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Maggie McQueen Hodges Date

Quantification of the Impact of Climate Change on Water-, Sanitation-, and Hygiene-Attributable Disease in China

By

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Master of Public Health

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Quantification of the Impact of Climate Change on Water-, Sanitation-, and Hygiene-Attributable Disease in China

By

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B.S.
The University of Georgia
2007

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An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
in partial fulfillment of the requirements for the degree of
Master of Public Health
in Global Environmental Health
2013

Abstract

Quantification of the Impact of Climate Change on Water-, Sanitation-, and Hygiene-Attributable Disease in China
By Maggie McQueen Hodges

OBJECTIVE: Climate change can impact the burden of water, sanitation, and hygiene-attributable (WASH) disease, and this impact is expected to be particularly significant in regions such as China, with greater than 450 million cases of diarrhea attributable to unsafe water and sanitation annually. The purpose of this study was to estimate the impact of climate change on WASH disease for China in 2020 and 2030.

METHODS: The World Health Organization's Comparative Risk Assessment (CRA) methodology and other previously described methods for projecting climate sensitive disease burdens were used to project WASH disease burdens. Using unique baseline data produced by Carlton *et al* (2012), literature-derived rate ratios linking climatic variables and WASH disease incidence were applied to estimate future IRs of WASH disease in China. Projections of temperature from the HadGEM2-ES global circulation model, as well as province-specific rates of urbanization, infrastructure improvement, and population growth, were used to generate population-based estimates of the incidence rate for WASH disease in China, for the years 2020 and 2030.

RESULTS: Output from the HadGEM2-ES global climate model indicated that China is anticipated to warm 0.22°C by 2020 and 0.82°C by 2030, under RCP 2.6. Under RCP 8.5, China is expected to experience a slight overall cooling of 0.0015°C by 2020 and a general warming of 0.99°C by 2030. Urbanization, improvements in water and sanitation infrastructure, and the demographic transition will cause the overall incidence rate (IR) of diarrheal disease in China to decrease. However, climate change has the potential to slow this decrease, resulting in a delayed achievement of the previously predicted lower IR, a delay of greater than 2 years for a scenario consistent with linear increase in water and sanitation access. The IR of vector-borne disease (malaria, dengue fever, Japanese encephalitis) is similarly impacted by climate change, with the potential delay ranging from 3 to 13 years.

DISCUSSION: Climate change-attributable increase in water and sanitation-attributable disease has the potential to delay the developmental advantage afforded by improvements to water and sanitation infrastructure by greater than 2 years, strengthening the call for increased mitigation of greenhouse gas emissions.

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Acknowledgements

With far more people to thank here than I can often remember, I will strive to keep it brief. I would not be where I am today without the encouragement, guidance, and unflagging support of my parents, John and Cindy Hodges; from you both, I have absorbed an unquenchable curiosity, a crippling desire to challenge myself, and an endless dose of love and laughter to carry me throughout life. Cassandra O'Lenick has been a tireless proof-reader and ever-present throughout this process; thank you for your friendship and your perfectly-timed humor.

Tremendous thanks go to Dr. Justin V. Remais, for driving my own standards ever higher, for being always available and quickly ready with feedback, and for presenting me with the challenge of my MD/MPH career; thank you for your faith and reinforcement. Jessica Belle deserves unending accolades for her patience with the GIS-naïve and her encouragement along the way; the baseline analysis and data were generously provided by Dr. Elizabeth Carlton, and her feedback on the analytical design has been invaluable; finally, Dr. Song Liang has been an absolute pleasure to work with, and his assistance was vital to this process.

Additionally, this work was supported in part by the Ecology of Infectious Disease program of the National Science Foundation under Grant No. 0622743, by the National Institute for Allergy and Infectious Disease (K01AI091864) and by the Global Health Institute at Emory University.

I also acknowledge the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and thank the Met Office Hadley Centre and Instituto Nacional de Pesquisas Espaciais for producing and making available

their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Table of Contents

Introduction

In the year 2000, the global burden of disease attributable to unsafe water, sanitation, and hygiene (WSH) was estimated to be responsible for 2.2 million deaths worldwide (nearly 4% of all deaths in 2000), and the loss of more than 76 million disability adjusted life-years (DALYs; 5.3% of the total global burden of disease) [1]. The uneven distribution of this disease burden highlights well-recognized, persistent disparities in global health, with 90% of the WSH-attributable burden borne by children under the age of 5 years-old, and 73% of the burden occurring in only 15 developing countries [2]. Mortality and morbidity attributable to unsafe WSH can stem from infections associated with soil transmitted helminths (STHs), schistosomiasis, vector-borne diseases (e.g., malaria and dengue fever), and any of the numerous bacterial, viral, and protozoan diarrheal pathogens [2, 3]. Indeed, the burden of disease attributable to unsafe WSH is composed both of the acute sequelae stemming from exposure to these infectious agents, as well as the long-term sequelae from chronic diarrhea, persistent intestinal parasitosis, and tropical enteropathy, such as malnutrition, stunting, impaired school performance, immunodeficiency, and impaired cognitive functioning [2, 4]. When chronic sequelae are initiated in early childhood, they can confer more DALYs to the overall burden than do the deaths attributable to WSH [2], which in part explains the disproportionate burden of disease borne by children under the age of 5-years old.

Transmission of diseases attributable to unsafe WSH is sensitive to a range of environmental variables, including ambient temperature, precipitation, relative humidity, presence of standing or flowing water and the variability in these conditions [5, 6].

Climate change has the potential to impact the burden of WSH-attributable disease through multiple pathways, as indicated by both observational and experimental studies. As climate change intensifies the hydrologic cycle, increased precipitation is projected to increase the risk of inland flooding, while sea level rise associated with thermal expansion of the oceans and loss of land ice is expected to increase coastal flooding [7, 8]. These flooding events have the potential to overwhelm existing, previously adequate, water and sanitation systems in developed countries [9] and mobilize existing sources of pathogens in regions with poor infrastructure [10]. Meanwhile, increased temperatures can impact disease rates by influencing the replication rate and survival of pathogens and vectors in the environment [11], while drought conditions can increase transmission through altered water use and decreased hygiene practices [12, 13]. Importantly, studies in North America and Europe indicate that high-income countries are also susceptible to the effects of climate change on water and sanitation-attributable disease [10, 14-16]. Globally, an estimated 47,000 deaths and 1.459 million DALYs due to diarrhea were attributed to the climate change experienced up to the year 2000 (relative to a 1961-1990 climate baseline), and this burden is projected to increase from 1-19% by 2030 depending on the region and emissions scenario considered [17].

China has made tremendous progress reducing WSH-attributable disease through decades-long improvements in water supply and sanitation [18]. Yet, considerable disparities remain in the burden of WSH-attributable disease [3], consistent with observations that China's rapid economic growth has served to increase disparities between China's urban and rural populations [19, 20]. Similar to the global burden, 97 % of China's WSH-attributable deaths and 83% of WSH-attributable DALYs are borne by children under the age of 5-years old [3]. WSH-attributable disease in China is dominated by diarrheal disease, accounting for 99.7% of the deaths and 98.0% of DALYs. It has been estimated that if the 2015 Millennium Development Goals (MDGs) for both water and sanitation are met, the improvements would save China over US$11 billion annually as a result of the direct and indirect health costs saved [21]. While the MDG for drinking water was met in 2009, six years ahead of schedule, the MDG for sanitation has been more difficult to achieve [22].

Investments in China's water and sanitation infrastructure during the 2006-2010 time period exceeded US$54 billion (RMB$430 billion), and the population served by municipal water utilities has increased from 50% in 1990 to 95% in 2008 [23]. Climate change threatens to stress urban water and sanitation infrastructure, potentially eroding the gains made through these rapid investments in infrastructure. China has particular vulnerabilities to the adverse effects of climate change, including risks associated with flooding, drought, and infectious disease [24]. Where average global temperatures are expected to increase in the range of 1.4-5.8°C by 2100 depending on future global greenhouse gas emissions, China is projected to experience a 3.9-6.0 °C increase, and has already warmed 0.9°C over the past 30 years [25-27]. Meanwhile, China's water resources are limited, with overall per capita supply at 25% of the world average, and an imbalanced distribution between the dry northern regions and water-rich south [18]. Of considerable concern, then, is the anticipated decreased precipitation in the already-dry northeast and southwest, and increased precipitation in the wet southeast [28].

No assessment of the anticipated change in WSH-attributable disease in response to projected changes in China's climate has been carried out to date. Such an assessment, particularly at the provincial scale, would allow for improved targeting of infrastructure investments, and would provide much-needed information about the consequences of greenhouse gas mitigation policies. Here, we quantify the burden of WSH-attributable disease in China attributable to climate change in 2020 and 2030, looking specifically at the disease burden of diarrheal disease, malaria, dengue fever, schistosomiasis, STH infections, and Japanese encephalitis.

Methods

This analysis extends previous estimates of the burden of disease attributable to unsafe WSH in China [3], using comparative risk assessment (CRA) methods to estimate the burden of disease attributable to climate change [1, 17, 29]. The goal was to project the burden of WSH-attributable disease in China forward under climate change conditions at the provincial scale. Following previous application of CRA methods, the analytical steps included: identification of climate sensitive health outcomes; quantitative estimation of the climate-health relationship, including modifying or confounding factors; definition of exposure scenarios; and estimation of the attributable and avoidable burdens of disease. The analysis was carried out for 31 provincial level administrative districts within China, consisting of 22 provinces, 5 autonomous regions, and 4 municipalities, and the estimates have been adjusted to account for population growth, urbanization, changes in provincial age distribution, and varying rates of water and sanitation infrastructure improvement.

