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Mapping Global Vulnerability
to *Dengue* using the
*Water Associated
Disease Index*

LAURA M. FULLERTON, SARAH K. DICKIN, CORINNE J. SCHUSTER-WALLACE

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PREFACE

Water-associated diseases, such as cholera, dengue, and schistosomiasis, threaten the health and wellbeing of billions worldwide. They are most prevalent in tropical and sub-tropical regions, and are spread through contact with contaminated water or exposure to disease-carrying vectors (such as mosquitoes) that depend upon water to survive. Exacerbated by poor water and waste management, rapid urbanization, high population density, and changing climate conditions, water-associated diseases are of increasing concern in a rapidly changing and increasingly globalized world.

With limited resources to treat or combat the spread of water-associated disease in many endemic regions, preventative interventions must be appropriately targeted and timed to maximize their efficacy. This requires accurate identification of regions most vulnerable to disease, and the timely delivery of interventions to prevent, mitigate, and manage disease in these regions.

In this report, we apply the Water Associated Disease Index (WADI) to calculate and visually communicate vulnerability to dengue on a global scale. While a number of tools exist to measure vulnerability to disease, most focus on when and where environmental conditions are optimal for an outbreak to occur, with little or no consideration of the role social determinants play in shaping vulnerability. As with any disease, we

believe that vulnerability is shaped by a diverse range of environmental and social conditions. With this in mind, the WADI was developed to assess vulnerability by integrating disease-specific measures of environmental exposure (i.e., temperature, precipitation, land cover etc.) with disease-specific measures of social susceptibility (i.e., life expectancy, educational attainment, access to healthcare etc.) to provide a holistic picture of vulnerability to disease.

The WADI is a practical disease-specific tool for assessing vulnerability at a range of different spatial and temporal scales using publicly available data. It provides a new way of conceptualizing and communicating vulnerability to disease and, in this instance, demonstrates clear patterns of dengue vulnerability and how these may change over time.

It is our hope that the WADI will be used to inform mid- to long-term allocation of resources to reduce or eradicate the burden of water-associated disease.

Corinne Schuster-Wallace
Senior Research Fellow, UNU INWEH



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Introduction

Water-associated diseases are responsible for approximately 3 million deaths annually and countless hours of lost productivity and illness (WWAP, 2009). They are spread by a range of transmission routes including ingestion of water, contact with water, and vectors that require water to proliferate. Approximately 10% of the global burden of disease could be prevented by improved access to safe water, sanitation and hygiene, and better water management (Prüss-Ustün et al., 2008). Most prevalent in tropical and sub-tropical regions, the spread of these diseases, such as dengue, cholera, and schistosomiasis, is exacerbated by global changes including rapid population growth, uncontrolled urbanization, changing climate conditions, and decreasing water security. While preventative measures can be taken to lower the burden of disease, interventions must be appropriately targeted for greatest impact. In order to effectively direct resources for disease control, it is crucial to understand key disease determinants and dynamics, and the differential distribution of vulnerability. Vulnerability assessment is an approach that can be used to represent multi-dimensional information in order to identify priority regions and populations, and

support disease control and health promotion interventions. This report describes the use of a Water-Associated Disease Index (WADI) to map global dengue vulnerability, a pragmatic tool that can be implemented with limited data or technical input, which is critical for decision-making in low-resource settings. By combining key factors that represent exposure, individual susceptibility, and community susceptibility to dengue transmission, regions most vulnerable to dengue are identified and mapped.

DENGUE: A COMPLEX WATER-ASSOCIATED DISEASE

Dengue is a water-associated disease transmitted by mosquito vectors, *Aedes aegypti* and *Aedes albopictus*, in tropical and sub-tropical regions. *A. aegypti* is predominantly an urban mosquito that often lays eggs in household water containers, while *A. albopictus* is often found outdoors in vegetated areas. Both mosquitoes feed during daylight hours, and commonly bite several different people with each blood meal, allowing for transmission of dengue virus to multiple people within a short period of time (Gubler, 1998).

Global incidence of dengue has grown rapidly, putting more than half the world's population at risk (WHO, 2013). Dengue is estimated to infect close to 400 million people and cause 250,000–500,000 cases of severe dengue annually, leading to hundreds of thousands of hospitalizations, countless hours of lost productivity, and approximately 20,000 deaths per year (Bhatt et al., 2013; Gubler, 1998; Suaya et al., 2007). Most prevalent in Southeast Asia, the Americas, and Western Pacific regions, dengue is characterized by a fever lasting two to seven days, and non-specific symptoms such as headache, rash, body aches, and joint pain (Gubler, 1998). Following the febrile phase of infection, dengue can progress into the more severe forms of Dengue Hemorrhagic Fever and Dengue Shock Syndrome (DHF, DSS). DHF and DSS are life-threatening conditions requiring hospitalization and are believed to occur most frequently among children, the elderly, and those previously infected with at least one of four strains (DENV-1, DENV-2, DENV-3, DENV-4) of dengue virus.

With no available vaccinations or specific treatments, actions taken in the home and community to reduce mosquito habitats are of vital importance for dengue prevention. The WHO Global Strategy for Dengue Fever/Dengue Haemorrhagic Fever Prevention and Control is comprised of five key components:

1. Selective integrated vector control, with community and intersectoral collaboration,
2. Active disease surveillance based on a strong health-information system,
3. Emergency preparedness,
4. Capacity building and training, and
5. Vector-control research (Nathan & Dayal-Drager, 2006; WHO, 2012).



However, many endemic countries lack the health systems and data collection tools required for extensive disease surveillance. The WADI can be applied in these settings because it provides a targeted and adaptable approach to address widespread data and resource limitations.

Furthermore, due to its non-specific influenza-like symptoms, dengue is commonly misdiagnosed and underreported, especially where diseases with similar symptoms such as malaria, chikungunya, leptospirosis, and typhoid are prevalent, and where rapid testing for dengue is unavailable (Suaya et al., 2007). For instance, new research indicates that dengue may represent a much higher burden of disease in Africa than previously believed, almost equivalent to that of the Americas (Bhatt et al., 2013). Widespread misdiagnoses and underreporting not only make dengue a



Charles Rondeau

challenging disease to monitor and measure, but also make it difficult to accurately quantify the global burden of disease. For this reason, data on incidence rates and resulting burden of disease are incomplete or unavailable for some dengue-endemic countries and regions. Thus, innovative tools and strategies which identify key regions for action are of critical importance for informing and validating policy decisions, research priorities, prevention programmes, and training initiatives.

The development of novel tools to assess vulnerability is of additional relevance because many water-associated diseases are expanding globally, often linked to global changes in human-environment systems. Dengue is considered a re-emerging disease, which has experienced an exponential increase in the number of reported global dengue cases in the last decade (Nathan et

al., 2007). Global changes contributing to dengue expansion include rapid global population growth, rural to urban migration, the absence of effective vector controls in dengue-endemic regions, increased transportation from region to region, and poor public health infrastructure in many dengue-endemic countries (Gubler, 1998).

Despite existing evidence that identifies key disease determinants and thresholds in the literature, limited tools exist to translate and operationalize this understanding to improve decision-making. In light of these challenges, this report applies the WADI tool to map existing vulnerability to dengue in order to visualize global regions under greatest threat. Outcomes enhance understanding of factors mediating dengue transmission globally, which can contribute to better allocation of targeted resources for long-term disease prevention and control planning.

CHAPTER TWO

Objectives

The overall goal of this report is to apply the Water Associated Disease Index to visualize vulnerability to dengue at a global scale. This can be broken down into several key objectives:

- » To identify and integrate global indicators of susceptibility and exposure to dengue
- » To develop a strategy for addressing gaps in global datasets
- » To visually communicate global vulnerability to dengue based on susceptibility and exposure indicators in map format





UNU-INWEH, Sarah Dickin

Applying a vulnerability framework to water-associated disease

“Accurate assessment of the global, regional, and country health situation and trends is critical for evidence-based decision making for public health.”

