, which associated different types of water and sanitation facilities with varied risks of diarrhoeal disease. To use the risk ratios for different categories of water access from GBD, we combined our estimates of water access with household water treatment prevalence data from GBD to create concordant categories of water facility exposures. With these data, we calculated population attributable fractions of child diarrhoeal deaths to unsafe water and sanitation. We then used access estimates in 2000 to calculate a counterfactual population attributable fraction. Using these population attributable fractions in conjunction with the Reiner and colleagues estimates of child diarrhoeal disease mortality across units, we calculated attributable under-5 deaths for water and sanitation in 2017, as well as the number of averted child deaths in 2017 due to changes in water and sanitation access since 2000. We propagated uncertainty by repeating the calculation for values from each of the 250 draws of the posterior from our model. This methodology is further outlined in the appendix (p 11).

Additionally, we estimated inequality using subnational variation across units and the Gini coefficient, which summarises the distribution of each indicator across the population, with a value of zero representing perfect equality and a value of one representing maximum inequality (appendix pp 11–12).

Role of the funding source
The funder had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results
Access to all facility-type indicators for drinking water varied spatially and temporally. Across all LMICs assessed, access to piped water increased between 2000 and 2017 (from 40·0% [95% UI 39·4–40·7] to 50·3% [50·0–50·5] of the population), but this trend differed across regions (figure 2). Access to improved water overall varied spatially and temporally. Across all LMICs, the 95% UIs were generated by calculating the 2·5th and 97·5th percentiles of the drawn samples. Uncertainty for the posterior distribution and taking the mean of these draws. For each model (appendix pp 10–11).

To identify the water and sanitation facility indicators to use in the model, we fitted a geospatial model to estimates from the Reiner and colleagues estimates of child diarrhoeal deaths to unsafe water and sanitation. We then used access estimates in 2000 to calculate a counterfactual population attributable fraction. Using these population attributable fractions in conjunction with the Reiner and colleagues estimates of child diarrhoeal disease mortality across units, we calculated attributable under-5 deaths for water and sanitation in 2017, as well as the number of averted child deaths in 2017 due to changes in water and sanitation access since 2000. We propagated uncertainty by repeating the calculation for values from each of the 250 draws of the posterior from our model. This methodology is further outlined in the appendix (p 11).

Additionally, we estimated inequality using subnational variation across units and the Gini coefficient, which summarises the distribution of each indicator across the population, with a value of zero representing perfect equality and a value of one representing maximum inequality (appendix pp 11–12).

Role of the funding source
The funder had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results
Access to all facility-type indicators for drinking water varied spatially and temporally. Across all LMICs assessed, access to piped water increased between 2000 and 2017 (from 40·0% [95% UI 39·4–40·7] to 50·3% [50·0–50·5] of the population), but this trend differed across regions (figure 2). Access to improved water overall increased from 82·6% [95% UI 82·3–82·8] in 2000 to 87·0% [86·8–87·1] in 2017 (figure 2; appendix p 32). Access levels for each unit are presented in the appendix and online through our data visualisation tool.

For the data visualisation tool see https://vizhub.healthdata.org/fbd/wash.
Although access to piped water was lowest in sub-Saharan Africa compared with other regions in 2017, notable areas of high access are apparent within sub-Saharan Africa (figure 2). Across sub-Saharan Africa, at least 80% of the population had access (henceforth referred to as high access) to piped water in 2017 in 5-9% (95% UI 5-7-6-2) of units, but 54.0% (53-5-54-8) of units had decreases in piped water access from 2000 to 2017, such as the Western Urban district of Sierra Leone (52-9% decrease [50-2-55·1]; figure 2). Units with high access to piped water facilities in sub-Saharan Africa mostly corresponded to large urban centres, such as Addis Ababa, Ethiopia (97-7% [95% UI 97.0-98-1]), and the Department of Guédiaway in Dakar, Senegal (92-9% [91-0-94-2]). However, in urban centres and other densely populated areas, a high absolute number of people continued to have no access even where unit-level access was high. For example, unit-level access to piped water was 90-5% (95% UI 85-2-95·3) in Casablanca, Morocco, yet 398 300 (198 500-618 500) people had no access. Large increases in piped water access also occurred from 2000 to 2017 for several African countries. In Niger, national-level piped water access increased from 23-5% (95% UI 22-7-24·4) to 47-6% (46-6-48-5), with a 1-3% mean annual percentage-point increase. In sub-Saharan Africa, 19-3% (95% UI 16-2-19-1) of units increased piped water access by more than 10 percentage points (figure 2). Access to improved water facilities overall was widespread in Africa, despite the relatively lower levels of piped water access: 56-8% (95% UI 56-3-57·3) of units had high access (>80%) to improved water in 2017 (appendix p 32).

In south Asia, piped water access was relatively low, with just 8-5% (95% UI 7-8-9-2) of units with high access to piped water in 2017 (figure 2). However, improved water access overall was relatively high in the region, increasing from 83-1% (95% UI 82-9-83-3) in 2000 to 92-5% (92-3-92-6) in 2017. Access to piped water was much higher in southeast Asia, east Asia, and Oceania in 2017, where 58-1% (95% UI 57-5-58-5) of units had high access. However, most of this piped water access was concentrated in China; when excluding China, access to piped water was just 3-2% (95% UI 2-8-3-7) in the region. Access to improved water remained relatively stable in southeast Asia, east Asia, and Oceania over the study period. Access was 91-2% (95% UI 90-6-91-7) in 2000 and 88-7% (88-3-89-1) in 2017. In southeast Asia, east Asia, and Oceania, access to improved water was high (>80%) in 77-0% (95% UI 76-1-77-8) of units in 2017, and the mean annual change in access was more than 2 percentage points in 7-1% (6-3-7-8) of units since 2000.