Data sources

Exposure based estimates, national health surveys, and data from the China's national infectious disease reporting system (NIDR) were drawn from our previous work describing the burden of diarrheal disease, STH infections, schistosomiasis, malaria, dengue fever, and Japanese encephalitis attributable to unsafe water and sanitation in China in 2008 [3]. STH and schistosomiasis prevalence were drawn from national survey data [3]; vector-borne disease incidence was derived from the NIDR [3]; and diarrheal disease incidence was estimated from an exposure based analysis using methods described elsewhere [1, 3]. Together, these estimates of STH infections, schistosomiasis, vector-borne disease and diarrheal disease rates served as the baseline values for the current analysis. The China-specific rate ratios (RRs) from our previous work [3] served as baseline RRs that are adjusted in the current analysis following an assessment of the climate sensitivity of diarrheal disease based on the literature review, described next.

Identification of climate sensitive health outcomes and literature review

WSH-attributable disease was defined to include disease resulting from consumption of contaminated water, poor personal, domestic, or agricultural hygiene associated with a lack of clean or adequate water access, exposure to contaminated aerosols from improperly managed water systems, and direct contact with water-dwelling vectors or pathogens, as described previously [1]. A comprehensive literature review was conducted to identify studies describing the climate sensitivity of diseases stemming from these exposures: diarrheal disease, malaria, dengue fever, STH infections, schistosomiasis, and Japanese encephalitis. A broad search of medical, environmental health, environmental science, and demographic journals was conducted using PubMed, EBSCO Host, and Google Scholar and using the following MeSH terms and keywords: ‘climate change,’ ‘global warming,’ ‘temperature,’ ‘precipitation,’ ‘rainfall,’ ‘humidity,’ ‘health’ and ‘diarrhea,’ ‘malaria,’ ‘dengue,’ ‘schistosomiasis,’ ‘helminths,’ ‘Japanese encephalitis,’ and ‘risk.’ In accordance with established methods [17, 30], the results of this review were used to identify RRs or changes in incidence that describe the response of WSH-attributable disease to variations in climate components, including temperature, precipitation and relative humidity. Studies were prioritized for use based on study design, generalizability of results, and the biological plausibility of the underlying assumptions and climate-health relationships.

Quantitative estimation of climate-health relationships

Diarrheal Disease

As the baseline estimates of diarrheal disease used in our prior analysis were based on exposure to defined scenarios of water and sanitation access [3], the analysis of the climate-diarrheal disease relationship was also stratified by water and sanitation access scenarios. In order to apply risk ratios (RRs) that most closely approximated the conditions found in China, studies were classified, based on the water and sanitation access of the study populations, into the scenarios described in our earlier work. While Pruss and colleagues (2002) describe six water and sanitation access scenarios, they note that scenarios I and III do not occur on a large scale, and are therefore negligible in larger scale analyses. Our 2008 analysis provided China-specific RR for WSH-attributable disease stratified by water and sanitation access scenario for scenarios II, IV, Va, Vb, and VI [3]. Due to the limited number of available studies identified by our review of literature quantifying the climate sensitivity of diarrheal disease, and limited data on the water and sanitation access of the study populations in reviewed literature, we were unable to confidently distinguish between studies fitting scenario Va versus scenario Vb. Thus, we used the more conservative (smaller) baseline RR of the two scenarios, as determined by the China-specific literature review described previously [3], and grouped the populations of scenarios Va and Vb into 'Scenario V' for the remainder of the present analysis.

When more than one study provided a RR for a given water and sanitation access scenario, the results of the studies were aggregated, using standard random effects meta-analysis techniques [31], in order to develop a single estimate of the diarrheal disease response to a given change in a climate variable in a population experiencing that scenario. Given that assignment of the study populations described in Table A1 into one water and sanitation access scenario was not trivial, a parallel analysis was also carried out using a single RR estimate obtained by combining, using standard random-effects meta-analysis techniques, all of the effect measures identified in the literature review. Detailed descriptions of the water and sanitation access scenarios can be found in the Appendix, Table A8.

The climate sensitivity of diarrheal disease was most often reported as a percentage increase in incidence of diarrheal disease (observed per 1°C increase in ambient temperature). Thus, we define α as the percent increase in the RR of diarrhea observed for each water and sanitation access scenario for a 1°C increase in temperature [30]. The α estimates drawn from the literature review were used to adjust the risk ratios of diarrheal disease attributable to unsafe water and sanitation determined by our 2008 analysis ('*Baseline RR*'; see equation 1.1 and Table A8) [3]. The result was an adjusted rate ratio (*aRR*) generated by equation (1.1) based on the anticipated change in the temperature expected for a specific area (i.e., ΔT is the population weighted anticipated temperature change in °C; see 'Definition of exposure scenarios' below).

$$aRR = Baseline\ RR * (1+ \alpha \Delta T) \tag{1.1}$$

Vectorborne Disease, Schistosomiasis, and Soil Transmitted Helminth Infections

The baseline incidence estimates for malaria, dengue fever, Japanese encephalitis (JE), schistosomiasis, and the STH infections were obtained from national surveys and NIDR data, and the proportion of these diseases attributable to unsafe water and sanitation has been previously described [3]. The climate sensitivity of these diseases was most often reported as either a RR or an increase in incidence per unit change in a given climate variable. When multiple estimates of the climate-disease relationship existed, standard meta-analysis techniques were used to develop a single α value that was applied to the *Baseline RR*s obtained previously to obtain *aRR*s.

Definition of exposure scenarios

Monthly mean temperature values were obtained from the CMIP5 multi-model ensemble climate projections, specifically from the HadGEM2-ES global climate model based on models run using the four representative concentration pathways (RCP) scenarios used by the Intergovernmental Panel on Climate Change (IPCC) in the upcoming fifth assessment report (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5) [32, 33]. Gridded projections (1.25° lat x 1.875° long; approximately 107.8 km x 207.8 km) for the yearly mean temperature in 2018, 2019, 2020, 2021, and 2022 for each RCP scenario were subtracted from gridded annual mean temperature in 2008, and then averaged using ArcGIS 9.3 (ESRI, 2008) to produce a semi-decadal mean annual temperature deviation for each province (Td, °C) by RCP scenario, centered at 2020. This was repeated for the years surrounding 2030 (Table A3), and the resulting 2020 and 2030 Td values were entered into equation (1.1) to obtain province-specific *aRRs* where ΔT=Td. The population within each province was assumed to be exposed to this *aRR* as described below for each outcome.

Estimation of the climate change attributable burden of disease

Diarrheal Disease

Disease and water and sanitation scenario specific *aRRs* were applied to the proportion of each provincial population that fell into a given water and sanitation access scenario. Gridded population density projections for 2000, obtained from the National Aeronautics and Space Administration's Socio-Economic Data and Applications Center (SEDAC) [34] were projected to 2020 and 2030 using province-specific growth rates that produced estimates compatible with the 2020 and 2030 United Nations midline population projections[34-36]. Population density data were entered into ArcGIS 9.3 (ESRI, 2008) in an ASCII grid format and summed across each province. Within each province, the population was stratified by water and sanitation access as described in our prior analysis [3]. The *aRRs* for each province were combined with the proportion of the provincial population experiencing each water and sanitation access scenario (F_n) in order to calculate the anticipated incidence rate (IR) of WSH-attributable disease under climate change conditions, as shown in equation (1.2).

China's population growth and rapid rates of urbanization and internal migration were accounted for in population projections as follows. Predictions of the overall urban proportion of each provincial population for 2020 and 2030, which were developed using province-specific estimates of internal migration and urbanization [35], were first used to define the proportion of the population experiencing the urban water and sanitation access scenario (scenario II). The projected rural proportions of the provincial populations were then assigned into the remaining water and sanitation access scenarios following the method used to define the baseline distributions reported in our earlier work [3]. The projected province-specific age-distributions were used to calculate a baseline incidence rate of diarrheal disease in the established market economies ($IR_{baseline}$) for each province [35]. Combining this province-specific $IR_{baseline}$, and the proportion of the provincial population exposed to each water and sanitation access scenario (F_n), the anticipated incidence of WSH-attributable disease under climate change conditions was calculated for each province, as shown below in equation (1.2).

$$IR = IR_{\mathrm{baseline}} \sum_{n=2}^{6} [F_{\mathrm{n}}(aRR_{\mathrm{n}} - 1)] \tag{1.2}$$

The anticipated IR of WSH-attributable diarrheal disease was calculated for each province, and age- and sex-specific estimates of incidence and death-rates were produced. For the purpose of this analysis, the province-specific sex ratio in each province was assumed to be identical to the ratio identified by the 2000 China census, which was also utilized in our prior analysis [3]. The province-specific age distributions used for our 2020 projection were originally projected for 2015; however, application of these 2015 age distributions results in a China-wide age distribution that agrees with the projected UN midline age distributions within three percentage points for each age group (0-14yo; 15-64yo; 65yo+) [35].

Vectorborne Disease, Schistosomiasis, and Soil Transmitted Helminth Infections

When determining the burden of WSH-attributable disease in China, our prior work utilized conservative estimates obtained from the literature for the proportion of disease attributable to unsafe water and sanitation[3]. Using the age-specific baseline incidence rates of disease obtained from those calculations, this analysis assumed an increase in

WSH-attributable disease due to climate change that is equal to the overall increase in disease due to a measured change in a climate variable, as determined above. The output obtained from the global climate models was used to calculate the Td (°C) for each province, as described for our analysis of diarrheal disease. The analysis of the impact of climate change on the baseline incidence of malaria, dengue fever, and Japanese encephalitis began by recalculating the baseline incidence rate of each disease given the projected age-distributions of each province in 2020 and 2030[35]. The analysis was continued by projecting this baseline incidence rate of disease forward for each province under the anticipated climate change conditions, using the aggregated measures of disease specific climate sensitivities (α values) identified during the literature review, as determined by equation 1.1.