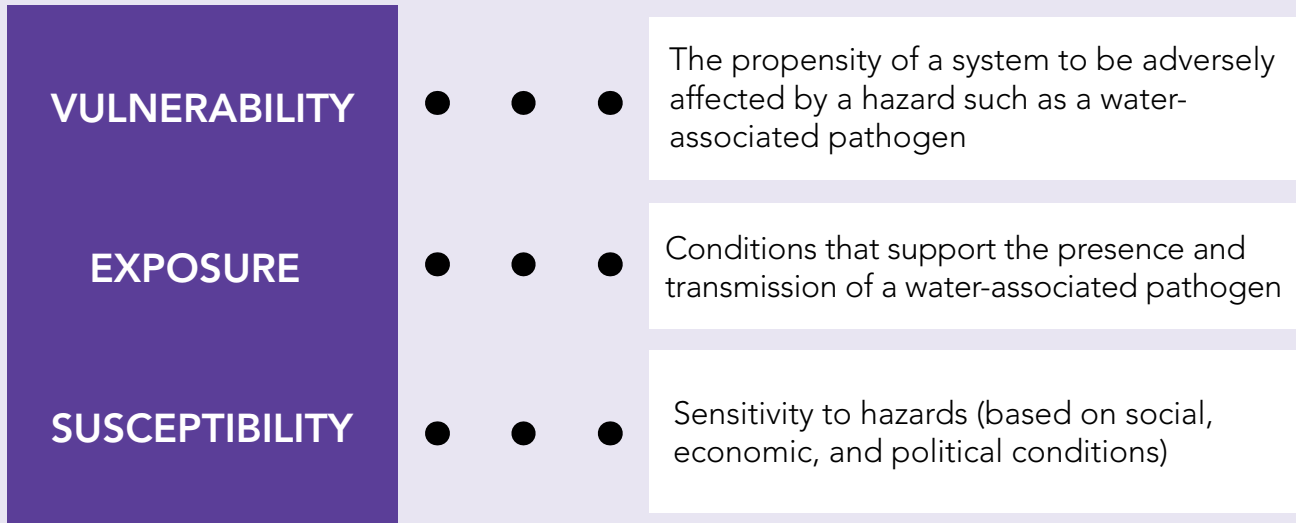
- Margaret Chan, WHO Director-General

While commonly used to assess the impacts of climate change and natural disasters, vulnerability assessment can be a useful tool in the context of health and wellbeing applications. Understanding vulnerability to water-associated diseases, such as dengue and schistosomiasis, can make significant contributions to effective monitoring, prevention and control strategies. However, the concept of vulnerability is often contested among scholars who conceptualize the term differently according to their purpose and discipline (Füssel, 2009). In many cases vulnerability is determined by considering dimensions of exposure, susceptibility and ability to adapt or cope with a hazard (Adger, 2006). In this study, vulnerability is defined as “the degree to which a system is susceptible to, or unable to cope with, adverse effects” (McCarthy et al., 2001). When applied to the water-associated disease context, vulnerability is determined by a population’s exposure to conditions that

support the presence and transmission of a water-associated pathogen, and susceptibility to social, cultural, and economic conditions that shape sensitivity to a water-associated pathogen (Figure 1).

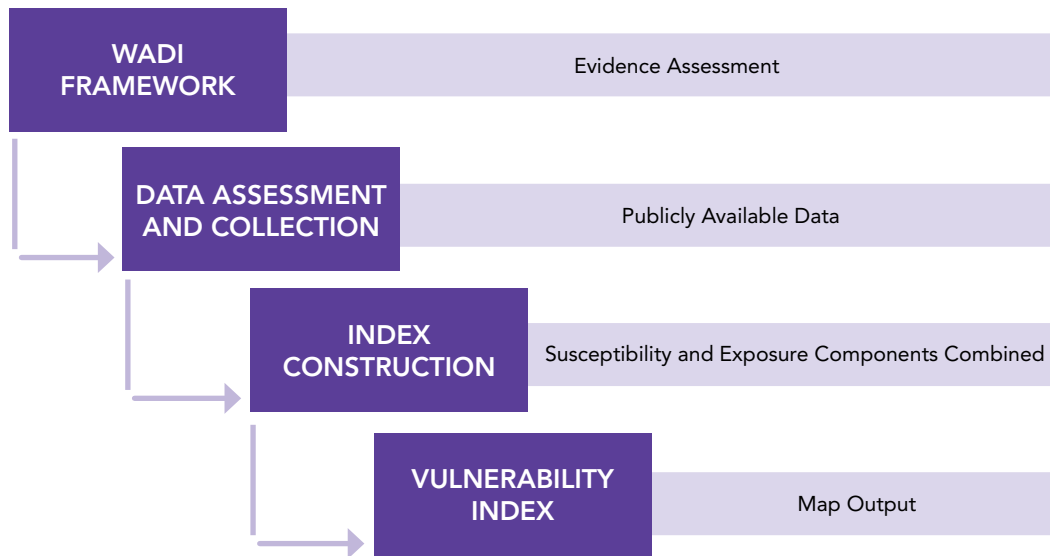
A challenge of vulnerability assessment is the synthesis of diverse social and environmental determinants in order to communicate, and often quantify, the implications of a specific hazard. For instance, relevant factors may act across multiple spatial and temporal scales and may be represented by a range of qualitative and quantitative data. Because measures of exposure and susceptibility are often multi-dimensional, indicators are commonly used as proxies to allow for the simplification and integration of diverse measures into a composite index (Hahn et al., 2008). Indicators are useful for summarizing large volumes of data into formats that are useful for decision-makers.

FIGURE 1: COMPONENTS OF VULNERABILITY ASSESSMENT USED IN THE WADI APPROACH



“Vulnerability assessment offers a novel way to conceptualize the complex web of factors and interactions mediating the water-associated disease burden, by focusing less on the likelihood of the hazard occurring, and instead on analyzing a wide range of factors that impact exposure, susceptibility, and ability to cope and recover from a disease” (Dickin et al., 2013).”

FIGURE 2: PATHWAY OF WADI: DENGUE INDEX CONSTRUCTION

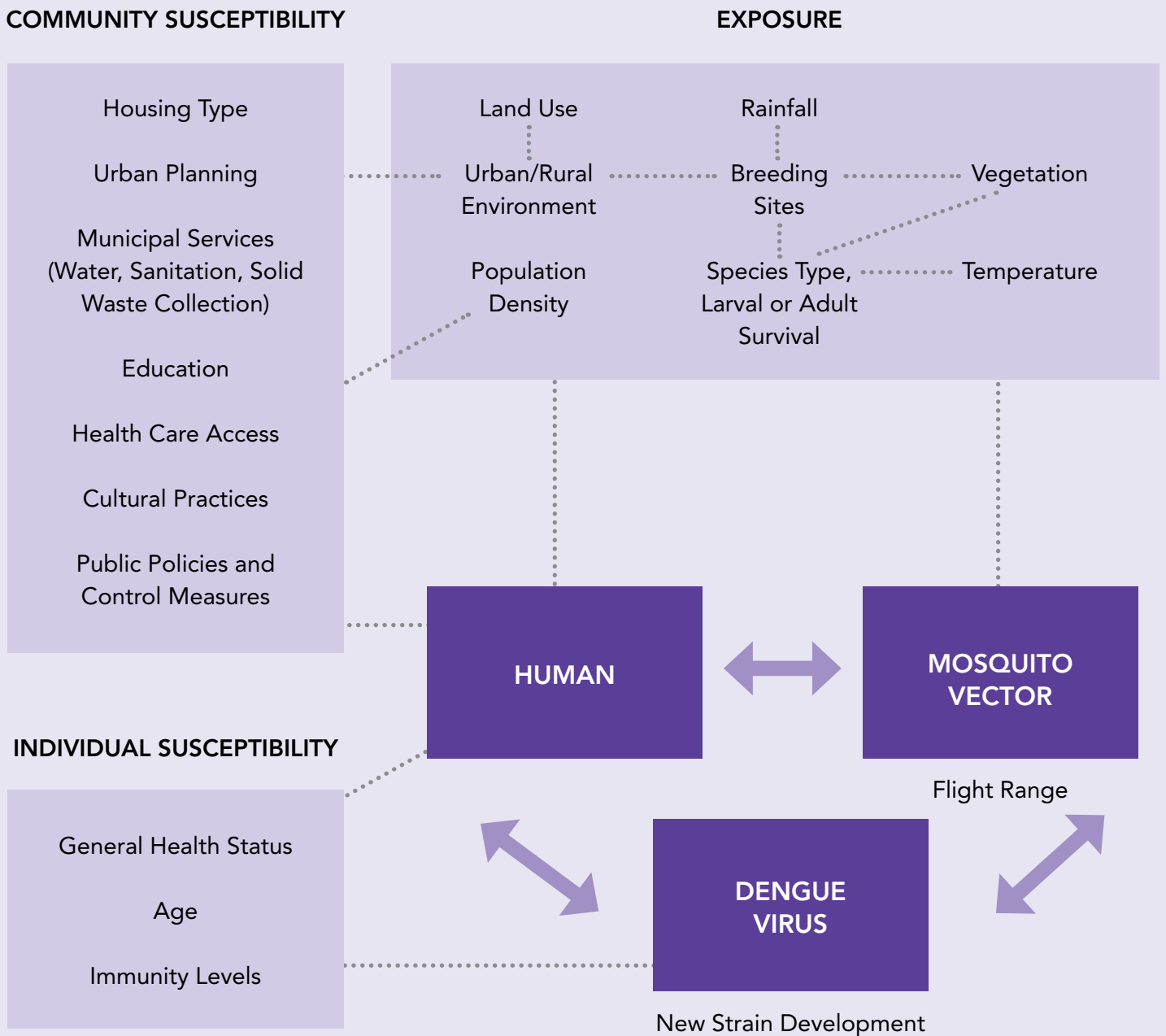



WATER-ASSOCIATED DISEASE INDEX (WADI) APPROACH

The Water-Associated Disease Index (WADI) is designed to measure and visualize the vulnerability of communities and regions to infectious water-related diseases in the face of global changes such as increasing urbanization, land use intensification and climate change. The WADI approach integrates environmental and social datasets to identify regions most vulnerable to specific water-associated diseases at a spatial scale of interest. Index components representing susceptibility or exposure are combined to provide an overall score of vulnerability for each disease assessed. The pathway of index construction is illustrated in Figure 2. See Dickin et al., 2013 for technical details describing the Water Associated Disease Index methodology and construction.