Access to piped water was relatively high in much of Latin America: 51-0% (95% UI 49-0-53-1) of units had high access to piped water in 2017 (figure 2). Improved water access increased in Latin America since 2000, from 89-6% (89-3-89-7) to 93-2% (93-1-93-3). Individual units also had large increases in access to improved water—eg, 96-4% (94-4-97-9) of units in Peru increased improved water access by more than 10 percentage points.

We sought to identify which units made transitions from no facility (ie, surface water or open defecation) in 2000 to improved facilities in 2017, compared with more gradual transitions (from no facility to unimproved facilities, or unimproved to improved facilities) over the study period. To do so, we compared the most common type of water and sanitation access in each unit (access level of more than 60% of the population; figure 3). Across all LMICs, 397 (95% UI 371-428) units in 2000 had 60% or more of their populations that relied on surface water. Of these, 176 (156-197) units had substantial upgrades—transitioning to 60% or more using improved facilities by 2017. In comparison, 780 (95% UI 741-825) units had 60% or more of people relying on surface water or 60% or more of people using unimproved facilities in 2000; of these, relatively incremental upgrades (either from surface water to unimproved facilities, or from unimproved to improved water facilities) occurred in 182 (95% UI 160-205) units. The full array of model outputs can be accessed online via our customised online visualisation tools.
Figure 2: Access to piped water and sewer or septic sanitation at the second-administrative-unit level, 2000 and 2017

Access was modelled with use of model-based geostatistics for continuous continent-wide surfaces and aggregated to the second administrative level. The results for piped water are shown for years 2000 (A) and 2017 (B). The results for sewer or septic sanitation are also shown for 2000 (C) and 2017 (D). Maps reflect administrative boundaries, land cover, lakes, and population; dark grey-coloured grid cells were classified as barren or sparsely vegetated and had fewer than ten people per 1 x 1-km grid cell, or were not included in these analyses.38–43 Interactive visualisation tools are available online.

For the visualisation tools see https://vizhub.healthdata.org/lbd/wash
Mozambique by 2017, but the lowest access level was similar in 2000 and 2017, while the highest level of access increased, widening the total range. Inequalities as determined with use of the Gini coefficient revealed additional trends. In 2000, 25 LMICs had Gini coefficients that exceeded 0·15 for improved water access, whereas in 2017, only nine remained higher than that level.

Access to sewer or septic sanitation across all LMICs increased from 28·7% (95% UI 28·5–29·0) in 2000 to 46·3% (46·1–46·5) in 2017, whereas access to improved sanitation overall increased from 60·0% (59·8–60·1) to 75·8% (75·7–75·9; figure 2, appendix p 36). Some regions saw large increases in access to sewer or septic sanitation since 2000, whereas access remained low across the study period in others.

Access to sewer or septic sanitation in sub-Saharan Africa was concentrated in similar areas to piped water, but just 1·0% (95% UI 1·0–1·0) of units had high access in the region, such as Bulawayo, Zimbabwe (96·5% access [95·8–97·1]; figure 2). In places with high unit-level access, many individuals can remain without access to sewer or septic sanitation. For instance, despite 88·6% (87·2–89·7) of the population of Harare, Zimbabwe having access, more than 25,300 people did not have access in 2017.

In south Asia, there was high access to sewer or septic sanitation in 11·3% (95% UI 9·4–12·9) of units in 2017 (figure 2). Improved sanitation overall had high unit-level access in 69·0% (95% UI 67·6–70·4) of units in south Asia, increasing from a regional access level of 29·4% (29·1–29·6) in 2000 to 79·4% (79·2–79·7) in 2017. Access to sewer or septic sanitation was higher in southeast Asia, east Asia, and Oceania compared with south Asia in 2017; 42·0% (95% UI 40·8–43·1) of units in the region had high access. Substantial increases in sewer or septic sanitation access occurred over the study period, such as in Rapti District, Mid-Western Region, Nepal, 49·3% (95% UI 43·5–54·9) increase; mean annual change of 2·7 percentage points). Unit-level access to improved sanitation was high in 67·8% (95% UI 66·8–69·0) of units in southeast Asia, east Asia, and Oceania, increasing from 81·6% (81·2–82·0) to 85·9% (85·7–86·2) over the study period.

In Latin America, there was high access to sewer or septic sanitation in 32·8% (95% UI 31·7–33·8) of units in 2017 (figure 2). Latin America notably had an 11·8% increase in access to sewer or septic sanitation over the period (from 59·5% [59·3–59·8] to 71·3% [70·9–71·6]). Large increases occurred in sewer or septic sanitation from 2000, including in San Pedro Sula, Cortés, Honduras (increase of 35·9% [32·4–39·5], mean annual change of 2·0 percentage points). Access to improved sanitation overall was also high across the region, with more than half (54·5% [53·6–55·6]) of units in Latin America with high (>80%) access.

Of the 1,830 (95% UI 1,797–1,863) units in which 60% or more of people practised open defecation in 2000, 686 (664–711) transitioned substantially to having access to improved facilities in 2017 (figure 3). By contrast, 580 (550–610) of the 5,630 (5,560–5,690) units in which 60% or more of people practised open defecation or in which 60% or more of people used unimproved facilities in 2000 transitioned incrementally by 2017. Subnationally, many units in Ethiopia, such as Afder Zone, Somali, increased access to improved sanitation (11·6% [12·4–16·8] in 2000; 26·0% [22·8–29·0] in 2017) while substantially reducing open defecation (79·7% [77·0–82·1] in 2000; 43·3% [39·1–47·2] in 2017) over the period.