Sensitivity analyses

An analysis of the sensitivity of the impact of climate change on diarrheal disease to changes in the baseline water and sanitation access projections was carried out as follows. We calculated the climate-attributable incidence of disease in 2020 and 2030 assuming (1) access to water and sanitation infrastructure held constant at the 2008 level; (2) a linear increase in access to improved water and sanitation infrastructure consistent with the data reported by the Joint Monitoring Program[37, 38]; and (3) an exponential increase in the rate of provision of improved water and sanitation. The sensitivity of the impact projections to the α values used was carried out by replacing the α values stratified by water and sanitation access scenario with a single α obtained by aggregating all of the effect measures identified through the course of the diarrheal disease and climate literature review.

Results

Literature review and quantitative estimation of climate-health relationships

For diarrheal disease, the literature review identified six studies that quantified the relationship between diarrheal disease incidence and climate variation (see Appendix, Table A1). The α, defined as the change in diarrheal disease incidence per 1°C increase in temperature, extracted from each study was matched to a water and sanitation access scenario, as summarized in Table A2. Where more than two studies were found appropriate for a given water and sanitation access scenario, the α values of the studies were combined as described above. In addition to the α values used in the final analysis (Appendix, Table A2), the weighted mean of all α values (0.073; 95% CI 0.049, 0.097) was used in the sensitivity analyses.

The majority of studies describing the relationship between malaria and climate variation focused on the biological response of vectors and *Plasmodium spp.* to changes in temperature, precipitation and other factors[39-41]. The literature review identified four studies quantifying the relationship between temperature variation and malaria incidence (see Appendix, Table A1). A random effects meta-analysis produced an aggregated α of 0.125 (95%CI 0.0356, 0.214), which was used in the present analysis (see Table A2**)**.

For dengue fever, several studies were excluded for reporting only biological models (e.g. vector larvae response models) [42], SARIMA and ARIMA models from which we were unable to derive α values[43, 44], and global models that did not provide an estimate of the impact of climate variables on disease incidence [45]. The literature review identified several studies that described the relationship between climate variation and the incidence of dengue fever (see Appendix, Table A1), and the aggregated α resulting from the meta-analysis was 0.2602 (95%CI -0.052, 0.572) (see Table A2). A review of the literature regarding the climate sensitivity of Japanese encephalitis identified two studies (see Table A1), but for reasons described elsewhere (see Appendix), the α describing the sensitivity of Japanese encephalitis incidence to temperature was taken from Bi *et al* (2007) (see Table A2) [46]. Finally, a review of the literature describing the climate sensitivity of schistosomiasis and STHs failed to identify suitable estimates of α (see Appendix), and thus these diseases were excluded from further analysis.

Estimation of the climate change-attributable burden of disease

Anticipated Climate Change

HadGEM2-ES model output for the 10 years and four RCP scenarios described above was used to derive estimates of anticipated temperature change relative to the 2008 baseline for each province in 2020 and 2030. The estimated mean temperature deviation (Td) from the 2008 baseline under RCP 2.6 indicate that China is expected to undergo 0.22°C of warming nationwide between 2008 and 2020 (see Figure 1 and Appendix, Table A3). RCP 2.6 projects an additional 0.6°C of warming between 2020 and 2030. Under this scenario, 17 provinces are expected to cool between 2008 and 2020, with the most intense cooling anticipated in Liaoning (Td= -1.01°C), Jilin (Td= -0.93°C), and Jiangsu (Td= -0.71°C). Of the remaining 14 provinces anticipated to experience warming, the largest changes are projected for Hainan (Td= 0.97°C), Xizang (Td= 0.0.84°C), Yunnan (Td= 0.71°C), and Guangdong (Td= 0.70°C).

Under RCP 8.5, China is expected to experience a very slight, average cooling nationwide (Td= -0.0015°C) between 2008 and 2030, with overall nationwide warming

(Td= 0.99 °C) between 2008 and 2030. RCP 8.5 projects 19 provinces will cool from 2008 to 2020, with Jilin (Td= - 1.75°C), Liaoning (Td= -1.55°C), and Neimenggu (Td= -1.01°C) expected to experience the most intense cooling. Twelve provinces are expected to warm in this period, with Xizang (Td= 0.83°C), Yunnan (Td= 0.57°C), and Guangxi (Td= 0.54) projected to experience the most intense warming.

By 2030, RCP 2.6 projects an average nationwide warming of 0.82°C over 2008 temperatures, with every province projected to warm during the period. The most intense warming is projected in Hainan (Td= 1.56°C), Guangxi (Td= 1.47°C), and Guangdong (Td= 1.44°C) (see Figure 1 and Table A3). Similarly, RCP 8.5 anticipates that every province will warm between 2008 and 2030, with the most intense warming projected for Hainan (Td= 1.69°C), Yunnan (Td= 1.55°C), and Guangdong (Td=°C).

Diarrheal Disease

Accounting for projected urbanization, population growth and changes in population age distribution, and assuming a linear increase in access to improved water and sanitation infrastructure, the nationwide diarrheal disease incidence rate is anticipated to decrease by 39.8% between 2008 and 2020 and by 57.8% between 2008 and 2030 (see Table 1 and Table 2). When the impact of climate change under RCP 2.6 is included in the analysis, the nationwide decrease is virtually unchanged between 2008 and 2020, with incidence decreasing by 40.0%. However, between 2008 and 2030 the nationwide decrease in diarrheal disease incidence slows to 54.4% when accounting for the impact of climate change. For RCP 8.5, the nationwide decrease in diarrheal disease increases to 41.2% between 2008 and 2020, and then slows to 54.1% between 2008 and 2030. Comparing the rate of decrease from 2020 to 2030 with and without the impact of climate change reveals that climate change slows the rate of decrease in diarrheal disease incidence by 19.3% under RCP 2.6 and 26.9% under RCP 8.5 (see Tables 2A and 2B). Regionally, in both 2020 and 2030 and under both RCP 2.6 and RCP 8.5, the greatest incidence rate of diarrheal disease is projected in Xizang, Yunnan, and Guizhou provinces (see Appendix, Tables A4 through A7). Under RCP 2.6, Gizhou, Tianjin, Sanghai, and Beijing are expected to experience increases in diarrheal disease incidence, yet diarrheal disease incidence is anticipated to decrease in every other province, with the greatest decrease in incidence rate between 2020 and 2030 projected for Hubei (42.9% decrease), Ningxia (39.6% decrease), and Sichuan (35.2% decrease). RCP 8.5 projects that diarrheal disease incidence rates will increase in Guizhou, Beijing, Shanghai, Tianjin, Jiangsu, Guangdong, and Zhejiang, while decreasing in all other provinces from 2020 to 2030.

Vector-borne Disease

Largely as a result of population growth and demographic shifts, the incidence rate of malaria and dengue fever are projected to increase 127.0% and 38.3%, respectively, from 2008 to 2020 (see Table 3). Conversely, the overall incidence of Japanese encephalitis is projected to decrease by 14.4% from 2008 to 2020. Beyond 2020, when accounting for population growth and changes in population age distribution, the nationwide incidence rate of malaria is projected to decrease by 2.2% from 2020 to 2030. However, when the impact of climate change under RCP 2.6 is included in the analysis, the incidence rate of malaria is projected to increase by 7.8% from 2020 to 2030 (11.9% under RCP 8.5). Similarly, the incidence rate of dengue fever is projected to increase by 4.0% from 2020 to 2030 in the absence of climate change, but 20.8% when the impact of climate change is included in the analysis (35.4% under RCP 8.5). While China’s movement through the demographic transition is projected to yield a decreased incidence of Japanese encephalitis in both 2020 and 2030 when compared to 2008, the decrease from 2020 to 2030 slows when the effect of climate change is considered in the analysis.

Sensitivity analyses

Sensitivity to diarrheal disease α values

When the uncertainty associated with each α, as expressed by the 95% confidence interval, is propagated through the analysis using the output from the RCP 2.6, the range of diarrheal disease incidence rates assuming a linear rate of increase in water and sanitation access is centered around 20,950 (95%CI 20,882 to 21,018) cases per 100,000 in 2020, and 15,913 (95%CI 15,334 to 16,491) cases per 100,000 in 2030 (see Table 2). The variance associated with the 95% confidence intervals of α values contributes ±0.3% to diarrheal disease incidence rates in 2020, and ±3.6% to diarrheal disease incidence rates in 2030. When using the output from the RCP 8.5 to explore the impact of the uncertainty associated with the α-values, the range of diarrheal disease incident rates assuming a linear rate of increase in water and sanitation access is centered around 20,523 (95%CI 20,234 to 20,812) per 100,000 in 2020 and 16,051 (95% CI 15391 to 16,711) per 100,000 in 2030, with the variance associated with the 95% confidence intervals of α contributing ±1.4% to diarrheal disease incident rates in 2020 and ±4.1% in diarrheal disease incidence rates in 2030. An analysis using a simple mean α (see Methods) reveals that stratifying the population by water and sanitation access, and assigning the associated effect measures, produces slightly higher estimates of the diarrheal disease incidence rates than does the use of the aggregated α; 0.08% higher in

2020 and 0.24% higher in 2030, under RCP 2.6 (under RCP 8.5 the estimates are 0.07% higher in 2020 and 0.21% higher in 2030) (data drawn from Tables 2A and 2B).