In order to identify indicators of susceptibility and exposure that describe vulnerability to a water-associated disease, a WADI framework was developed based on evidence in the literature. This framework provides a comprehensive view of the many factors and interactions contributing to disease presence and transmission. The WADI framework developed in this report identifies determinants of exposure and susceptibility that together describe linkages between human, vector and virus elements in the dengue transmission cycle (Figure 3). This framework was used to inform the development of the ‘WADI: Dengue’ global approach through the identification of datasets to populate the index.

FIGURE 3: WADI FRAMEWORK FOR DENGUE DESCRIBING LINKAGES BETWEEN HUMAN, VECTOR AND VIRUS ELEMENTS IN THE DENGUE TRANSMISSION CYCLE

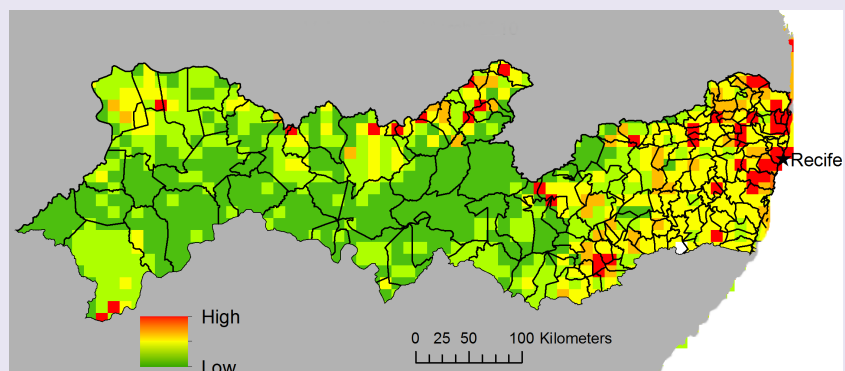


A hand is shown holding a pipette, dispensing liquid into a petri dish. In the background, a microscope is visible, suggesting a laboratory or research setting. The entire image is overlaid with a semi-transparent purple filter.

“The WADI: Dengue approach provides a robust, easily applicable tool for assessing potential water-associated disease hotspots across spatial and temporal domains. Global vulnerability data created using the WADI: Dengue approach provides valuable information to decision-makers for improved planning and resource allocation for the prevention of disease.”

CASE STUDY: APPLYING THE WADI TO DENGUE TO ASSESS CHANGES IN VULNERABILITY AT REGIONAL LEVEL IN NORTHEAST, BRAZIL

Vulnerability was assessed and compared in 2000 and 2010 in Pernambuco, Northeast Brazil (Dickin et al., 2014). Highest vulnerability was observed in the densely populated capital Recife and surrounding coastal areas in both time periods, illustrated in the below figure showing conditions in March, 2010. Throughout the period of analysis climate conditions were found to create seasonal trends in exposure to dengue. While more remote areas in the semi-arid Sertão (western region) showed low vulnerability overall, increases were observed in some areas between 2000 to 2010 due to land use changes and growing populations. These findings illustrate the insight that analysing short-term and long-term regional changes can provide to a vulnerability assessment using the WADI approach.



Applying the WADI-Dengue at a global level

This report applies the WADI: Dengue approach to assess, visualize and compare trends in vulnerability to dengue on a global scale, providing a key source of information for decision-makers to target resources for water-associated disease intervention.

DATA SELECTION PROCESS

The global WADI: Dengue was constructed with vulnerability components representing exposure and susceptibility to dengue (Table 1). Identification of indicators to describe these components was guided by a framework illustrated in Figure 3, based on social and ecological factors and thresholds thought to mediate dengue transmission in the literature (Table 2). Selection of data to measure these indicators was based on the quality and availability of global datasets identified from publicly accessible data repositories online.

In order to identify datasets to populate the indicators, search terms were used to identify website with relevant datasets, which led to WHO and UN divisional websites. Databases searched in this research included: WHO Global Health Obser-

vatory, WHO/UNICEF Joint Monitoring Programme, UN Statistics Division, UN Data, UNESCO Institute for Statistics, UN DESA Population Division, UN MDG Indicators, and World Bank Data. Published documents consulted in this research include WHO World Health Statistics Report 2012 and World Bank 2010 World Development Indicators (WDI) Report. Original data sources were used for each measure where available, i.e. if the same dataset appeared on multiple data platforms the organization responsible for collecting the data was used as the source.

While acceptable datasets to measure exposure were readily available, measures of susceptibility indicators were more challenging to obtain, and in some countries this susceptibility information was not available. In order to determine the best types of information to measure indicators comprising the global WADI: Dengue, it was necessary to set indicator selection criteria to guide the assessment and selection process. Indicator selection criteria ensure measures are selected systematically based on their quality and appropriateness (Cole et al., 1998). Indicators of susceptibility were selected for their ability to

TABLE 1: INDICATORS USED IN THE WADI: DENGUE APPLIED AT A GLOBAL LEVEL, GUIDED BY DATA AVAILABILITY

VULNERABILITY COMPONENT	CATEGORY	WADI: DENGUE INDICATOR	IDEAL INDICATOR MEASURE	ACTUAL INDICATOR MEASURE
EXPOSURE	CLIMATE	TEMPERATURE	TEMPERATURE	MAXIMUM TEMPERATURE
		PRECIPITATION	PRECIPITATION	MONTHLY PRECIPITATION
	LAND ENVIRONMENT	TYPE OF LAND USE	DISTRIBUTION OF URBAN, RURAL AND UNINHABITED LAND USES	FOREST, MIXED VEGETATION, CROPLAND, OR URBAN LAND USES
	HUMAN ENVIRONMENT	POPULATION DENSITY	POPULATION DENSITY	POPULATION/ SQUARE KM
SUSCEPTIBILITY	INDIVIDUAL	YOUNG OR OLD AGE	AGE < 15 YEARS AGE > 60 YEARS	AGE < 15 YEARS AGE > 60 YEARS
		IMMUNITY LEVEL	DENGUE SEROPREVALENCE	NOT AVAILABLE
	COMMUNITY	HEALTHCARE ACCESS	ACCESS TO NEARBY HEALTHCARE SERVICES	PHYSICIAN DENSITY
		WATER ACCESS	ACCESS TO AFFORDABLE, RELIABLE WATER SOURCE	UNIMPROVED DRINKING WATER SOURCE
		HOUSING QUALITY	HOUSING CONSTRUCTION AND SOLID WASTE COLLECTION	UNIMPROVED SANITATION FACILITIES
		HEALTH STATUS	EXISTING HEALTH CONDITIONS	LIFE EXPECTANCY AT BIRTH
		HOUSEHOLD DENGUE CONTROL	FEMALE KNOWLEDGE OF DISEASE PREVENTION	FEMALE PROGRESSION TO SECONDARY SCHOOL
		GOVERNMENT POLICIES AND ACTIVITIES	SURVEILLANCE AND CONTROL MEASURES	NOT AVAILABLE
SOCIAL CAPITAL	PARTICIPATION IN COMMUNITY DENGUE ACTIVITIES	NOT AVAILABLE		

TABLE 2: RATIONALE FOR INCLUSION OF SELECTED MEASURES FOR WADI: DENGUE INDICATORS USED IN THIS REPORT

VULNERABILITY COMPONENT	INDICATOR MEASURE	RATIONALE FOR INCLUSION	DATA SOURCE
EXPOSURE	MAXIMUM TEMPERATURE	High temperature is conducive to vector proliferation	WorldClim climate grids (Hijmans et al. 2005)
	MONTHLY PRECIPITATION	Rainfall provides outdoor breeding sites	WorldClim climate grids (Hijmans et al. 2005)
	FOREST, MIXED VEGETATION, CROPLAND, OR URBAN LAND USES	<i>Aedes</i> vectors prefer human environments, especially urban land uses	Globcover land cover map (2010)
	POPULATION/SQUARE KM	Densely populated areas increase human reservoirs of virus of required for dengue transmission	LandScan 2000-Global Population Database
SUSCEPTIBILITY	AGE < 15 YEARS AGE > 60 YEARS	Children 0-15 years of age have a higher susceptibility to severe dengue than the adult population. Older adults are more susceptible to dengue infections	UN DESA Population Division
	PHYSICIAN DENSITY	Physician density indicates availability and accessibility of health care	WHO Global Health Observatory
	UNIMPROVED DRINKING WATER SOURCE	Lack of access to water supplies requires storage of water around the home	WHO/UNICEF Joint Monitoring Programme (JMP)
	UNIMPROVED SANITATION FACILITIES	Unimproved sanitation indicates possible proximity to poorly managed water resources and poor quality housing	WHO/UNICEF Joint Monitoring Programme (JMP)
	LIFE EXPECTANCY AT BIRTH	Life expectancy at birth provides an estimate of general population health status	UN DESA World Population Prospects Report
	FEMALE PROGRESSION TO SECONDARY SCHOOL	Progression to secondary school indicates a sufficient level of educational attainment to read, interpret and act upon public health information about water-associated diseases	UN Statistics Division
	SURVEILLANCE AND CONTROL MEASURES	Provides information on government actions to reduce dengue transmission	Not available
	PARTICIPATION IN COMMUNITY DENGUE ACTIVITIES	Provides information on community actions to reduce dengue transmission	Not available

meet indicator criteria outlined by Garriga and Foguet (2010), and their ability to closely describe the susceptibility indicator they were chosen to represent. However, where no exact measures were available, proxies were used to describe indicators, such as in the case of health care access. In other instances, some indicators could be measured in a number of different ways (i.e., female educational attainment could be measured using female completion of primary school, female literacy rate, female progression to secondary school, female completion of secondary school, etc.). In this case, closely related measures were extracted and entered into a global database for potential use if the optimal indicator measure was unavailable. Potential indicator measures and substitutes were compared and assessed by the research team, according to the selection criteria described above, to determine optimal susceptibility measures for use in the global WADI: Dengue tool. Data entry was verified by the researcher and by a research assistant to ensure accuracy.