Populations with high reliance on open defecation in 2017, were mostly concentrated in trans-border regions in southern Angola–northern Namibia and in west and central Africa.

According to our comparative risk assessment framework, in 2017, 182,300 (95% UI 159,900–208,200) under-5 child deaths in sub-Saharan Africa were attributed to unsafe sanitation, whereas increases in safe sanitation access averted at least 10,100 (8,970–11,400) child deaths in the region (figure 4). In southeast Asia, east Asia, and Oceania, increases in safe sanitation averted at least 2,750 (95% UI 2,530–3,040) child deaths, with 7,810 (7,050–8,700) child deaths attributable to unsafe sanitation in 2017, compared with 18,400 (16,600–20,700) averted child deaths and 4,400 (4,080–4,690) child deaths attributable to unsafe sanitation in Latin America in 2017.

Subnational disparities in improved sanitation decreased in 53·9% (95% UI 50·6–59·6) of countries from 2000, and large decreases occurred in Vietnam and Cambodia, among other locations, although disparities were evident across LMICs in 2017 (figure 5). The lowest-access unit in Cambodia was 4·9 times less than the national mean in 2000, and just 1·4 times less than in 2017. Temporal trends in disparities varied in LMICs. In Namibia, mean access to improved sanitation increased overall from 2000 to 2017, but the lowest level of access remained relatively unchanged since 2000. Conversely, the highest level of access and the lowest level of access increased substantially in Cambodia over the study period. With use of the Gini coefficient, we found that many countries had consistent subnational inequality in improved sanitation, with Gini coefficients of more than 0·15 in 37 LMICs in 2000 and 30 LMICs in 2017. Notably, Chad, Libya, and Togo had Gini coefficients of more than 0·35 in 2017.

Discussion

Access to safe drinking water and sanitation facilities has improved globally between 2000, and 2017, but disparities in access varied across LMICs, presenting a barrier to achieving the SDG goal of universal access (100% access). Many units, such as in Cambodia for drinking water, had sizeable transitions, with the great majority of the population relying on the lowest quality of facility types in 2000 but accessing improved facilities by 2017. These units are exemplars that merit further study to identify
Figure 3: Water and sanitation facility types used at the second-administrative-unit level, 2000 and 2017

The co-distribution of improved, unimproved, and no facility access is shown for water for 2000 (A) and 2017 (B) and sanitation for 2000 (C), and 2017 (D). Green denotes second administrative-level units where most of the population (>60%) had access to improved facilities, blue denotes a more than 60% reliance on unimproved facilities, and red denotes more than 60% relying on surface water in A and B or practicing open defecation in C and D. Yellow indicates that there was no single dominant facility type used by more than 60% of the unit’s population. Maps reflect administrative boundaries, land cover, lakes, and population; dark grey-coloured grid cells were classified as barren or sparsely vegetated and had fewer than ten people per 1 x 1-km grid cell, or were not included in these analyses.38–43
Figure 4: Effect of changes in access to water and sanitation in 2017 on child diarrhoeal deaths at the second-administrative-unit level
Deaths are calculated under the counterfactual scenario in which access to safe water and sanitation remained at the values observed in the year 2000. The number of deaths attributed given access levels observed in 2017 is shown for water (A) and sanitation (C). The number of deaths averted (shown in green) or caused (shown in purple) in 2017 due to changes in access levels compared with 2000 is shown for water (B) and sanitation (D). Maps reflect administrative boundaries, land cover, lakes, and population; dark grey-coloured grid cells were classified as barren or sparsely vegetated and had fewer than ten people per 1 × 1-km grid cell, or were not included in these analyses. 38–43
drivers of success for replication elsewhere. In many countries, however, such progress was concurrent with increasing geographical inequality, as some units were effectively left behind. Our local-level estimates provide information to better target interventions to ensure progress towards greater access without increasing geographical inequality.

Estimates of access at the unit level support local monitoring of progress towards the SDG targets. Although our estimates of access to safe drinking water and sanitation facilities represent a best-case scenario of SDG attainment, in that they do not capture all the elements of safe management as defined by the JMP, even in the best-case scenario it is evident that many locations will need to scale up access to attain the goal of universal coverage. These results also show that estimates of access stratified by urban or rural status only or at the first administrative level are likely to mask further localised heterogeneity. By providing estimates at the second administrative level, in which programmatic decisions are often made, our results enable local decision makers to target resources and programmes with greater precision. Given that household-level water, sanitation, and hygiene interventions have had mixed results, these estimates can support targeting interventions at the community level to maximise efficiency and serve areas most in need of access.