Sensitivity to water and sanitation improvement assumptions

When keeping access to improved water and sanitation constant at the 2008 level, but adjusting for urbanization and climate change, the estimated incidence rate of diarrheal disease will fall by 19.8% by 2020 and 24.0% by 2030 (RCP 2.6). Under RCP 2.6, the decrease in diarrheal disease incidence rate is unsurprisingly steeper in the scenario assuming a linear increase in access to improved water and sanitation infrastructure; falling 40.0% by 2020 and 54.4% by 2030 (with a decrease of 41.2% by 2020 and 54.1% by 2030 under RCP 8.5). As expected, the most rapid decreases are achieved under the scenario assuming an exponentially increasing proportion of the population gaining access to improved water and sanitation infrastructure, where the diarrheal disease incidence rate is projected to fall by 53.8% by 2020 and 65.7% by 2030 under RCP 2.6 (under RCP 8.5 the incidence rate falls by 54.9% by 2020 and 65.3% by 2030). In the scenario assuming exponential growth in access to improved water and sanitation infrastructure, six provinces are estimated to have complete (100%) access to both improved water and sanitation in 2020, with that number increasing to 21 provinces in 2030.

Discussion

This analysis represents the first national and sub-national assessment of the impact of climate change on water-, sanitation-, and hygiene-attributable disease in China. In 2030, as in 2008 (when excluding schistosomiasis and STHs), diarrheal disease is projected to represent 99.9% of all WSH-attributable disease cases, as well as 99.5% of all WSH-attributable disease deaths [3]. The demographic and epidemiologic transitions in China, as well as increasing access to improved water and sanitation infrastructure, are expected to rapidly decrease the incidence of diarrheal disease. The results presented here indicate that this decrease in the incidence rate of diarrheal disease is delayed by the impact of climate change, even while controlling for demographic changes and urbanization. Assuming a linear increase in access to improved water and sanitation infrastructure, the climate change-attributable delay in the decrease of the diarrheal disease incidence rate amounts to over 28 months under RCP 2.6, and over 44 months under RCP 8.5. In other words, in the presence of climate change, China loses over 2 years (and potentially over 4 years) of developmental progress in reducing diarrheal disease; an additional 28 to 44 months of continued infrastructure investment, urbanization, and demographic shifts will be required in order to achieve the benefit in decreased disease burden that the country would otherwise experience if not for climate change (Figure 2). Under RCP 8.5, assuming access to improved water and sanitation remains constant at 2008 level, this developmental delay increases to over 14 years (with a delay of almost 21 years under RCP 2.6). Assuming exponentially increasing rates of access to improved water and sanitation infrastructure, the developmental delay is 9.5 months under RCP 2.6 and over 24 months under RCP 8.5.

While diarrheal disease dominates the burden of WSH-attributable disease in China, climate change is anticipated to have similar impacts on WSH-attributable vector-borne disease. The incidence rate of malaria is anticipated to decrease 2.2% from 2020 to 2030 (Tables 3A and 3B) as a result of migration and demographic shifts; however, climate change leads to a 7.8% (RCP 2.6) or 11.9% (RCP 8.5) increase in the incidence rate of malaria from 2020 to 2030, effectively erasing the developmental advantage afforded by internal migration and shifting demographic trends. The incidence rate of dengue fever is expected to increase between 2020 and 2030 regardless of the impact of climate change; yet climate change more than quadruples the rate at which dengue fever incidence is projected to increase under RCP 2.6, with the increase bordering on an order of magnitude under RCP 8.5. As a result, China will experience the (higher) incidence rate of dengue fever in 2022 it otherwise wouldn't have experienced until 2030. As a result of demographic shifts and internal migration, the incidence rate of Japanese encephalitis is expected to decrease 16.9% between 2020 and 2030; yet the impact of climate change slows this rate of decrease to 12.8% under RCP 2.6 and to 10.9% under RCP 8.5, and projections indicate China will not achieve the incidence rate of JE it would otherwise have experienced in 2030 until 2033 or later.

Conservative assumptions were made throughout the analysis, and the uncertainty associated with key assumptions was explored through sensitivity analysis. In the application of the α-values obtained during the literature review, the effect measures were stratified by water and sanitation access scenario of the study populations in order to better account for the mediating effect of water and sanitation access on the climate-disease relationship. Acknowledging that this was not easily accomplished given the lack of definitive information in the reviewed studies regarding the distribution of study populations into the specific water and sanitation access scenarios used here, we performed a parallel analysis using a pooled α from all reviewed studies. The projected incidence rate of diarrheal disease using the pooled α differed from the incidence rate produced by the stratified analysis by 0.2%, demonstrating the limited sensitivity of our findings to the decision to stratify the literature-derived effect measures by water and sanitation access scenario. What is more, in an effort to produce the most conservative estimate of the impact of climate change on diarrheal disease for the population apportioned into the new 'scenario V,' this α value derived from the literature review was applied to the more conservative *Baseline RR* of diarrheal disease described in our prior work for scenario Va (Table A8) [3].

Uncertainty in effect measures describing the climate-health relationships drawn from the literature also provide a potential source of uncertainty in the present analysis. The 95% confidence intervals bounding the original effect measures were propagated through the analysis to develop confidence intervals bounding the projected incidence rates, accounting for the uncertainty inherent in the parent studies. The confidence intervals for the dengue fever and for diarrheal disease scenario V α values included the null value (zero). Propagation of the α-associated uncertainty for diarrheal disease resulted in an incidence rate, in a scenario consistent with linearly increasing access to improved water and sanitation, within 0.3% of our point estimate for 2020 and within 3.6% of our point estimate for 2030 (depending on the RCP scenario used). Furthermore, we limited our consideration to the most common, linear models of diarrheal disease incidence response to temperature, despite the limited plausibility of such simple relationships [30]. As more complex relationships are identified and characterized, these should be included in a more comprehensive meta-analysis and the climate change-attributable calculation presented herein should be repeated.

A further source of uncertainty is the rate at which improved water and sanitation access will increase as China invests in infrastructure. Tables 2A and 2B demonstrate the sensitivity of our final results to the three water and sanitation access scenarios we considered. The scenario assuming a linear increase in access to improved water and sanitation is most consistent with China's development path as put forward by the Joint Monitoring Program [37, 38], and thus was considered the mid-line estimate for our analysis. The scenario assuming constant water and sanitation access in 2008 appears at first glance highly unrealistic. Yet in the presence of rural-to-urban migration and population growth, even maintaining 2008 levels of access will require tremendous investments. The gains made through slow improvements to infrastructure are, unsurprisingly, easily disrupted by climate change, and our analysis assuming maintenance of 2008 access levels accordingly showed the longest developmental delay, as described above. However, even should China exponentially increase the proportion of the population with access to improved water and sanitation, nearly 10 months of developmental delay is projected due to climate change by 2030.

The source of our baseline population density data was obtained from SEDAC and projected forward using the province specific growth and urbanization rates obtained from two different sources [34, 35]. These sources were chosen in order to produce results most consistent with the midline UN projections for total and urban population for all of China. While the sex-ratio was held constant at the level obtained from 2000 census data, the province-specific age distributions for 2030 were provided by projections made by Toth *et al* (2003) **[35]**. The 2020 province-specific age distributions were taken from predictions for 2015; however, the province-specific age distributions projected by Toth *et al* (2003) **[35]** result in a country-wide age distribution that matches the UN midline predictions for China in 2020 to within three percentage points [35, 47].

A large potential source of uncertainty is the use of the HadGEM2-ES model output utilized in this analysis. However, the HadGEM2-ES model accounts for the direct and indirect effects of aerosols (including sulfates, black carbon, organic carbon, mineral dust, and sea salt), anthropogenic and biogenic emissions of methane and carbon dioxide, the impact of iron deposition on ecosystems, land use changes, the impact of ozone, methane, and oxidants on tropospheric chemistry. A complex analysis of the predictive accuracy of the model indicates that is does not require the inclusion of any artificial correction terms [48]. However, the use of any model introduces an aspect of unquantifiable uncertainty; therefore, in an effort to reduce this possible source of bias, we have utilized the mean annual temperature deviation from the 2008 baseline, instead of the projected absolute temperature. Given the unknown degree of radiative forcing anticipated as result of greenhouse gas emissions, the climate data was obtained from the output of the four models to be utilized in the forthcoming IPCC AR5; RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. The RCP 2.6 and RCP 8.5 scenarios focused upon in this analysis project China will experience general warming, amounting to 0.82-0.99°C, from 2008 to 2030. The Fourth Assessment Report (AR4) of the IPCC, projected 0.5-1.5°C for China during the 2020-2029 time period [7]. However, the AR4 results were calculated compared to a 1980-1999 baseline period. The warming trend observed over the 1951-2001 period suggests that China will have warmed 0.2°C from 1999 to 2008[26]. With this change in mind, the IPCC AR4 results anticipate 0.3-1.3°C of warming from 2008 to 2029, which is consistent with our estimated warming of 0.82 to 0.99°C over the same time. In addition to deriving the output from these models for 2020 and 2030, we also sought to minimize the impact of inter-annual variability on our results. For each province, we produced five estimates of Td (°C) projected by each RCP scenario (for the year of interest, as well as the two years on either side), and the analysis was performed using the mean Td anticipated in each province for both 2020 and 2030, under RCP scenarios 2.6 and 8.5.