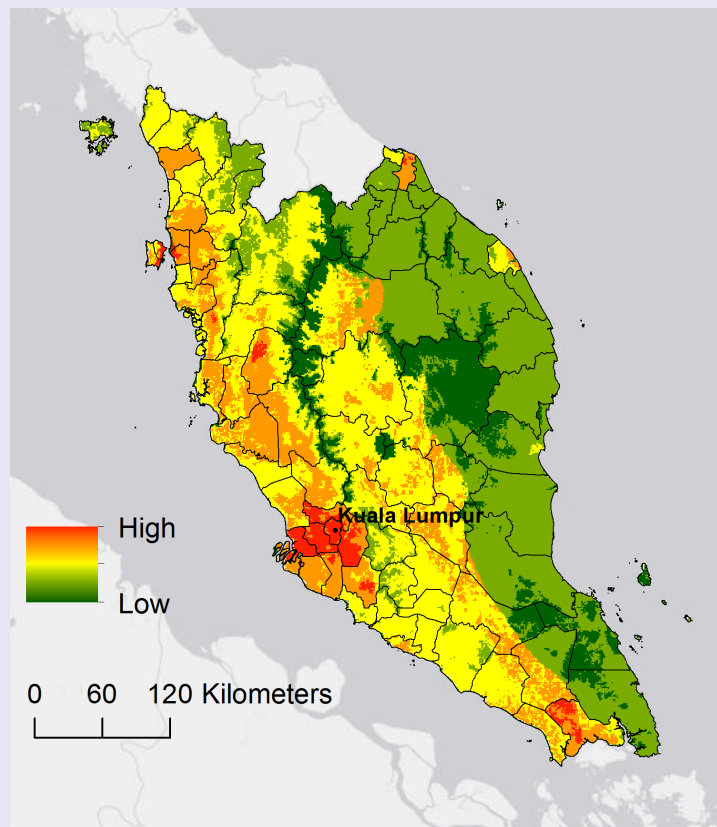
Following indicator selection, a sensitivity analysis was conducted to test the robustness of susceptibility measures used in the global WADI: Dengue assessment. A one-way sensitivity analysis approach was applied to evaluate the influence of changes on the susceptibility index. The analysis focused on assessing the impact of missing data and substitution indicator measures on index outcomes.

CREATING MAPS FROM VULNERABILITY COMPONENTS

In order to construct the index and create map outputs, each indicator dataset was standardized to a range from 0 to 1 and converted into a raster format (see Appendix I). Indicators comprising

“Garriga and Foguet (2010) recommended that indicators are: 1) available (without prohibitive costs); 2) understandable (clearly defined); 3) accurate (from reliable sources); 4) scalable (ability to move between levels of analysis); 5) relevant (adaptable to change); 6) regularly updatable; and 7) integrative (can work across disciplinary sectors).”

exposure (e.g. temperature) were weighted equally to create the exposure component as were indicators comprising the susceptibility component (e.g. water access). The resulting exposure and susceptibility raster layers were combined to produce vulnerability maps by month. A larger weighting towards the overall vulnerability index was attached to the exposure component, based on weightings identified in a WADI proof of concept study (Dickin et al., 2013) and evidence in the literature describing the relative contributions of environmental and social factors to dengue transmission. Global maps were created for each month of the year using ArcGIS software (version 10.1; Esri, Redlands, CA) in order to visually communicate temporal changes in vulnerability to dengue. Regions that did not reach the temperatures required to support dengue transmission had no vulnerability, despite the possible presence of other indicators of exposure or susceptibility.



CASE STUDY: APPLYING THE WADI TO DENGUE AT A NATIONAL LEVEL IN MALAYSIA

The WADI was applied to dengue at a subnational level in Malaysia, where urban environments, especially the Kuala Lumpur region, were highlighted as highly vulnerable areas (Dickin et al., 2013). This figure, illustrating vulnerability conditions in December, shows that eastern Malaysia is strongly affected by the monsoon season, which brings heavy rainfall to the coast, possibly washing away mosquito breeding sites. However, in drier months, exposure in this region increases, possibly due to more moderate rainfall. With high susceptibility in the region, this increases vulnerability. In contrast, some areas of Malaysia have consistently low vulnerability due to low exposure from unsuitable land uses for *Aedes* vectors, as well as low population density. No vulnerability is observed in areas where temperatures are too low, mainly the mountainous regions in central Malaysia.

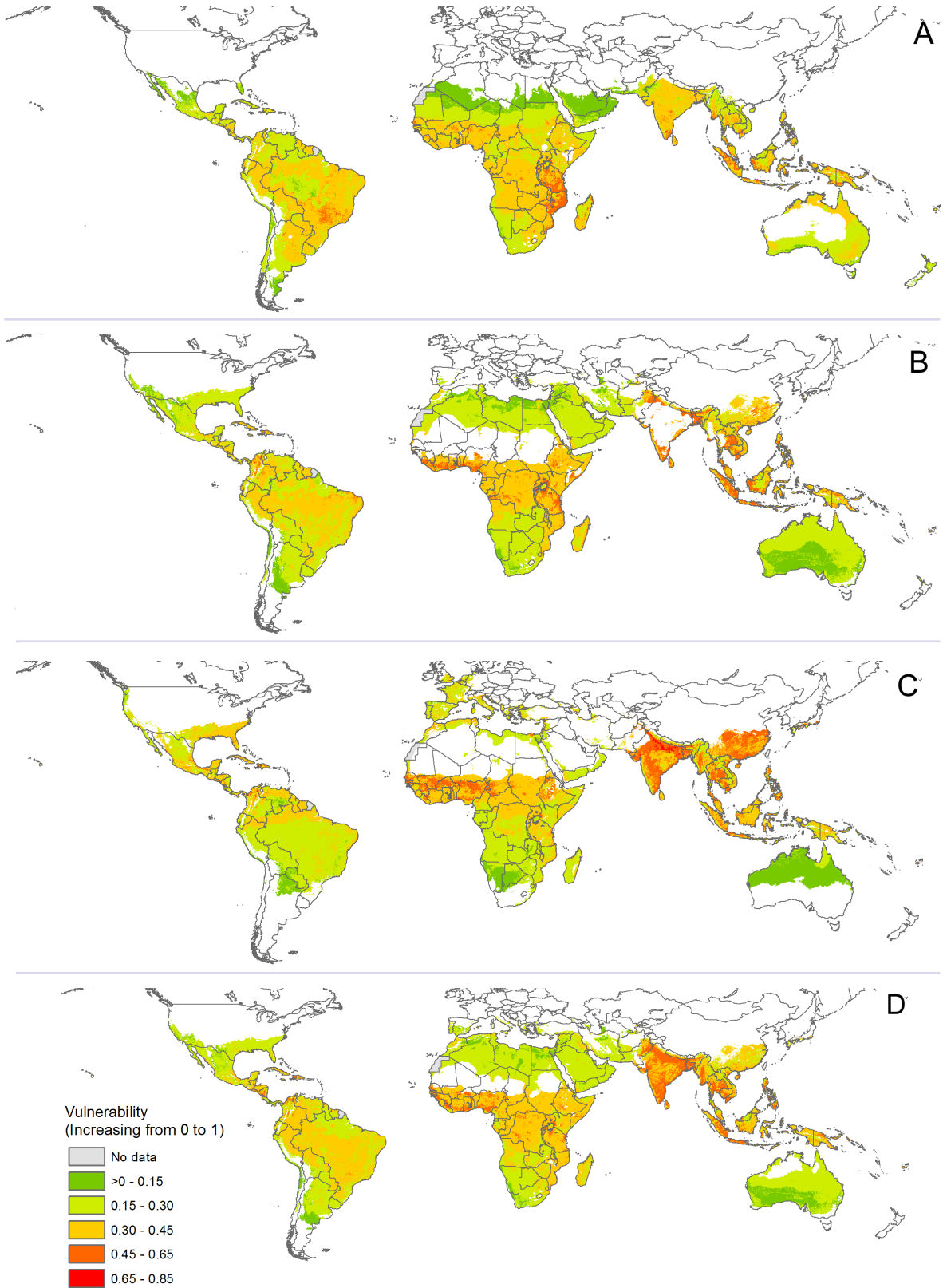


Figure 4: Overall vulnerability to dengue in January (A), April (B), July (C), and October (D) (showing countries with data on at least 5 of 7 susceptibility indicators).