Although increases in access to improved water facilities overall were observed in sub-Saharan Africa, access to piped water remained low in 2017. Decreases in piped water access were particularly apparent in some regions of sub-Saharan Africa, where demographic changes might be outpacing infrastructure development. The bulk of interventions in sub-Saharan Africa have focused on increasing access to improved wells or springs, and the relatively high rates of access to other improved water facilities in LMICs in 2017 indicates that...
these interventions have largely been successful. Further investment in piped drinking water is needed to scale up and maintain access and to ensure consistent and quality access. Although initially costly, these efforts will ultimately improve economic productivity, supporting national development and stability.16,46

Our estimates revealed several units in which access to the safest facility types improved substantially. Exemplars in increasing piped water access include Svay Pao District, Battambang, Cambodia; Jantetelco Municipality, Morelos, Mexico; and Harari People’s National Regional State, Ethiopia. Alongside economic growth nationally, the autonomous Phnom Penh Water Supply Authority has been credited with substantial expansion of Cambodia’s urban piped water supply, whereas national and regional policy and government investment are likely to have played a role in Mexico and Ethiopia.50–53 Further research on successful interventions in these locations could help other units to adapt similar strategies. The same is true for exemplars of increased sewer or septic sanitation, including Kampong Chhnang District, Cambodia, and Bagmati Zone, Central Development Region, Nepal, where potential drivers include governance guided by national and regional policies, infrastructure construction and management, and (in the case of Nepal) social movements.12–15 Urbanisation generally leads to increased water and sanitation infrastructure, although informal settlements in urban areas are often excluded, presenting a challenge to achieving equity in access.15

Although access to the safest facility types is lowest across sub-Saharan Africa, several units have high access in the region. These exemplars indicate that increasing access to piped systems in sub-Saharan Africa is entirely possible, despite demands on infrastructure and long-term maintenance. Here, we consider the safest facilities to be those with the lowest health risk, defined as the lowest associated risk-ratio for diarrhoeal disease. Considerations of cost-effectiveness and logistical needs will probably influence what technology is the most appropriate for any single community, and these decisions can be more effectively made at the local level.

In countries where access to safer facilities increased only in units with existing access to improved facilities—e.g. transitioning from improved wells to piped—the population relying on the worst facility types was effectively left behind. Transitions to the safest facility type have the greatest potential to protect health compared with more moderate transitions.11,57 Improved facilities might not prevent environmental contamination and disease transmission after long-term use or in poor environmental conditions.58 Although piped water and sewer or septic sanitation have the greatest potential to prevent deaths from enteric diseases,57 piped systems are also susceptible to contamination,59 and water quality is not currently captured in our estimates. Despite having a smaller effect on health outcomes, transitions from surface water or open defecation to unimproved facilities, nonetheless represent important progress and potentially improved quality of life, including time saved for education and economic productivity.59,60 Decision makers would benefit from detailed local information on the differences in increases by type of access to better target future interventions.

Achieving universal access in line with the SDG target is likely to require tailored interventions framed within a broader focus on reducing disparities. Countries such as Mozambique were able to increase mean access to improved water facilities, but although the highest level of access increased, the lowest level was relatively stable from 2000 to 2017, potentially reflecting improvements concentrated in urban centres with large populations where access was already higher. Targeted rural interventions might be needed to serve those with the lowest levels of access, for whom increases in access have not been as substantial. Ethiopia, for example, was able to increase the lowest levels of access to improved water facilities by 2017. In remote communities where a small number of people continue to have no access despite a high national access level, local-level investments in infrastructure are probably most suitable to address this disparity. Conversely, in Nigeria, where large numbers of people concentrated in single units do not have access to safe sanitation, more centralised solutions might best serve these dense urban populations. Examples such as improved water access in Cambodias, which saw pronounced increases in both the lowest access and highest access relative to 2000 levels, potentially present models for adoption elsewhere. Previous studies have identified poor, indigenous, and rural communities as the least likely to have access.55,57 Although the disparity in access between urban and rural areas has long been recognised, our estimates underscore the ongoing need for investment in rural water and sanitation.

Our results identified several units in which changes in access to safe water averted relatively few child deaths, or decreased access to safe water led to increased child diarrhoeal mortality. This finding largely reflects decreases in piped water access in some units—potentially driven in part by conflict and instability;60 particularly in areas such as in northeastern Nigeria—and suggests that what improvements in access did occur were not for the safest forms of facilities or that the improvements were not of a sufficient magnitude to have a major effect. In addition, our estimates do not capture other elements of safety, such as safe water storage and safe disposal of child faeces, which could drive reductions in diarrhoeal deaths.61 Although the absolute number of deaths averted in a unit might not be large, the number of deaths attributable to unsafe water and sanitation in 2017 remains high, indicating that efforts to expand access would also reduce child mortality. Investments in increasing access to improved water and sanitation facilities are likely to have the greatest effect on reducing child deaths due to diarrhoea when coupled with other measures that protect
Our estimates facilitate targeting treatment of some NTDs, such as lymphatic filariasis and podoconiosis. More broadly, strengthening primary health-care systems and addressing social and economic determinants of health will also be imperative to successfully reduce disease and prevent child deaths. Our estimates can help by identifying areas susceptible to disease spread, aiding vaccine-targeting efforts, and assisting disease elimination campaigns in focusing on where they will be most successful. The relationship between access to water and sanitation and the spread of NTDs provides a particular opportunity to coordinate and improve disease prevention efforts across sectors.

Water, sanitation, and hygiene are also integral to the Global Trachoma Mapping Project, and low levels of infrastructure investments toward communities with a high burden of NTDs, such as those identified through the Global Trachoma Mapping Project, and low levels of access to drinking water and sanitation facilities.

The geostatistical nature of this analysis allows for explicit incorporation of geopositioned data, more effectively capturing local variation in access over space and time, compared with studies that use exclusively areal data. Additionally, the use of a continuation-ratio modelling framework appropriately accounts for the ordinal relationships between indicators of water or sanitation facility type. This study also uses an extensive suite of covariates to leverage the complex relationships between water and sanitation access and environmental, social, and public health correlates at the local level. Our findings highlight the need to increase investment, assess existing interventions, scale up and expand successes, and improve monitoring of access to these facilities. Ultimately, these estimates, in combination with parallel work on oral rehydration therapy, provide an actionable atlas to progress toward universal access, reduce child diarrhoeal mortality and the spread of disease, and improve wellbeing worldwide.