We sought to direct the source of bias introduced by our analytical assumptions towards the null. For instance, we assumed that any urban population has access to improved water and sanitation, despite several studies suggesting urban centers in China suffer from overwhelmed and inadequate water treatment facilities, inconsistent provision of piped water, and improper discharge of effluent in urban settings [2, 18]. Furthermore, we limited our consideration of to a small subset of WSH-related sequelae associated with climate change. For instance, we did not include the WSH-related impacts of sea level rise, salt-water intrusion, subsidence, flooding events, destruction of existing infrastructure, increased Urban Heat Island effect, or drought on the incidence of WSH-attributable disease [26, 49]. Thus, the baseline burden of diarrheal disease presented in our prior analysis is likely an underestimate, as are the results of the analysis presented here. Also, our analysis did not account for vector range expansion or contraction, and instead simply considered the change in incidence anticipated in the provinces where malaria, dengue fever, and Japanese encephalitis are currently observed.

Conclusion

In every aspect of the analysis, across diseases and scenarios, our findings are consistent with the assertion that climate change has the potential to delay progress toward decreasing the burden of WSH-attributable disease in China; through our analysis, this delay was determined to be two years or greater if linear increases in water and sanitation infrastructure are continued. The two years of delay imposed by climate change represents the additional period of time before China will achieve the lower incidence rate of WSH-attributable disease that would otherwise have been achieved in 2030; during this time China would need to continue providing financial investments, dedicated personnel, and infrastructure development at the same rate provided from 2000 to 2010. For China, this two-year delay by 2030 amounts to 458 million cases of diarrheal disease that would have been prevented by mitigation of climate change. This two-year incidence approximates the annual incidence of diarrheal disease in 2008 [3].

The impact of WSH-attributable disease extends beyond the burden of disease discussed here; the inextricable relationship between poverty and disease is magnified at the population level, and climate change threatens to perpetuate this relationship [2, 50]. Despite the assumption that development cannot progress without concomitant increases in per capita greenhouse gas emissions [51], countries must acknowledge the delay in development that climate change, driven by the increase in greenhouse gas emissions, will impose. Given the tremendous financial and political drive to provide improved water and sanitation throughout China, two years of investment negated by climate change should motivate the country to assume a role of international leadership in the effort to reduce greenhouse gas emissions.

Our analysis assuming a linear increase in access to improved water and sanitation infrastructure estimated that 24 months of gains (reduced incidence) associated with development, urbanization, internal migration, and demographic shifts can be counteracted by the effects of climate change. China's investments in improved water and sanitation infrastructure observed from 2006 to 2010 amounted to approximately

US$10.8 billion per year [23], and thus delays in development as characterized by our analysis come at a potentially large cost. Additionally, such costs do not account for the direct and indirect costs of the burden of WSH-attributable disease itself, which is estimated to cost China as much as $11 billion per year [21]. Most strikingly, this analysis focused on only one family of health impacts associated with climate change, and thus the true developmental delay imposed by climate change on China is likely much larger.

Tables and Figures

Table 1A: Estimated incidence rates and mortality rates (per 100,000) of WSH-attributable disease in 2008, 2020, and 2030 under RCP 2.6, using mean α

Incidence rates and mortality rates are estimated using mean Td for each province (calculated from the semi-decadal annual mean centered at each time point), province-specific linearly increasing water and sanitation access rates, and projections of province-specific urbanization rates and age-distribution.

	2008		**2020**		**2030**	
Td (°C)	baseline		0.22		0.82	
	IR	**MR**	**IR**	**MR**	**IR**	**MR**
Diarrheal Disease	34,932	4.79	20,950	2.75	15,913	1.99
Malaria	0.79	0.0007	1.74	0.0016	1.88	0.0017
Dengue Fever	0.016	0	0.025	0	0.031	0
Japanese Encephalitis	0.25	0.0121	0.22	0.0109	0.19	0.0099

Table 1B: Estimated incidence rates and mortality rates (per 100,000) of WSH-attributable disease in 2008, 2020, and 2030 under RCP 8.5, using mean α.

Incidence rates and mortality rates are estimated using mean Td for each province (calculated from the semi-decadal annual mean centered at each time point), province-specific linearly increasing water and sanitation access rates, and projections of province-specific urbanization rates and age-distribution.

	2008		**2020**		**2030**	
Td (°C)	baseline		-0.0015		0.99	
	IR	**MR**	**IR**	**MR**	**IR**	**MR**
Diarrheal Disease	34,932	4.79	20,523	2.70	16,051	2.00
Malaria	0.79	0.0007	1.68	0.0016	1.88	0.0018
Dengue Fever	0.016	0	0.023	0	0.032	0
Japanese Encephalitis	0.25	0.0121	0.22	0.0107	0.19	0.0100

Table 2A: Impact of climate change (RCP 2.6) on incidence rate (per 100,000) of diarrheal disease in China, given 2008 access, linear and exponential increases in water and sanitation access.

Wat/San Scenario	α	Baseline Diarrheal Disease Incidence Rate			Diarrheal Disease Incidence Rate with Climate Change		
		2020	%Δ	2030	2020	%Δ	2030
2008 Wat/San Access	mean	28,079	-10.76	25,057	28,004	-5.17	26,555
Linear Improvement in Wat/San Access	min.	21,014	-29.81	14,750	21,018	-27.04	15,334
	mean				20,950	-24.04	15,913
	max.				20,882	-21.03	16,491
	alt.*				20,936	-24.15	15,879
Exponential Improvement in Wat/San Access	mean	16,171	-27.65	11,700	16,126	-25.62	11,995

*Analysis was performed using the alternative α derived from the aggregation of all studies identified in the literature review (see Table A2).

Table 2B: Impact of climate change (RCP 8.5) on incidence rate (per 100,000) of diarrheal disease in China, given 2008 access, linear and exponential increases in water and sanitation access.

Wat/San Scenario	α	Baseline Diarrheal Disease Incidence Rate			Diarrheal Disease Incidence Rate with Climate Change		
		2020	%Δ	2030	2020	%Δ	2030
2008 Wat/San Access	mean	28,079	-10.76	25,057	27,514	-7.36	25,488
Linear Improvement in Wat/San Access	min.	21,014	-29.81	14,750	20,812	-26.05	15,391
	mean				20,523	-21.79	16,051
	max.				20,234	-17.41	16,711
	alt.*				20,506	-21.92	16,012
Exponential Improvement in Wat/San Access	mean	16,171	-27.65	11,700	15,742	-23.02	12,117

*Analysis was performed using the alternative α derived from the aggregation of all studies identified in the literature review (see Table A2).

Table 3A: Impact of climate change (under RCP 2.6) on the incidence rate of vector-borne disease in China (per 100,000), using mean α.

	Baseline Incidence			Incidence Rate with Climate Change		
Disease	**2020**	**%Δ**	**2030**	**2020**	**%Δ**	**2030**
Malaria	1.79	-2.24	1.75	1.74	7.84	1.88
Dengue Fever	0.0221	4.00	0.0230	0.0253	20.84	0.0306
Japanese Encephalitis	0.2186	-16.85	0.1817	0.2216	-12.83	0.1931

Table 3B: Impact of climate change (under RCP 8.5) on the incidence rate of vector-borne disease in China (per 100,000), using mean α.

	Baseline Incidence			Incidence Rate with Climate Change		
Disease	**2020**	**%Δ**	**2030**	**2020**	**%Δ**	**2030**
Malaria	1.79	-2.24	1.75	1.68	11.85	1.88
Dengue Fever	0.0221	4.00	0.0230	0.0233	35.36	0.0315
Japanese Encephalitis	0.2186	-16.85	0.1817	0.2179	-10.88	0.1942

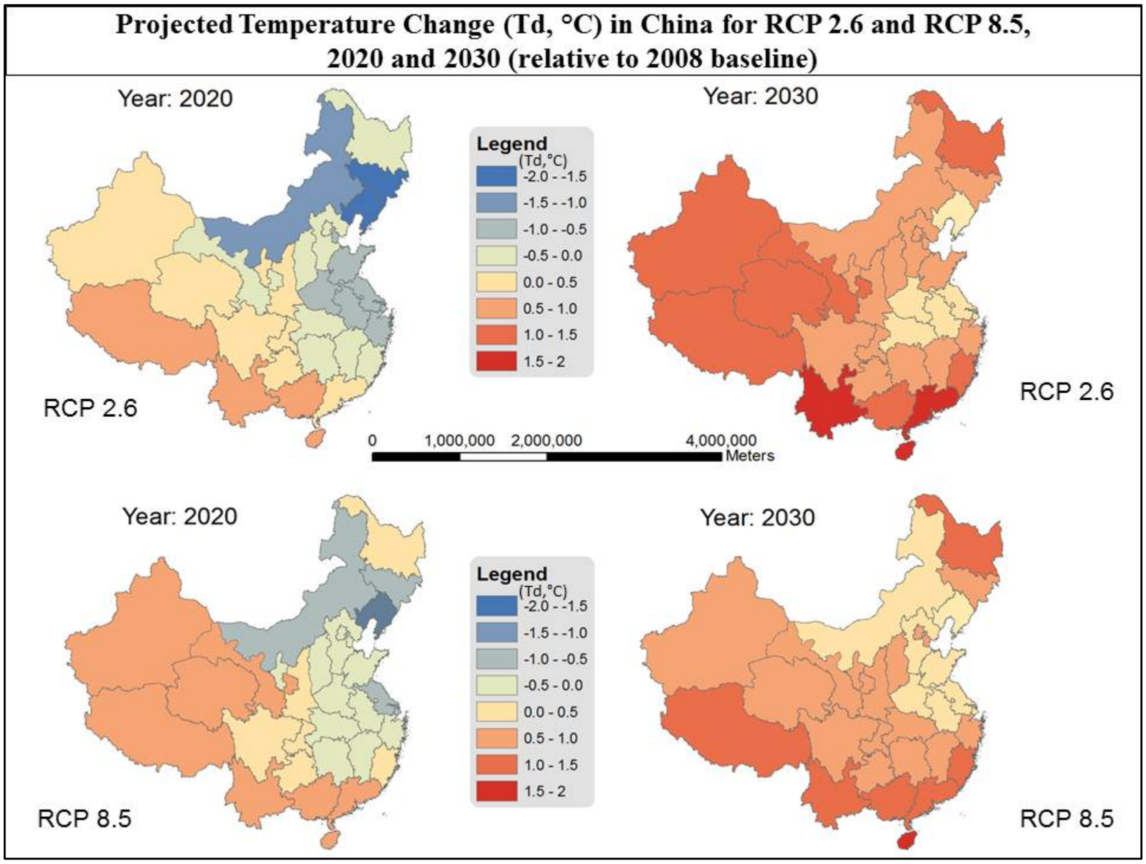

Figure 1: Images demonstrating anticipated climate change (as Td, °C) for China in 2020 and 2030, under RCPs 2.6 and 8.5.