GLOBAL PATTERNS OF VULNERABILITY TO DENGUE

The vulnerability maps produced using the WADI: Dengue approach illustrate heterogeneous spatial and temporal trends in vulnerability at a global level (Figure 4). These trends are discussed in the context of exposure to dengue, followed by susceptibility. Overall, highest levels of vulnerability to dengue are observed in South Asia and Southeast Asia. In addition, countries located close the equator tend to maintain some level of vulnerability to dengue throughout the year because they experience moderate to high susceptibility and consistently favourable exposure conditions (e.g., Colombia, Sierra Leone, Nigeria, Southern India, Indonesia).

When exposure conditions are optimal for mosquito vector survival and virus transmission, adequate control measures are very important because the disease can easily transmitted, even in conditions of low susceptibility. Vulnerability to dengue is generally higher in areas with exposure to urban and agricultural land use, as well as regions with high population density. High population density increases exposure by providing human virus reservoirs that allow rapid dengue transmission. For instance, in Asian countries where population density is high, such as India, Bangladesh, China, and Indonesia, vulnerability to dengue is also high (Figure 5). Similar trends are observed in Central America and Western Africa where regions with high population density also have a high vulnerability to dengue. Although high population density increases exposure to dengue, vulnerability may still be high in regions with a moderate or low population density if other conditions of exposure and susceptibility are high, illustrating complex interactions between social and environmental factors. For example, Colombia has a relatively low population density, yet experiences

high vulnerability to dengue because of other optimal indicators of exposure and susceptibility. Although many regions within Europe, North America, Northern China, and Japan are characterized by high population density or large urban areas, they are not exposed to dengue because climate thresholds are not conducive for mosquito vector populations.

In addition to population density and anthropogenic land uses, it is clear that exposure to dengue is significantly mediated by global climate trends and does not remain static. Maps display considerable seasonal variation in levels of vulnerability to dengue on all continents, due mainly to annual fluctuations in temperature and precipitation that contribute to exposure (Figure 6). Areas shown in white indicate no exposure, and thus no vulnerability, to dengue, because temperatures are too low to sustain vector populations year-round. All regions vulnerable to dengue are located in tropical and subtropical regions where minimum temperature is always -2°C or higher.

By highlighting vulnerability to dengue across four time periods January, April, July and October, it is possible to track dynamic expansion and contraction of hotspots. While exposure is more consistent in equatorial regions, sub-tropical latitudes experience greater seasonal trends. Temperatures and rainfall amounts that are too low or high for vector proliferation contribute to these trends that have important impacts on dengue transmission. For example, large temporal trends are observed in South Asia due to varying conditions throughout the year. In addition, less well defined seasonal trends can be observed in Central Africa and South America. Although most regions experience highest exposure during their hottest months, hot and dry regions such as North Africa and the Middle East experience highest exposure to dengue in the months before and after their

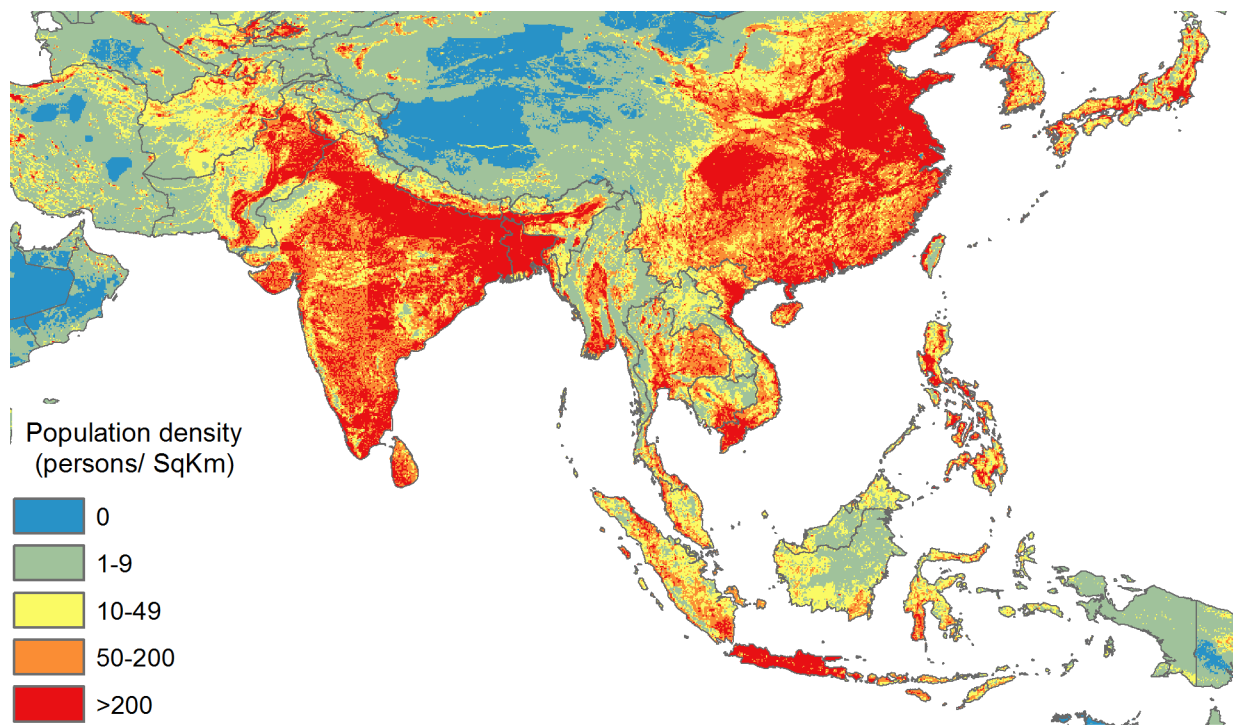


Figure 5: Regional population density in 2000
(adapted from the LandScan 2000-Global Population Database)

hottest months, when temperatures and rainfall are most conducive to mosquito survival. In addition, regions at the most northern and southern ranges of vulnerability are characterized by moderate exposure conditions during their hotter months, but zero vulnerability in their cooler months (e.g., Argentina and Southern United States). For instance, southern Europe experiences moderate vulnerability from May until September, but zero vulnerability from October until April due to the onset of colder conditions.

Countries with high susceptibility in this WADI: Dengue report were generally characterized by higher vulnerability to dengue than countries with low susceptibility — even when experiencing similar exposure conditions. For example, differences in susceptibility indicators (healthcare access,

water and sanitation access, etc.) in Southeast Asian countries resulted in different levels of susceptibility and subsequently vulnerability to dengue. Because certain countries report higher female educational attainment, better health status, improved water and sanitation facilities, and better access to healthcare than others, they are less susceptible to dengue — because the populations are less sensitive to the presence of disease vectors, and because national ability to adapt and manage disease is improved (Figure 7). Similar trends are observed among countries in Central America where access to improved water, sanitation facilities, and healthcare varies, despite similar conditions of dengue exposure. However, these susceptibility conditions do not provide a complete picture because information on community and government dengue control