The data and methodology underlying these results have several limitations. First, SDG 1.4.1 aims to achieve universal access to basic services, and SDG 6 aims to achieve universal access to safely managed services; however, current data are insufficient to produce reliable estimates of these dimensions of access at the spatial and temporal scale presented here. Consequently, this analysis focused on access by facility type classification (figure 1), and our estimates provide a best-case scenario for the SDGs (all improved facilities are safely managed and provide basic services). Second, despite the fine spatial resolution of this study, these results might not fully represent intra-urban disparities in water and sanitation. Third, to incorporate the vast quantity of areal data in a geostatistical framework, areal data were transformed into geopositioned point data over the corresponding geographical area. This method could result in smoothed estimates in areas with predominantly areal data. Fourth, our data do not capture the impacts of conflicts or climate change-related weather events and disasters, and data for locations affected by these factors might not reflect current conditions. Fifth, survey data are subject to known biases and inaccuracies in reporting, and these issues coupled with data scarcity in some locations could affect the accuracy of our estimates. Sixth, our analysis of inequality is limited to variation in access and does not encompass social and economic factors affecting inequality in access. Seventh, uncertainty in existing population estimates affects the precision of our count estimates of access. Finally, although our model generates estimates of uncertainty considering the covariates as well as spatiotemporal trends, uncertainty is not explicitly incorporated from the survey design or the intermediate covariates generated from our stacking procedure (appendix p 9) due to computational limitations.

We plan to adopt the newly updated global indicators of water and sanitation access, including categories of basic and safely managed, by the WHO–UNICEF JMP. Although our study identified the best performing units and diverse modes of improvement across facilities, it was beyond our scope to identify the specific factors and interventions that contributed to these successes. Further research on potential shared characteristics across countries and units achieving high and equitable access could inform potential avenues for policy makers to adopt, particularly in light of the shifting focus from improved facility access to safely managed services. This analysis provides a comprehensive set of estimates across all facility types and locations; additional research with these methods to explore aspects presented here in greater detail would further enable prioritisation and targeting of water and sanitation interventions at the local level.

Despite substantial gains in some regions, accelerated progress will be necessary to achieve universal and equitable access to the safest forms of drinking water and sanitation facilities in line with SDG targets. Sub-Saharan Africa, in particular, would probably benefit from a precision public health approach to increasing access. This analysis improves on traditional national and subnational estimates, providing an analysis of both absolute and relative progress and identifies communities with low access as well as exemplars of improved access at the second administrative level. Our results indicate that vast geographical inequalities persist in both the proportion and number of people with access within countries, as well as in improvements of the quality of facilities over time. Local estimates can guide targeting of disease prevention efforts, particularly vaccines and interventions for nutrition and NTDs, to the communities with the lowest access. Ultimately, our estimates provide
a resource for researchers, policymakers, and implementers to improve drinking water and sanitation access at local to national geographical scales, ensuring that all have access to this basic human right.