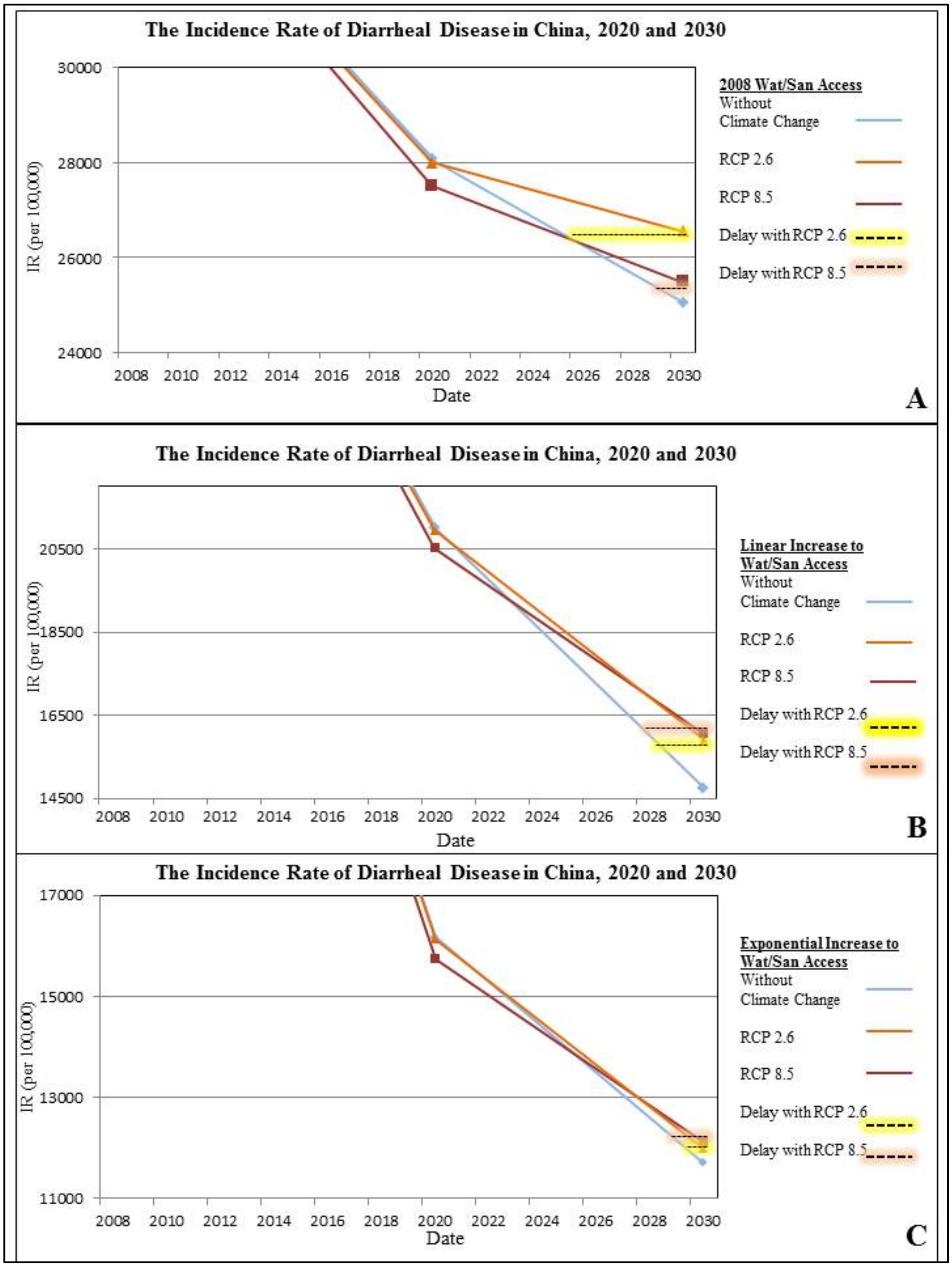

Figure 2: Demonstration of the impact of climate change on diarrheal disease incidence in China in 2020 and 2030, by water and sanitation access scenario, and by RCP (mean α).

Appendix

Summary of literature review and quantitative estimation of climate-health relationships

Diarrheal disease. Perhaps the most well-known of these studies, Checkley *et al* (2000) observed the daily number of children under the age of 10-years old admitted to a Peruvian hospital with diarrhea before, during, and after an El Niño event and described an increase in diarrheal disease incidence of 8% for each 1°C increase in mean ambient temperature (relative risk 1.08; 95% CI 1.07-1.09)[12]. For patients over the age of 13-years old in Lima, Peru, Lama *et al* (2004) described a similar increase in the monthly incidence of diarrheal disease of 8.1% (95% CI 2.5-14.1) for every 1°C increase in mean monthly temperature[52]. In Dhaka, Bangladesh, Hashizume *et al* (2007) described a 5.6% increase in the number of weekly, non-cholera diarrheal cases for every 1°C increase in mean weekly temperature (95%CI 3.4-7.8)[53]. Focusing on the impact of temperature on bacillary dysentery incidence in Jinan, China, Zhang and colleagues (2008) described an 11.4% increase in incidence for every 1°C increase in maximum ambient temperature (95% CI 10.19, 12.69)[13]. Singh and colleagues (2001) observed a 3.0% increase in the incidence of diarrhea among infants in Fiji for every 1°C increase in mean monthly temperature, on a one-month lag (95%CI 1.2,5.0)[54]. Finally, Onozuka *et al* (2010) described a 7.7% increase in the incidence of infectious gastroenteritis cases with every 1°C increase in weekly mean temperature (95%CI 4.6, 10.8), observed in over 120 institutions across Fukuoka, Japan[55]. These studies were stratified by the water and sanitation access of their respective study populations, and assigned to the water and sanitation access scenarios described previously[1, 3]**.** Studies pertaining to observed relationships between diarrheal disease incidence and discrete precipitation events[11, 15, 53, 56], continuous precipitation[53, 54], and relative humidity[12, 55] were also discovered during the course of the literature review; however, due to the difficulty in developing estimates of the compounded impact of more than one climate variable on disease incidence, the analysis was restricted to the impact of temperature alone.

Malaria. Zhang and colleagues (2010) described the results of a 20-year time-series analysis of the incidence of malaria in Jinan, China; the results of two SARIMA regression models demonstrated a 10.2% (95%CI 7.7, 12.7) increase in malaria incidence for every 1°C increase in minimum temperature or a 13.8% (05%CI 11.8, 15.8) increase in malaria incidence for every 1°C increase in maximum temperature[57]. A time-series analysis of climate variables and malaria incidence in Yunnan, China demonstrated a 4.7% (95%CI 4.5, 5.0) increase in malaria incidence for every 1°C increase in mean monthly temperature[58]. Most recently, an analysis of civilian malaria cases from the Republic of Korea described a 16.1% (95%CI 15.3, 16.9) increase in malaria incidence for every 1°C increase in un-lagged mean weekly temperature, with the effect intensifying to a 17.7% (95% CI 16.9, 18.6) increase in malaria incidence for every 1°C increase in mean weekly temperature observed at a three week lag[59].

Dengue fever. Lu and colleagues (2009) described a risk ratio of 1.42 (95% CI 1.27, 1.57) associated with every 1°C increase in mean monthly temperature in Guangzhou City, China[60], while Pham *et al*(2011) observed a risk ratio of 1.21 (95%CI 1.10, 1.34) associated with every 2°C increase in mean monthly temperature in Dak Lak, Vietnam[61]. In addition to these studies, Chen et al (2010) observed a risk ratio of 1.15 associated with a 1°C increase mean weekly minimum temperature in Taipei, Taiwan, as well as a risk ratio of 1.705 associated with a 1°C increase mean weekly minimum temperature in Kaohsiung, Taiwan[62], and Hi *et al* (2009) described a risk ratio of 1.23 associated with every 10°C increase mean weekly temperature in Singapore[63]. However, the studies by Chen *et al* (2010) and Hii *et al* (2009) provided neither confidence intervals nor standard errors for their effect measures and therefore could not be aggregated using the random effects meta-analysis technique utilized here.

Japanese encephalitis. One study by Bi *et al* (2007) performed in Jinyi City, China described a 7.9% (95% CI 3.3, 12.6) increase in the incidence of Japanese encephalitis for every 1°C increase in mean maximum monthly temperature[46]. A similar study by Bi *et al* (2003) in Jieshou City, China observed a 7.68% increase in incidence for every 1°C increase in mean maximum monthly temperature[64]; however this latter study failed to include confidence intervals or standard errors and was therefore excluded from the analysis.