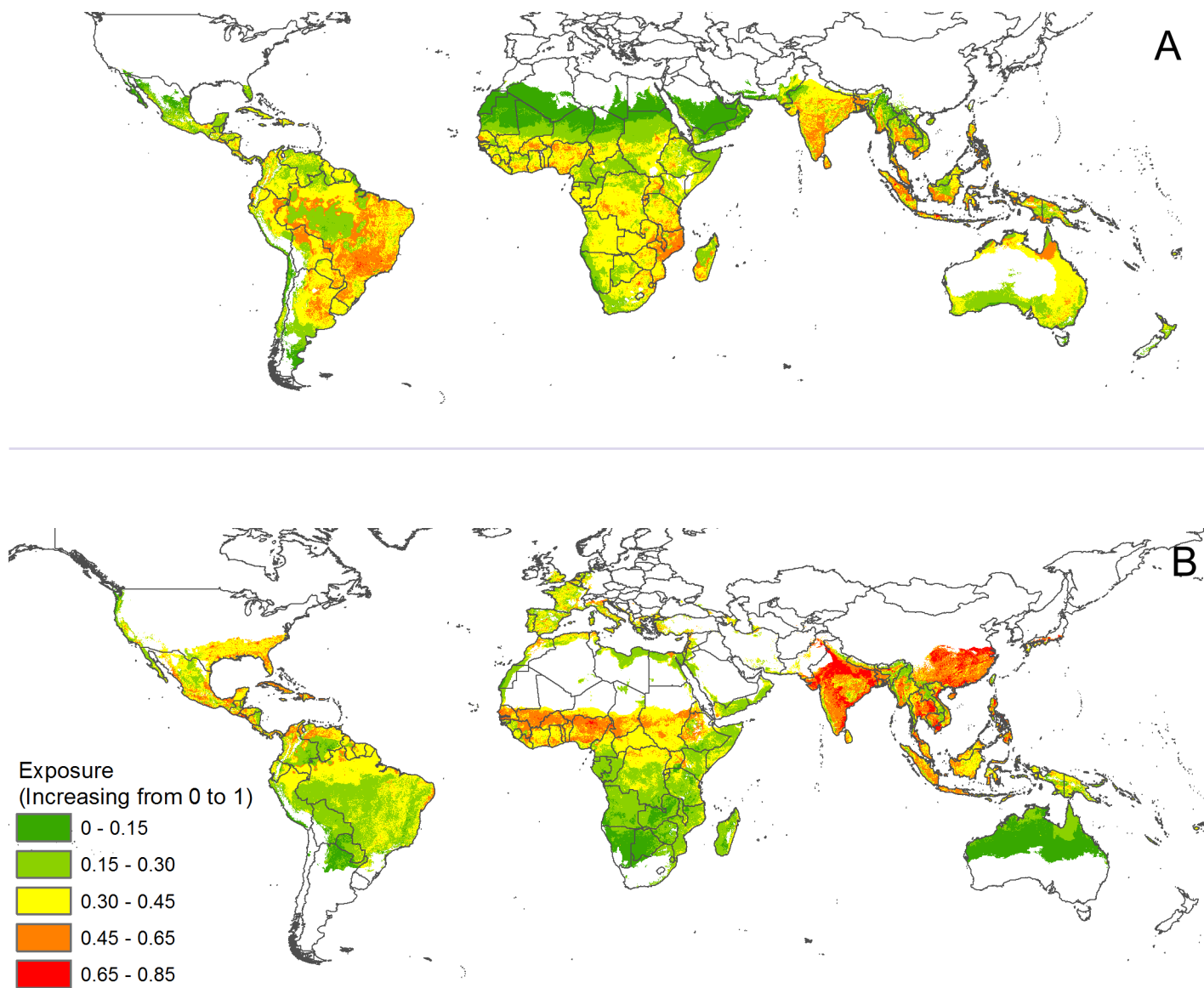


Figure 6: Comparison of global exposure to dengue in January (A) and July (B)

activities were not available. In addition, existing water access data does not provide information on reliability or affordability of water supplies. Collection of these types of data at a global level will improve understanding of dengue susceptibility and allow better comparisons to be made.

In Central and West African regions, susceptibility to dengue was very high because most indicator measures were elevated, including access to water resources, sanitation facilities and health care services. With very high susceptibility to dengue, vulnerability in this region was higher than other regions with similar exposure levels but lower levels of susceptibility to dengue. These regions are of importance because future increases in exposure conditions would lead to expansion of vulnerability in areas without dengue surveillance or control programs. In addition, while extensive dengue virus circulation has not been reported in these regions it is a possible future risk.

“A strength of the WADI: Dengue approach is that it directs attention to areas of high vulnerability that may not be currently reporting dengue cases – where dengue may be a future challenge.”

Suceptibility by Country

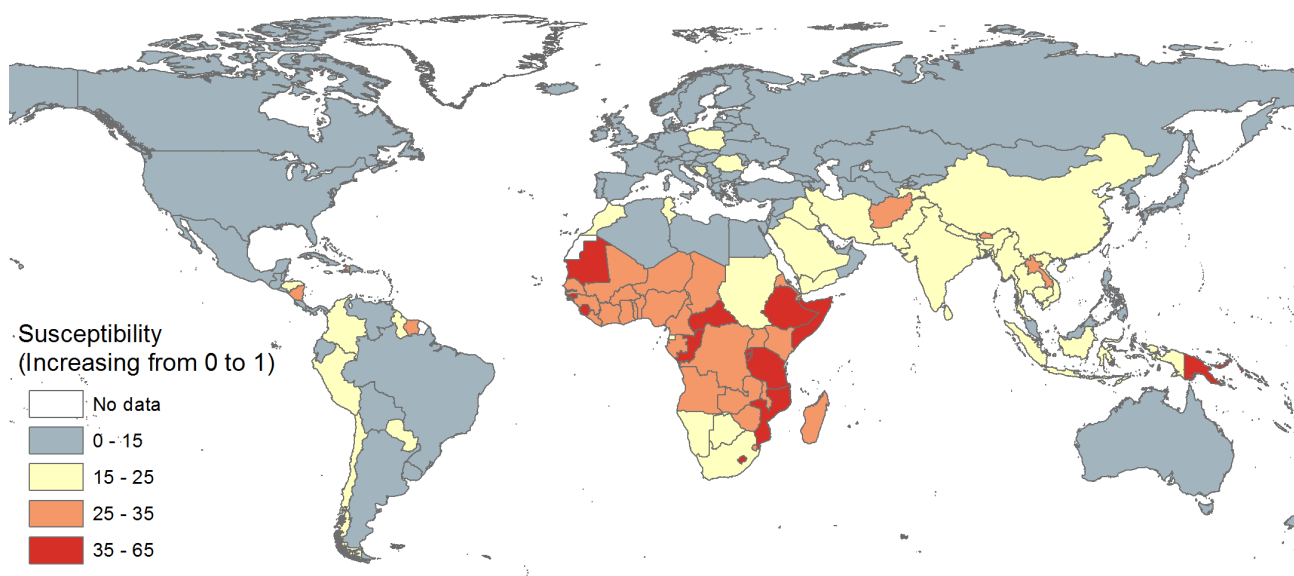


Figure 7: Susceptibility by country (for countries with data for at least 5 of 7 indicators)

Average dengue cases reported to the WHO (2004-2010)

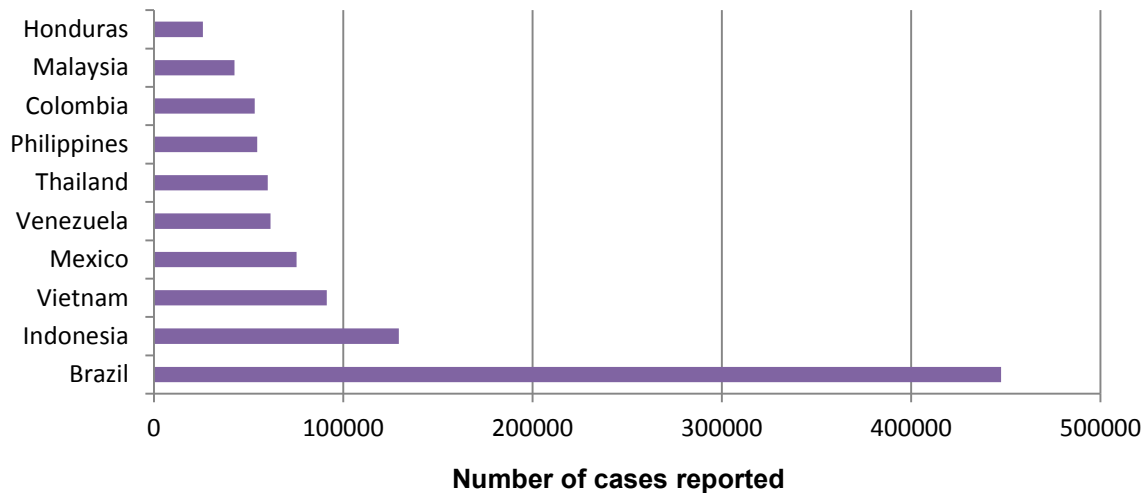


Figure 8: Average annual cases reported to the WHO in the top ten endemic countries (Adapted from Global Strategy for Dengue Prevention and Control: 2012–2020, 2012)

WADI: DENGUE IN THE CONTEXT OF CURRENT GLOBAL OF DENGUE PATTERNS

Dengue is endemic in more than 100 countries and continues to expand. The WADI: Dengue maps showing areas of high vulnerability correspond to many of the countries and regions threatened by dengue (Figure 8). They advance existing global dengue maps that rely on isotherms to show exposed areas. Similar trends have been observed in modeling-based approaches that predict dengue risk using variables including temperature, precipitation, land use and poverty (Bhatt et al., 2013). It is important to consider that the WADI: Dengue approach is a tool which highlights areas of exposure and susceptibility that contribute to vulnerability, however the dengue virus must be present to result in actual risk of infection. Despite similar conditions of vulnerability, some regions may experience more virulent forms of the dengue virus, or display varying levels of immunity in the population which

have important impacts on dengue transmission. A strength of the WADI: Dengue approach is that it directs attention to areas of high vulnerability that may not be currently reporting dengue cases, where dengue may be a future challenge.