Local Burden of Disease WaSh Collaborators

that all have access to this basic human right.
Determinants of Health Research Center (M Anjomshoaa PhD), Kafsanjan University of Medical Sciences, Rafsanjan, Iran; School of Public Health (A Aryanidro PhD), Hasunuddin University, Makassar, Indonesia; Department of Applied Social Sciences (C T Antonio), University of Nursing (P H Lee PhD), Hong Kong Polytechnic University, Hong Kong, China; Menzies Institute for Medical Research (B Antony PhD, A Singh M Tech), University of Tasmania, Hobart, TAS, Australia; Agribusiness Study Program (E Antriyandarti Dr. Agr.Sc.), Surakarta, Indonesia; Neurology Department (Prof H M A Aref PhD, Prof N El Nahas MD, Prof A S Shalash PhD), Department of Entomology (A M Samy PhD), Ain Shams University, Cairo, Egypt; Department of Public Health (O Aremen PhD), Birmingham City University, Birmingham, United Kingdom; Social Determinants of Health Research Center (B Armoon PhD), Sabe University of Medical Sciences, Sabe, Iran; Social Determinants of Health Research Center (B Armoon), Yasuj University of Medical Sciences, Yasuj, Iran; School of Health Sciences (A Arora PhD), Western Sydney University, Campbelltown, NSW, Australia; Disciple of Child and Adolescent Health (A Arosa), University of Sydney, Westmead, NSW, Australia; Monitoring Evaluation and Operational Research Project (K K Aryan PhD), Abt Associates Nepal, Lalitpur, Nepal; School of Nursing and Midwifery (A Arzani DrPh), Social Determinants of Health Research Center (A Bijani PhD, S Moudii PhD), Department of Clinical Biochemistry (A Mamanpoor PhD), Student Research Committee of Health Research Center (M Zamani MD), Babol University of Medical Sciences, Babol, Iran (A Arzani); Department of Nursing (H T Atalay MSc, A Girmay MSc, A Badawi PhD), Public Health Agency of Canada, Toronto, Canada; Hubert Department of Global Health and Public Health (A Arora), University of Sydney, Westmead, NSW, Australia; Determinants of Health Research Center (O Aremu PhD), Department of Public Health (Prof H M A Aref PhD, Prof N El Nahas MD, Prof A S Shalash PhD), Shiraz University of Medical Sciences, Iran; Department of Biology (S Athari MPH), Lorestan University of Medical Sciences, Mahshahr, Iran; Department of Microbiology (A Hasanzadeh), Arzhang University of Medical Sciences, Arzang, Iran; Department of Statistics and Econometrics (Prof M Ausloos PhD, Prof M Ausloos, Prof C Hertelti PhD, A Pana PhD), Bucharest University of Economic Studies, Bucharest, Romania; King George's Medical University, Lucknow, India (Prof S Awasthi MD); Department of Nursing (N Awoke MSc), School of Public Health (T L Lenjebo MPH), Department of Midwifery (K Paulos MSc), Wolaita University, Wolaita, Ethiopia; School of Public Health (G Ayano MSc, D Hendrie PhD, AM Majeed MD, Prof S Rawaf MD), Shiraz University of Medical Sciences, Iran; Department of Epidemiology and Biostatistics (M Behzadifar MSc), Social Determinants of Health Research Center (M Behzadifar PhD), Department of Public Health (M Imani-Nasab PhD), Lorestan University of Medical Sciences, Khorramabad, Iran; Department of Medicine (D F Bejargan Ramirez BN), El Bosque University, Bogota, Colombia; Transplant Service (D F Bejargan Ramirez), University Hospital Foundation Santa Fe de Bogota, Bogota, Colombia; School of the Environment (Prof M L Bell PhD), Yale University, New Haven, CT, United States; Nuffield Department of Population Health (D A Bennett PhD, B Lacey PhD), Centre for Tropical Medicine and Global Health (C Dolecek MD, S Lewycka PhD), Malaria Asia Project (J D Weiss PhD), University of Oxford, Oxford, United Kingdom; Department of Public Health (D A Berbada MPH, Y C D Geramo MSc, M B Sorrie MPH, F G W/hawariat MPH), Faculty of Health Human Resources Research Center, University of Health and Allied Sciences, Ho, Ghana; Department of Nursing (Y A Aynalem MSc, W S Shibaraw MSc), Debre Berhan University, Debre Berhan, Ethiopia; Public Health Risk Sciences Division (A Badawi PhD), Public Health Agency of Canada, Toronto, ON, Canada; Department of Nutritional Sciences (A Badawi PhD, Centre for Global Child Health (Prof Z A Bhutta PhD), Department of Medicine (V Chutt MD), University of Toronto, Toronto, ON, Canada; Department of Chemistry (Prof M Bagherzadeh PhD, N Rahbii MSc), Sharif University of Technology, Tehran, Iran; Department of Forensic Medicine and Toxicology (S M Bakhavannavar PhD), Centre for Bio Cultural Studies (CBI CS) (P Hoogar PhD), Manipal Academy of Higher Education, Manipal, India (Prof V Iha MD), Department of Medical Microbiology (S Balakrishnan PhD), School of Nursing and Midwifery (A Desalew MSc), School of Public Health (M G Tekle MPH), Haramaya University, Harar, Ethiopia; Department of Hypertension (Prof M Banach PhD), Medical University of Lodz, Lodz, Poland; Polish Mothers' Memorial Hospital Research Institute, Lodz, Poland; (Prof M Banach), Department of Internal Medicine (J A M Banouh MRCP), University of London, London, United Kingdom; Department of General Medicine (J A M Banouh), Pediatric Dentistry and Dental Public Health Department (Prof M El Tantiawi PhD), Alexandria University, Alexandria, Egypt; Clinic for Infectious and Tropical Diseases (A Banco PhD), Clinical Center of Serbia, Belgrade, Serbia; Faculty of Medicine (A Barac, Prof Z A Bhutta), Institute of Microbiology and Immunology (E Dubhanjin PhD), School of Public Health and Health Management (Prof M M Santric-Milicevic), University of Belgrade, Belgrade, Serbia; Department of Neurosciences (Prof M A Barboza MD), Costa Rican Department of Social Security, San Jose, Costa Rica; School of Medicine (Prof M A Barboza), University of Costa Rica, San Pedro, Costa Rica; Heidelberg Institute of Global Health (HIGIH) (Prof T W Bärnighausen MD, J De Neve MD, B Moazen MSc, S Mohammed PhD), Heidelberg