Schistosomiasis and soil transmitted helminths. A review of the literature describing the climate sensitivity of schistosomiasis and STHs identified two review articles[65, 66]; one article describing the relationship between schistosomiasis infection and modifiable risk factors[67]; and one analysis carrying out predictive risk mapping to identify the probable distribution of schistosomiasis under altered climate conditions[68]. Having failed to identify an estimate of α describing the relationship between climate variables and the incidence or prevalence of schistosomiasis and soil transmitted helminths, these diseases were excluded from the present analysis.

Table A1: Results of literature review regarding the sensitivity of WSH-disease to climate change

Diarrheal Disease	**Location**	**Population**	**Wat/San Scenario**	**% Increase in Incidence per 1°C Increase in Temp.**	**Variables in Model**	**Duration of Study**	**Source**
	Lima, Peru	<10yo	IV	8 (7.0, 9.0)	relative humidity	01/1/1993-11/15/1998	Checkley *et al,* 2000
	Lima, Peru	Adults	IV	8.1 (2.1, 14.1)	presence of cholera cases, presence of weak or strong El Nino	1/1/1993-6/30/1998	Lama et al, 2004
	Jinan, China	All patients	V	11.4 (10.19, 12.69)	total rainfall, mean relative humidity, mean air pressure	1987-2000	Zhang *et al,* 2008
	Fiji	Infants	V	3 (1.2, 5.0)	rainfall, seasonality	1978-1989	Singh *et al,* 2001
	Bangladesh	All patients	VI	5.6 (3.4, 7.8)	rainfall, seasonality	1/1996-12/2002	Hashizume *et al,* 2007
	Fukuoka, Japan	All patients	II	7.7 (4.6, 10.8)	relative humidity, seasonality	1999-2007	Onozuka *et al,* 2010
Malaria	**Location**	**Population**		**% Increase in Incidence per 1°C Increase in Temp.**	**Variables in Model**	**Duration of Study**	**Source**
	Jinan, China	All patients		10.2 (7.7, 12.7)	seasonality, maximum temperature	1959-1979	Zhang *et al*, 2010
	Jinan, China	All patients		13.8 (11.8, 15.8)	seasonality, maximum temperature	1959-1979	Zhang et al, 2010
	Yunnan, China	All patients		4.7 (4.5, 5.0)	seasonality, monthly rainfall, provincial mean temporal trend	01/1991-12/2006	Clements *et al*, 2009
	Yunnan, China	All patients		5.9049 (4.3767, 7.4331)	humidity, income, and slide positivity rate	1993-2008	Bi *et al*, 2012
	Republic of Korea	All civilian patients		17.7 (16.9, 18.6)	seasonality, interannual variation, relative humidity, precipitation, DTR	2001-2009	Kim *et al*, 2012
	Republic of Korea	All civilian patients		16.1 (15.3, 16.9)	seasonality, interannual variation, relative humidity, precipitation, DTR	2001-2009	Kim *et al*, 2012
Dengue Fever	**Location**	**Population**		**% Increase in Incidence per 1°C Increase in Temp. (95% CI)**	**Variables in Model**	**Duration of Study**	**Source**
	Guangzhou City, China	All patients		1.42 (1.27, 1.57)	monthly minimum temp, monthly wind velocity, incidence of previous month	2001-2006	Lu *et al,* 2009
	Taipei, Taiwan	All patients		1.15 (NP)	mean weekly min. temp, mean weekly relative humidity	1/1998-10/2008	Chen *et al*, 2010
	Kaohsiung, Taiwan	All patients		1.705 (NP)	mean weekly min. temp, mean weekly relative humidity, Bretau index (transmission)	1/1998-10/2008	Chen *et al*, 2010
	Singapore	All patients		1.23 (NP)	mean weekly temp., cumulative weekly precipitation	2000-2007	Hii *et al,* 2009
	Dak Lak, Vietnam	All patients		1.21 (1.10-1.34)	household index, household mosquito, mean tem., rainfall	2004-2008	Pham *et al*, 2011
Japanese Encephalitis	**Location**	**Population**		**% Increase in Incidence per 1°C Increase in Temp. (95% CI)**	**Variables in Model**	**Duration of Study**	**Source**
	Linyi City, China	All patients		7.9 (3.3, 12.6)	Mean max monthly temperature, mean monthly air pressure, monthly mean relative humidity, monthly total rainfall, year	1956-2004	Bi *et al*, 2007
	Jieshou County, China	All patients		7.68 (NP)	Mean max monthly temp, monthly precipitation	1980-1996	Bi *et al*, 2003

Table A2: Literature review derived α values utilized in analysis

Disease	Wat/San Scenario	α-value (95% CI)
Diarrheal Disease	II	0.077 (0.046, 0.108)
	IV	0.08 (0.070, 0.090)
	V	0.072 (-0.021, 0.166)
	VI	0.056 (0.034, 0.078)
	Aggregate	0.073 (0.049, 0.097)
Malaria		0.125 (0.036, 0.21)
Dengue Fever		0.260 (-0.052, 0.572)
Japanese Encephalitis		0.079 (0.33, 0.126)

Table A3: Estimated temperature deviation from 2008 baseline (Td, °C) by province and by RCP in 2020 and 2030

	RCP 2.6		RCP 4.5		RCP 6.0		RCP 8.5	
Province	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**	**2020**	**2030**
Anhui	-0.49	0.42	0.16	0.28	-0.51	-0.53	-0.77	0.33
Beijing	-0.19	0.59	0.32	0.47	-0.28	0.43	-0.41	0.88
Chongqing Shi	0.26	0.70	0.31	0.65	0.02	0.26	0.08	0.72
Fujian	0.22	1.05	0.46	0.93	0.17	0.48	-0.05	1.12
Gansu	0.56	0.57	0.64	0.92	0.20	0.51	-0.17	1.09
Guangdong	0.70	1.44	0.77	1.43	0.56	0.78	0.31	1.54
Guangxi	0.67	1.47	0.83	1.61	0.61	0.88	0.54	1.46
Guizhou	0.37	0.97	0.39	1.01	0.14	0.49	0.26	1.00
Hainan	0.97	1.56	1.02	1.72	0.66	0.90	0.51	1.69
Hebei	-0.39	0.43	0.11	0.51	-0.54	0.21	-0.50	0.66
Heilongjiang	0.16	1.41	0.59	0.34	0.53	0.30	-0.31	1.49
Henan	-0.46	0.36	0.36	0.61	-0.55	-0.50	-0.71	0.39
Hubei	-0.08	0.50	0.41	0.51	-0.21	-0.02	-0.23	0.49
Hunan	-0.08	0.61	0.25	0.70	-0.19	0.11	-0.13	0.60
Jiangsu	-0.71	0.43	0.10	0.05	-0.53	-0.61	-0.98	0.46
Jiangxi	-0.18	0.65	0.16	0.67	-0.20	0.09	-0.25	0.60
Jilin	-0.93	0.59	-0.12	-0.39	-0.35	-0.64	-1.75	0.57
Liaoning	-1.01	0.24	-0.17	-0.43	-0.75	-0.52	-1.55	0.27
Neimenggu	-0.68	0.37	0.29	0.05	-0.20	-0.03	-1.01	0.77
Ningxia	-0.01	0.58	0.50	0.83	0.19	0.31	0.20	0.73
Qinghai	0.59	0.89	0.27	1.10	0.22	0.65	0.41	1.10
Shaanxi	0.26	0.58	0.45	0.71	0.26	0.41	0.19	0.82
Shandong	-0.49	0.39	0.39	0.44	-0.71	-0.70	-0.80	0.58
Shanghai	-0.57	0.38	-0.03	0.22	-0.39	-0.26	-0.82	0.39
Shanxi	-0.06	0.58	0.10	0.67	-0.19	0.46	-0.04	0.67
Sichuan	0.37	0.81	0.12	0.74	0.05	0.35	0.14	0.90
Tianjin	-0.38	0.51	0.04	0.44	-0.67	0.21	-0.60	0.66
Xinjiang	0.66	0.89	0.87	1.13	0.19	0.83	0.45	1.11
Xizang	0.84	1.13	0.32	1.47	0.29	1.21	0.83	1.25
Yunnan	0.71	1.21	0.32	1.25	0.31	0.71	0.57	1.55
Zhejiang	-0.34	0.57	0.05	0.46	-0.19	-0.07	-0.53	0.59
China	**0.22**	**0.82**	**0.42**	**0.82**	**0.07**	**0.45**	**-0.0015**	**0.99**

Table A4: Incidence rate (per 100,000) of WSH-attributable disease per province in 2020 under RCP 2.6, using mean α, and assuming linear increases in access to improved water and sanitation infrastructure.