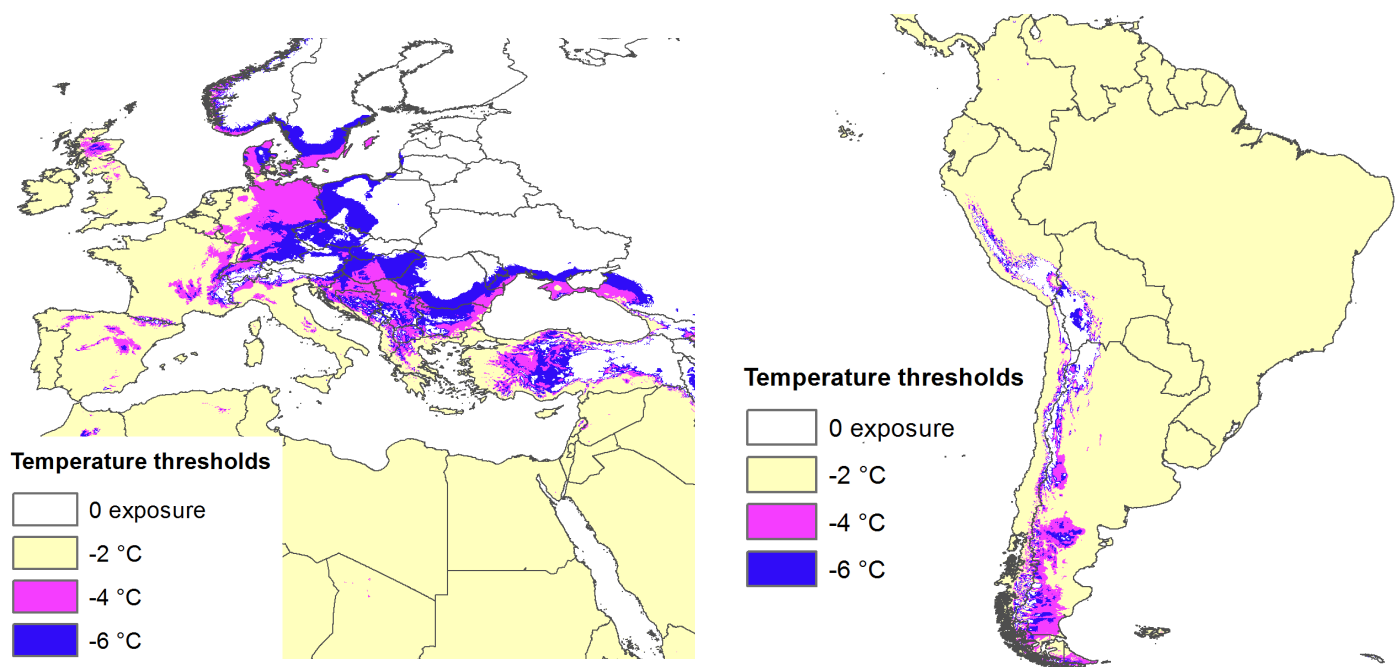


Figure 9: Comparison of dengue -2°C (current range) temperature, and range expansion using -4°C and -6°C thresholds

IMPACTS OF RISING GLOBAL TEMPERATURES

While exposure conditions may not be optimal in some areas with high susceptibility, changes to climate could result in increased exposure and pose a serious threat to areas that do not currently experience endemic dengue. Increasing temperatures will likely have the biggest impact at the most northern and southern range of dengue vulnerability. Although dengue-carrying mosquitoes do not reproduce in temperatures lower than approximately 14°C , *Aedes* eggs can survive long-term exposure to temperatures as low as -2°C (Thomas et al., 2012). This -2°C threshold was applied across all map outputs to eliminate areas that cannot support mosquito survival at any point during the year.

Climate change is expected to increase temperature extremes, resulting in less frequent cold days, cold nights and frost, and a rise in minimum temperatures (Field et al., 2012). This is likely to impact the survival of *Aedes* eggs, and could expand the

geographical range of the vector and therefore dengue. Thus, a temperature threshold of -4°C and of -6°C was compared with the -2°C threshold to highlight the possible changes in exposure to dengue representing a 2°C and 4°C increase in minimum temperature. This was applied to demonstrate that warmer conditions may have implications for dengue exposure, although it should be noted that climate change models would be required to make accurate spatial predictions of changing temperature impacts. Results show several key areas where temperature changes could make a difference, such as mountainous regions in South America that are currently too cold to sustain mosquito populations year round, and large areas in Europe that could potentially experience an increase in exposure (Figure 9). In addition, increased temperature maximums could shrink vector range in areas where it becomes too hot for mosquito populations.



SENSITIVITY ANALYSIS

A series of sensitivity analyses were applied to the susceptibility component of the global WADI: Dengue to determine the response to changes in input variables and missing data. Because many global datasets contain missing data, the impact of removing variables is an important consideration. The difference between the complete susceptibility index and an index with missing data was calculated (Figure 10), showing that certain types of missing information have a larger impact on the outcome. The largest % decrease is observed with the removal of the healthcare access variable. Another challenge is assessing the impact of using alternate variables when an ideal dataset is unavailable. A sensitivity analysis was applied by substituting variables from alternate data sources (see Appendix II). Each optimal susceptibility variable was substituted with a potential alternate variable and the change was assessed. The results of this analysis did not indicate that substituting variables would have a large impact on the WADI: Dengue susceptibility component (Figure 11). However, the ranking of highest and lowest countries by susceptibility did change with substitutions, an important consideration for decision-makers.

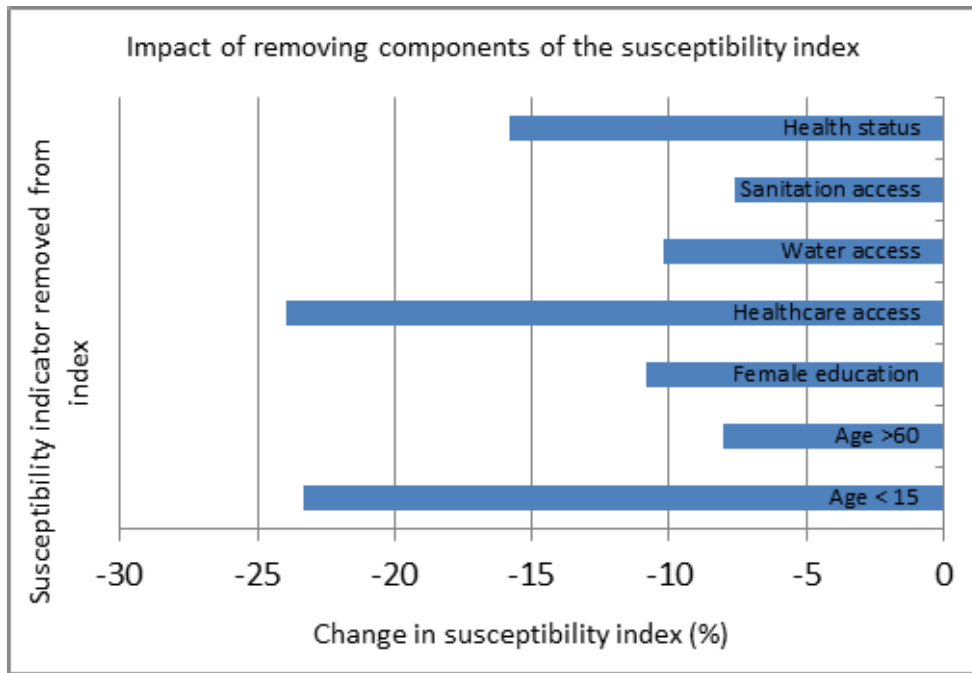


Figure 10: Sensitivity analysis of component removal on the susceptibility index. Results show the percentage change in the mean susceptibility index when each component is systemically removed.

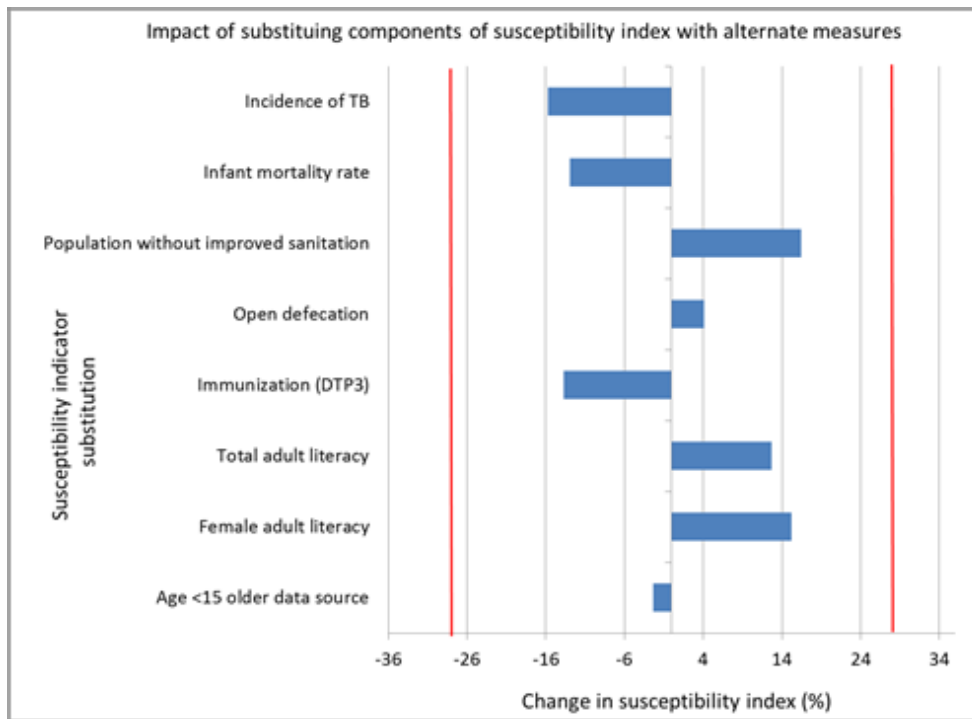


Figure 11: Sensitivity analysis of substituting alternate data sources (Substitutions described in Appendix II). The red line indicates a half a standard deviation in the original index for reference

Moving forward: challenges with the use of global datasets

Indicators are commonly used to summarize and simplify data to facilitate the communication and comparison of information (Hammond et al. 1995). The WADI: Dengue was applied at a global level using freely available datasets from a number of sources. Several challenges arose when attempting to identify global datasets for indicator measures of susceptibility as well as data on global dengue incidence. The most common challenges were incomplete and outdated datasets, inaccessible original data sources, inconsistent data reports from datasets of the same year or indicator measure, and unspecified statistical processes behind data configuration. In addition, when ideal indicator measures are not available, replacement measures may reflect conditions beyond the specific scope of interest. For example, as a measure health status life expectancy values for a country indicate not only the average age of a population, but also the physical and socio-economic conditions experienced by a population. While some challenges are more limiting than others, these issues influenced indicator selection for the susceptibility components used in the vulnerability index.