University, Heidelberg, Germany; T H Chan School of Public Health (Prof T W Bärnighausen), Center for Primary Care (S Basu PhD), Department of Global Health and Population (Prof O F Norheim PhD), Division of General Internal Medicine (Prof A Sheikh MD), Harvard University, Boston, MA, United States; School of Public Health (S Basu), Department of Primary Care and Public Health (J Car PhD, Prof A Majeed MD, Prof S Rawaf MD), Imperial College Business School (D Kusuma DSc), Imperial College London, London, United Kingdom; Faculty of Information Technology (V Bay PhD), Ho Chi Minh City University of Technology (HUTECH), Ho Chi Minh City, Vietnam; Health Human Resources Research Center (M Bayati PhD), Non-communicable Disease Research Center (Prof R Malekzadeh, S G Sepanlou), Shiraz University of Medical Sciences, Shiraz, Iran; Department of Health Policy Planning and Management (N Bedi), Gandhi Medical College Bhopal, Bhopal, India; Department of Physical Medicine and Rehabilitation (M Beheshti MD), Department of Epidemiology and Health Promotion (Prof H Benzian PhD), New York University, New York, NY, United States; Department of Public Health (M Rahman PhD, N G Keshtkavarz PhD, M Behzadifar MSc), Social Determinants of Health Research Center (M Behzadifar PhD), Department of Public Health (M Imani-Nasab PhD), Lorestan University of Medical Sciences, Khorramabad, Iran; Department of Medicine (D F Bejargan Ramirez BN), El Bosque University, Bogota, Colombia; Transplant Service (F Bejargan Ramirez), University Hospital Foundation Santa Fe de Bogotá, Bogota, Colombia; School of the Environment (Prof M L Bell PhD), Yale University, New Haven, CT, United States; Nuffield Department of Population Health (D A Bennett PhD, B Lacey PhD), Centre for Tropical Medicine and Global Health (C Dolecek MD, S Lewycka PhD), Malaria Asia Project (J D Weiss PhD), University of Oxford, Oxford, United Kingdom; Department of Public Health (D A Berbada MPH, Y C D Geramo MSc, D M Hayelom MSc, M B Sorrie MPH, F G W/hawariat MPH), Faculty of Business and Economics (G T Works MPH), Arba Minch University, Ethiopia; School of Public Health and Community Medicine (R S Bernstein MD), Eunry University, Atlanta, GA, United States; Division of General Internal Medicine (A G Bhat MD), University of Massachusetts Medical School, Springfield, MA, United States; Department of Statistical and Computational Genomics (K Bhattacharyya MSc), National Institute of Biomedical Genomics, Kalyani, India; Department of Statistics (K Bhattacharyya), University of Calcutta, Kolkata, India; Injury Division (S Bhauvik MBBS), The George Institute for Global Health, New Delhi, India (Prof V Jha); The George Institute for Global Health (S Bhamuk), Transport and Road Safety (TARS) Research Centre (R Biswas MSc, S Boufous PhD), School of Public Health and Community Medicine (S Karki PhD), School of Optometry and Vision Science (Prof K Pesudovs PhD, Prof S Resnikoff MD), University of New South Wales, Sydney, NSW, Australia; Centre of Excellence in Women & Child Health (Prof Z A Bhutta), Division of Women and Child Health (J K Das MD), Aga Khan University, Karachi, Pakistan; Mario Negri Institute for Pharmacological Research, Ranica, Italy (B Bkbov PhD); National Centre for Epidemiology and Population Health (M Bin Sayeed MSc, A Lal PhD), Research School of Population Health (K Wangdi PhD), Australian National University, Canberra, ACT, Australia; Department of Clinical Pharmaceutics and Pharmacology (M Bin Sayeed), School of Dentistry (S Bohlooli PhD), Islamic Azad University, Kermanshah, Iran; Department of Biomedical Technologies (A N Birko MSc), Bauman Moscow State Technical University, Moscow, Russia; Department of Epidemiology and Evidence Based Medicine (Prof N I Briko DSc, TARS) Research Centre (R Biswas MSc, S Boufous PhD), School of Public Health and Community Medicine (S Karki PhD), School of Optometry and Vision Science (Prof K Pesudovs PhD, Prof S Resnikoff MD), University of New South Wales, Sydney, NSW, Australia; Centre of Excellence in Women & Child Health (Prof Z A Bhutta), Division of Women and Child Health (J K Das MD), Aga Khan University, Karachi, Pakistan; Mario Negri Institute for Pharmacological Research, Ranica, Italy (B Bkbov PhD); National Centre for Epidemiology and Population Health (M Bin Sayeed MSc, A Lal PhD), Research School of Population Health (K Wangdi PhD), Australian National University, Canberra, ACT, Australia; Department of Clinical Pharmaceutics and Pharmacology (M Bin Sayeed), School of Dentistry (S Bohlooli PhD), Islamic Azad University, Kermanshah, Iran; Department of Biomedical Technologies (A N Birko MSc), Bauman Moscow State Technical University, Moscow, Russia; Department of Epidemiology and Evidence Based Medicine (Prof N I Briko DSc,
This study was funded by the Bill & Melinda Gates Foundation. Co-authors employed by the Gates Foundation provided feedback on initial mapped estimates and drafts of this manuscript. MLB reports grants from US Environmental Protection Agency, National Institutes of Health (NIH), and the Wellcome Trust Foundation, during the conduct of the study; and honoraria or travel reimbursement from NIH (for review of grant proposals). American Journal of Public Health (participation as editor). Global Research Laboratory and Seoul National University, Royal Society (London, UK), Ohio University, Atmospheric Chemistry Gordon Research Conference, Johns Hopkins, Bloomberg School of Public Health, Arizona State University, Ministry of the Environment, Japan, Hong Kong Polytechnic University, National University of Illinois—Champaign, and University of Tennessee—Knoxville, outside of the submitted work. AD, PL, MB, and GIH managed the appendix. All other authors provided data, reviewed results, initiated modelling infrastructure, or reviewed and contributed to the study.