Province	Population	IR Diarrheal Disease	IR Malaria	IR Dengue	IR JE
Anhui	55,848,105	30,241	21.1845	0.0018	0.3703
Beijing	21,491,673	9,314	0.2429	0.0193	0
Chongqing Sh	28,326,042	17,580	0.1585	0.0032	1.0124
Fujian	36,732,151	13,586	0.0725	0.0725	0.0706
Gansu	27,386,065	31,289	0.0471	0.0039	0.2570
Guangdong	172,296,044	13,851	0.1777	0.1231	0.1025
Guangxi	43,105,196	27,637	0.1283	0.0021	0.2917
Guizhou	40,005,718	35,100	3.5603	0	1.0004
Hainan	9,499,726	19,659	0.1314	0.0023	0.3169
Hebei	75,418,929	17,979	0.0363	0	0.0294
Heilongjiang	35,295,640	14,792	0.0150	0	0.0000
Henan	94,603,964	24,527	3.1165	0.0009	0.2917
Hubei	58,721,963	22,959	1.8776	0.0053	0.0721
Hunan	55,761,056	27,944	0.1110	0.0097	0.2241
Jiangsu	77,439,158	9,784	0.6821	0.0046	0.0510
Jiangxi	36,295,489	34,696	0.0505	0.0021	0.1123
Jilin	25,211,924	15,538	0.0369	0	0
Liaoning	39,762,225	12,259	0.0341	0.0034	0
Neimenggu	25,513,526	20,393	0.0085	0	0.0041
Ningxia	7,005,606	32,893	0.0482	0	0
Qinghai	5,629,742	24,599	0.0000	0	0
Shaanxi	38,823,495	21,673	0.1314	0.0059	0.1033
Shandong	91,447,403	16,347	0.1686	0	0.1094
Shanghai	22,566,391	8,798	0.7004	0.0383	0.0582
Shanxi	40,025,498	20,406	0.0128	0	0.0731
Sichuan	72,247,313	32,164	0.2058	0	0.7276
Tianjin	12,033,622	9,636	0.0328	0	0.0163
Xinjiang	28,598,017	24,323	0.0149	0	0.0047
Xizang	4,390,230	53,081	1.2516	0	0.0677
Yunnan	52,390,064	37,069	8.8507	0.1343	0.8273
Zhejiang	52,302,485	11,020	0.8802	0.0141	0.1031
Total	1,386,174,458	20,950	1.7432	0.0253	0.2216

Table A5: Incidence rate (per 100,000) of WSH-attributable disease per province in 2030 under RCP 2.6, using mean α, and assuming linear increases in access to improved water and sanitation infrastructure.

Province	Population	IR Diarrheal Disease	IR Malaria	IR Dengue	IR JE
Anhui	49,994,000	21,505	25.5776	0.0021	0.3448
Beijing	24,710,000	9,690	0.2559	0.0225	0
Chongqing Shi	32,540,000	12,057	0.1720	0.0034	0.8954
Fujian	44,566,000	11,307	0.0784	0.0825	0.0627
Gansu	30,813,000	20,687	0.0472	0.0041	0.2523
Guangdong	180,129,000	13,010	0.1979	0.1492	0.0871
Guangxi	39,300,000	18,594	0.1360	0.0023	0.2507
Guizhou	34,628,000	38,653	3.8677	0	0.8900
Hainan	10,739,000	16,009	0.1413	0.0026	0.2586
Hebei	74,319,000	15,833	0.0373	0	0.0293
Heilongjiang	31,077,000	13,255	0.0149	0	0.0000
Henan	88,900,000	17,273	3.9314	0.0010	0.2708
Hubei	65,164,000	13,100	2.3787	0.0058	0.0618
Hunan	56,894,000	18,628	0.1168	0.0105	0.1963
Jiangsu	78,510,000	9,739	0.8156	0.0058	0.0481
Jiangxi	41,011,000	23,975	0.0568	0.0025	0.0977
Jilin	29,542,000	11,334	0.0406	0	0
Liaoning	40,951,000	10,538	0.0348	0.0042	0
Neimenggu	25,623,000	13,503	0.0088	0	0.0041
Ningxia	8,506,000	19,867	0.0489	0	0
Qinghai	6,103,000	19,592	0.0000	0	0
Shaanxi	35,123,000	14,844	0.1421	0.0058	0.0974
Shandong	98,308,000	13,854	0.1855	0	0.1141
Shanghai	28,308,000	9,213	0.7445	0.0448	0.0587
Shanxi	41,435,000	16,363	0.0132	0	0.0899
Sichuan	69,328,000	20,834	0.2235	0	0.6308
Tianjin	12,708,000	10,120	0.0336	0	0.0161
Xinjiang	32,314,000	17,369	0.0184	0	0.0050
Xizang	4,190,000	48,340	1.3006	0	0.0716
Yunnan	54,460,000	24,234	9.3095	0.1440	0.7433
Zhejiang	57,125,000	10,760	0.9324	0.0166	0.0936
Total	1,427,318,000	15,913	1.8798	0.0306	0.1931

Table A6: Incidence rate (per 100,000) of WSH-attributable disease per province in 2020 under RCP 8.5, using mean α, and assuming linear increases in access to improved water and sanitation infrastructure.

Province	Population	IR Diarrheal Disease	IR Malaria	IR Dengue	IR JE
Anhui	55,848,105	29,477	20.3131	0.0016	0.3609
Beijing	21,491,673	9,044	0.2360	0.0182	0
Chongqing Shi	28,326,042	17,234	0.1548	0.0031	0.9973
Fujian	36,732,151	13,128	0.0699	0.0674	0.0691
Gansu	27,386,065	31,647	0.0479	0.0040	0.2598
Guangdong	172,296,044	13,149	0.1688	0.1114	0.0991
Guangxi	43,105,196	27,176	0.1254	0.0020	0.2875
Guizhou	40,005,718	34,705	3.5064	0	0.9906
Hainan	9,499,726	18,731	0.1246	0.0021	0.3062
Hebei	75,418,929	18,023	0.0364	0	0.0295
Heilongjiang	35,295,640	13,825	0.0139	0	0.0000
Henan	94,603,964	23,880	2.9986	0.0008	0.2849
Hubei	58,721,963	22,661	1.8412	0.0050	0.0712
Hunan	55,761,056	27,827	0.1103	0.0096	0.2232
Jiangsu	77,439,158	9,434	0.6574	0.0042	0.0499
Jiangxi	36,295,489	34,560	0.0502	0.0021	0.1119
Jilin	25,211,924	13,980	0.0320	0	0
Liaoning	39,762,225	11,425	0.0315	0.0027	0
Neimenggu	25,513,526	19,747	0.0082	0	0.0040
Ningxia	7,005,606	33,396	0.0493	0	0
Qinghai	5,629,742	24,243	0.0000	0	0
Shaanxi	38,823,495	21,469	0.1297	0.0058	0.1024
Shandong	91,447,403	15,791	0.1615	0	0.1065
Shanghai	22,566,391	8,493	0.6768	0.0354	0.0570
Shanxi	40,025,498	20,410	0.0128	0	0.0731
Sichuan	72,247,313	31,936	0.1998	0	0.7141
Tianjin	12,033,622	9,693	0.0330	0	0.0164
Xinjiang	28,598,017	24,458	0.0150	0	0.0048
Xizang	4,390,230	53,265	1.2582	0	0.0679
Yunnan	52,390,064	36,443	8.6403	0.1282	0.8145
Zhejiang	52,302,485	10,716	0.8560	0.0132	0.1013
Total	1,386,174,458	20,523	1.6838	0.0233	0.2179

Table A7: Incidence rate (per 100,000) of WSH-attributable disease per province in 2030 under RCP 8.5, using mean α, and assuming linear increases in access to improved water and sanitation infrastructure.

Province	Population	IR Diarrheal Disease	IR Malaria	IR Dengue	IR JE
Anhui	49,994,000	21,339	25.3084	0.0021	0.3424
Beijing	24,710,000	10,025	0.2645	0.0239	0
Chongqing Shi	32,540,000	12,090	0.1724	0.0034	0.8970
Fujian	44,566,000	11,427	0.0792	0.0841	0.0631
Gansu	30,813,000	21,179	0.0487	0.0043	0.2571
Guangdong	180,129,000	13,243	0.2014	0.1538	0.0882
Guangxi	39,300,000	18,604	0.1360	0.0023	0.2509
Guizhou	34,628,000	38,740	3.8804	0	0.8920
Hainan	10,739,000	16,197	0.1430	0.0026	0.2607
Hebei	74,319,000	16,137	0.0381	0	0.0297
Heilongjiang	31,077,000	13,260	0.0149	0	0.0000
Henan	88,900,000	17,326	3.9455	0.0010	0.2714
Hubei	65,164,000	13,043	2.3673	0.0057	0.0616
Hunan	56,894,000	18,617	0.1168	0.0105	0.1962
Jiangsu	78,510,000	9,762	0.8175	0.0059	0.0481
Jiangxi	41,011,000	23,819	0.0564	0.0024	0.0971
Jilin	29,542,000	11,328	0.0406	0	0
Liaoning	40,951,000	10,564	0.0349	0.0042	0
Neimenggu	25,623,000	13,988	0.0091	0	0.0042
Ningxia	8,506,000	20,158	0.0497	0	0
Qinghai	6,103,000	20,552	0.0000	0	0
Shaanxi	35,123,000	15,370	0.1477	0.0062	0.0999
Shandong	98,308,000	14,093	0.1890	0	0.1154
Shanghai	28,308,000	9,227	0.7456	0.0449	0.0587
Shanxi	41,435,000	16,528	0.0133	0	0.0905
Sichuan	69,328,000	20,823	0.2233	0	0.6303
Tianjin	12,708,000	10,367	0.0344	0	0.0163
Xinjiang	32,314,000	17,382	0.0184	0	0.0050
Xizang	4,190,000	48,453	1.3052	0	0.0718
Yunnan	54,460,000	24,878	9.5980	0.1520	0.7587
Zhejiang	57,125,000	10,773	0.9335	0.0166	0.0937
Total	1,427,318,000	16,051	1.8834	0.0315	0.1942

Table A8: Description of water and sanitation access scenarios, modified from Pruss *et al* (2002) and Carlton *et al* (2012).

Exposure Scenario	Description	Baseline RR of Diarrhea
II	Centralized, treated drinking water is piped to each residence AND improved sanitation facilities are appropriately installed	2.5
IV	Drinking water is available from centralized piped systems, but treatment is incomplete or non-existant (partially improved) AND improved sanitation facilities are appropriately installed.	4.53
V	Improved sanitation facilities are appropriately installed, but no improved or partially improved drinking water is available. OR Partially improved drinking water is available but improved sanitation is not available.	5.16
VI	No improved or partially improved drinking water or improved sanitation is available	11.2

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