Countries with missing, unavailable and/or outdated data were most often developing countries, small countries, island states, and countries with recent/ongoing conflict or newly formed borders. Some indicator measures had more complete datasets than others, likely related to how certain measures are prioritized by governments, international governing bodies and researchers. For example, in the construction of the global WADI: Dengue, the most complete data set considered measured life expectancy at birth, calculated by the UNDP as part of the Human Development Index (n=193/262). The measure with the most incomplete data set in the global application of WADI: Dengue was female educational attainment (n=156/262). Additionally, while some datasets are complete and freely available, they may not tell the entire story. For instance, data on access to improved water does not indicate whether there is consistent service, an important risk factor for dengue due to breeding habitats created in stored water around the home when a supply cannot be relied upon.

The absence of global data on disease incidence, burden, and other social and health-related measures, is part of a large challenge in global health research associated with the monitoring of basic health measures, such as birth and death rates, disease incidence and prevalence, and risk factors for disease (Bollyky, 2013). While some countries and regions have effective systems for the surveillance, monitoring and reporting of disease, others do not, resulting in incomplete data on the global distribution of disease (Brady et al., 2012). Missing data on a number of basic health measures makes it difficult both to monitor global patterns — and risk factors — of disease illness and injury, and to make evidence-informed decisions regarding resource allocation and intervention priorities for the prevention and control of disease. In the case of dengue, global data on housing quality were not available, despite being a key factor for breeding habitats, so sanitation access was used as an alternate measure. Housing quality is an important social determinant of health, relevant to many different infectious diseases, and represents a key gap in global data resources.

Current and comprehensive global data on the distribution and burden of disease is invaluable for the evidence-based prioritization of interventions and resources for the prevention, treatment and management of global illness, disease, and injury. Recognizing the need for improved global health data, the Global Burden of Disease (GBD) study was commissioned, a large and comprehensive study to assess global burdens of disease, injury, and risk over a twenty-year period from 1990-2010. Using the disability adjusted life year (DALY) measurement, the GBD study collected data to measure rates of morbidity and mortality, but also life years lost due to illness, disease, injury and premature death (WHO, 2013). Although

valuable, the GBD study has received criticism due the methods used to interpret water and health information (Wolf et al., 2014) and does not provide spatially explicit information.

While incomplete and outdated data was a challenge when searching for publically available global data for WADI: Dengue, so too was the inability to access original data sources for all indicator measures. Although original data sources were sometimes publically available, in a number of cases they could not be found or openly accessed. While it is preferable to use data from its original data source, in this research data was used from a secondary source when it could not be accessed from its original source. An additional challenge encountered was inconsistencies between datasets of the same year, indicator measure, and data source. For instance, this was observed when comparing World Bank Indicator Data from the World Bank website, with data from the World Bank's 2010 WDI Report. Although measures were defined the same way and presented for the same year, numbers were considerably different from one source to the other for e.g. measures of improved sanitation facilities (% of population with access in 2006) and age (% of population 0-14 years of age in 2008).

Finally, the statistical methods used to analyze and configure global data are often not specified or available from data sources. While statistical methods and processes may be complex and difficult to understand for those without technical training, they serve to inform the reader of the decisions and processes that lead to statistical outcomes. This allows for the transparent analysis, and accurate use of results, especially in the case of extrapolated datasets. While it may not be necessary to include full details in published documents or spreadsheets of statistical data,



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such information should be accessible and publically available for those who wish to examine the processes and decisions involved in data configuration to determine the accuracy and value of data.

Together these issues had a role in shaping which data sources and susceptibility variables were used in the global WADI: Dengue. While it was possible to collect the data needed for global WADI: Dengue, these challenges highlight key areas for improvement with how publically available global data are presented and detailed.

Conclusion

With no currently available vaccines or treatments to protect against dengue, appropriately timed and targeted preventative interventions are critically important to lower the burden of disease. The global WADI: Dengue approach applied in this research was used to map monthly global vulnerability to dengue through the integration of measures of exposure and susceptibility. Vulnerability maps are useful tools that increase understanding of areas experiencing the greatest threat from a particular hazard. This can assist in identifying areas in greatest need for appropriately timed and located preventative interventions. The results of the WADI: Dengue global report indicate more attention is needed in areas that are highly susceptible but that do not currently have exposure conditions suitable for vector populations, as exposure conditions may change in the context of increasing global environmental changes. In addition, planning is needed in areas that do not currently experience circulating dengue viruses but that are characterized by favourable exposure and susceptibility conditions (e.g. many regions in West and Central Africa).

Because vulnerability to dengue is dependent upon conditions for mosquito vector survival,

rising global temperatures caused by climate change — especially increases in minimum temperatures — may lead to expansion of global areas of vulnerability to dengue, and may elevate vulnerability in regions that are currently endemic. Conversely, more frequent and intense rainfall events may actually decrease amounts experienced may actually decrease exposure to dengue by preventing larval survival in outdoor breeding areas.

The WADI: Dengue approach provides a robust, easily applicable tool for assessing potential water-associated disease hotspots across spatial and temporal domains. Global vulnerability data created using the WADI: Dengue approach provides valuable information to decision-makers for improved planning and resource allocation for the prevention of disease, while employing freely available global datasets. In this report, the use of these datasets highlighted the need for greater integration across large databanks to ensure accuracy and completeness of data resources. Tools such as the Water Associated Disease Index also highlight a need for the collection of more data on social determinants of health on a global scale.



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APPENDIX I: INDEX CONSTRUCTION

To develop susceptibility and exposure indicators, thresholds were applied to each indicator measure to standardize data to a range from 0 to 1. Susceptibility measures were converted from percentages to a range from 0 to 1. In order to convert life expectancy at birth (expressed in years) into a percentage value, a maximum age of 85 years was applied (where 85 years = 100%). All life expectancy values were converted to percentage values by dividing the life expectancy by 85 and multiplying by 100.

TABLE A1: EXPOSURE THRESHOLDS APPLIED IN THE WADI: DENGUE GLOBAL REPORT

EXPOSURE INDICATOR	MEASURE	THRESHOLD
TEMPERATURE	MAXIMUM AND MINIMUM MONTHLY TEMPERATURE	Increase in exposure from 20 to 36°C maximum monthly temperature. No exposure if minimum temperature goes below -2°C at any point in the year, below which eggs may not be viable
PRECIPITATION	MONTHLY PRECIPITATION	Increase in exposure from 0 to 300mm monthly precipitation. No exposure beyond 300mm, where breeding habitats may be washed away
POPULATION DENSITY	PERSONS PER SQUARE KM	Increase in exposure corresponds to increasing population density
LAND COVER	TYPE OF LAND COVER	Exposure is low in mixed agricultural/ vegetated areas, moderate in agricultural areas and high in urban areas

APPENDIX II: DESCRIPTION OF SUBSTITUTE VARIABLE SELECTION

For each indicator measure variables were identified to address missing or unavailable data. The applicability of these substitute data were explored in the sensitivity analysis found in this report.

TABLE A2: INDICATOR SUBSTITUTIONS

INDICATOR	SUBSTITUTED WITH:	SUBSTITUTION DATA SOURCE
AGE (<15)	AGE (<15) OLDER DATASET USED	UN DESA Population Division Population Prospects and UN Demographic Yearbook
AGE (<60)	NONE IDENTIFIED	
FEMALE PROGRESSION TO SECONDARY SCHOOL	ADULT LITERACY, FEMALE (AGED 15+)	UN Statistics Division (Data from UNESCO Institute for Statistics)
	ADULT LITERACY, TOTAL (AGED 15+)	UN Statistics Division (Data from UNESCO Institute for Statistics)
PHYSICIAN DENSITY	IMMUNIZATION DTP3 (% CHILDREN AGED 12-23 MONTHS VACCINATED)	WHO / UNICEF, Immunization surveillance, assessment and monitoring
TOTAL UNIMPROVED DRINKING WATER SOURCE	NONE IDENTIFIED	
UNIMPROVED SANITATION FACILITIES	OPEN DEFECATION	WHO/UNICEF Joint Monitoring Programme (JMP)
	POPULATION WITHOUT IMPROVED SANITATION	WHO World Health Statistics
LIFE EXPECTANCY AT BIRTH (BOTH SEXES)	INFANT MORTALITY RATE	UN DESA World Population Prospects Report
	INCIDENCE OF TB	WHO Global TB Report



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