Declaration of interests

Contributors

AD, PL, MB, GCG, AB, and JA collected and cleaned the data. AD and PL vetted the data. AD produced estimates and AD, RCR, and KEW vetted the models and the results. AD and MMP prepared the draft of the manuscript. AD, KJ, MB, and PL constructed the figures and tables. RCR and SIH provided overall guidance, RBF, PCR, RCR, and SIH managed the project, AD, MFP, MB, BFB, and GH finalised the manuscript on the basis of comments from other authors and reviewer feedback. AD, PL, MB, and GIH managed the appendix. All other authors provided data, reviewed results, initiated modelling infrastructure, or reviewed and contributed to the study.

This study was funded by the Bill & Melinda Gates Foundation.

Co-authors employed by the Gates Foundation provided feedback on initial mapped estimates and drafts of this manuscript. MLB reports grants from US Environmental Protection Agency, National Institutes of Health (NIH), and the Wellcome Trust Foundation, during the conduct of the study; and honoraria or travel reimbursement from NIH (for review of grant proposals). American Journal of Public Health (participation as editor). Global Research Laboratory and Seoul National University, Royal Society (London, UK), Ohio University, Atmospheric Chemistry Gordon Research Conference, Johns Hopkins, Bloomberg School of Public Health, Arizona State University, Ministry of the Environment, Japan, Hong Kong Polytechnic University, National University of Illinois—Champaign, and University of Tennessee—Knoxville, outside of the submitted work.
outside of the submitted work. JJJ reports personal fees from Amgen, ALAB Laboratoris, Terva, Synexus, and Boehringer Ingelheim, outside of the submitted work. KRG reports grants from UGC Center of Advanced Study (CAS II), Department of Anthropology, Panjab University, Chandigarh, India, outside the submitted work. WM is a Program Analyst in Population and Development at the UNFPA Country Office in Peru, an institution which does not necessarily endorse this study. JFM reports grants from the Gates Foundation, during the conduct of the study. TP reports grants and personal fees from Boston Scientific, grants and personal fees from Biotronik, personal fees from HighLife SAS, outside the submitted work. MJ holds stocks in Ingress Health and Pharmacoeconomics Advice Groningen, and is advisor to Asc Academics, all pharmacoeconomic consultancy companies. MJF reports grants and personal fees from Merck Sharp & Dohme, GlaxoSmithKline, Pfizer, Boehringer Ingelheim, Novavax, Bristol-Myers Squibb, AstraZeneca, Sanofi, IQVIA, Seqirus, Quintiles, Nocartis, and Pharmerit; grants from Bayer, BioMerieux, WHO, EU, FIND, Antilope, DIKTI, LPDP, and Budi; and other support from Ingress Health, Pharmacoeconomics Advice Groningen, and Asc Academics, outside of the submitted work. JAS reports personal fees from Creatla/Horizon, Medisys, Fidia, UBM, Trio health, Medscape, WebMD, Clinical Care options, Clearview Healthcare Partners, Putnam Associates, Spherix, Practice Point Communications, NIH, American College of Rheumatology, and Simply Speaking; other support from Amarin Pharmaceuticals and Viking Pharmaceuticals; non-financial support from FDA Arthritis Advisory Committee, Steering committee of OMERACT (an international organisation that develops measures for clinical trials and receives arms-length funding from 12 pharmaceutical companies), Veterans Affairs Rheumatology Field Advisory Committee, outside of the submitted work. JAS is editor and director of the UAB Cochrane Musculoskeletal Group Satellite Center on Network Meta-analysis. All other authors declare no competing interests.

Data sharing

The source code used to generate estimates is available online. The study data, including full sets of estimates at the first and second administrative levels, are also available online.

Acknowledgments

This work was primarily supported by a grant from the Gates Foundation (OPP1133245). LGA has received support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Finance Code 001), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amaro à Pesquisa do Estado de Minas Gerais. OOA acknowledges the Department of Science and Innovation, National Research Foundation, and DSI/NRF Centre of Excellence for Epidemiological Modelling and Analysis, Stellenbosch, South Africa. SMAl acknowledges the Department of Health Policy and Management, Faculty of Public Health, Kuwait University and International Centre for Casemix and Clinical Coding, Faculty of Medicine, National University of Malaysia for the approval and support to participate in this research project. HTA acknowledges Aksum University. MAu and CH are partly supported by a grant from the Romanian National Authority for Scientific Research and Innovation, CNDS-UEFISCDI, project number PN-III-P1-1144-2016. AAZ acknowledges funding from the Gates Foundation (OPP1171700). ABad is supported by the Public Health Agency of Canada. TWB was supported by the Alexander von Humboldt Foundation. MJ and the Serbian part of this GBD contribution was co-funded through grant O1750914 of the Ministry of Education Science and Technological Development of the Republic of Serbia. JK is a recipient of the 2020 Benjamin V Cohen Peace Fellowship from Ball State University Center for Peace and Conflict Studies. YJK’s work was supported by the Research Management Centre, Xiamen University Malaysia, grants number XMUMRF/2018-C2/ITCM/0001. KKR is supported by a DST PURSE grant and UGC Center of Advanced Study awarded to the Department of Anthropology, Panjab University, Chandigarh, India. BL acknowledges support from the NIHR Oxford Biomedical Research Centre and the British Heart Foundation Centre of Research Excellence, Oxford. PTNM acknowledges the Council for the Development of Social Science Research in Africa. ANA acknowledges Debre Markos University for its support of office and internet access while reviewing this paper. AMSam received a fellowship from the Egyptian Fulbright Mission programme. MMS-M acknowledges the support of the Ministry of Education, Science and Technological Development of the Republic of Serbia (contract number 175087). AShi acknowledges the support of Health Data Research UK. MRS acknowledges the Clinical Research Development Centre of Inama Reza Hospital, Kermanshah University of Medical sciences for their wise advice. JBS is part of Centro de Investigación en Red de Enfermedades Respiratorias (CIBERES), Instituto de Salud Carlos III (ISCIII), Madrid, Spain. RT-S was supported in part by grant PI17/00719 from Instituto de Salud Carlos III-FEIS. BJI acknowledges Manipal Academy of Higher Education, Manipal. TWJ acknowledges the Migraine Foundation Australia and the Department of Medicine, Faculty of Medicine, University of Rajarata, Saliyapura, Anuradhapuraya, Sri Lanka. CSW was supported by the South African Medical Research Council. SBZ received a scholarship from the Australian Government research training program in support of his academic career.

Editorial note: the Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

References


Tatem AJ. WorldPop, open data for spatial demography. Sci Data 2017; 4: 170004.


