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Key Points:
- Water insecurity facilitated vector habitats are on the rise in arid and semiarid regions of Mexico and the Americas
- Temperature and rainfall changes are facilitating habitat spread and distribution of the *Aedes aegypti* and the *Aedes albopictus* mosquitoes
- Focus should be on improved water management, vector surveillance, and disease awareness among the most vulnerable and migrant populations

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Prioritizing Water Security in the Management of Vector-Borne Diseases: Lessons From Oaxaca, Mexico

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Abstract Changes in human water use, along with temperature and rainfall patterns, are facilitating habitat spread and distribution of *Aedes aegypti* and *Aedes albopictus* mosquitoes, the primary vectors for the transmission of Dengue, Chikungunya, and Zika viruses in the Americas. Artificial containers and wet spots provide major sources of mosquito larval habitat in residential areas. Mosquito abatement and control strategies remain the most effective public health interventions for minimizing the impact of these vector-borne diseases. Understanding how water insecurity is conducive to the establishment and elimination of endemic mosquito populations, particularly in arid or semiarid regions, is a vital component in shaping these intervention strategies.

Plain Language Summary: As urban growth and climate change facilitates the spread of *Aedes* mosquitos, risking substantial increases in Dengue, Zika, and Chikungunya in the Americas, managing disease burden will rely on effective interventions to reduce water insecurity. We use the case of Oaxaca, Mexico, to illustrate the relationship between water insecurity, the establishment of mosquito habitat, and heightened disease risk from vector-borne diseases.

1. Introduction

Water security encompasses the availability of water supplies, water storage practices, and management of water-related risks. Water insecurity can exacerbate public health issues including diseases transmitted by arthropod vectors, which transfer pathogens from one host to another. Although water-borne diseases are often the focus of dialogue relating public health consequences of water insecurity, many of its aspects directly or indirectly relate to the biology of insect vectors, particularly mosquitoes. Water insecurity may facilitate invasions of nonindigenous mosquito vectors, increase habitats both in terms of quantity and higher quality for mosquitoes, and extend the "mosquito season" by providing year-round habitat during otherwise dry periods. The recent pandemic of Zika underscores the global risk of expanding populations of two mosquito species in particular, *Aedes aegypti* and *Aedes albopictus* (Brady & Hay, 2020). As the distribution and abundance of these vectors expand, populations lacking prior exposure to mosquito-borne diseases are wholly susceptible and at risk for an outbreak (Lucey & Gostin, 2016). Though many factors contribute to mosquito-borne disease outbreaks, the indirect impacts of water insecurity on mosquitoes merit detailed consideration. Effective management of water resources, in contrast, can reduce vector populations and boost success in public health interventions to break down mosquito-borne disease transmission cycles.

2. *Aedes* Vectors and *Aedes*-Borne Arboviruses

Arboviruses transmitted by mosquitoes in genus *Aedes* continue to emerge and resurge across tropical climates worldwide. The emergence of some important *Aedes*-borne arboviruses is largely attributed to the decades-long rebounding and range expansion of *Ae. aegypti*, the yellow fever mosquito, as well as the invasive *Ae. albopictus*, the Asian tiger mosquito (Brady & Hay, 2020; Lounibus, 2002).

Dengue is endemic in 124 tropical and subtropical countries, where it is a significant health problem to over 2.5 billion people (Bhatt et al., 2013; Guzman et al., 2010). The disease has increased in frequency and distribution over the last 25 years, with temperature increases identified as a major factor in modeling future spread (Brady & Hay, 2020; Ryan et al., 2019). Dengue distribution is spreading in the Americas with a south to north trajectory. It is endemic in much of South America and the Caribbean and occurs regularly in the southern parts of North America, including Southern Mexico (Akanda & Johnson, 2018). Similarly, the 2015–2016 Zika pandemic in the Americas conservatively identified 800,000 cases, including in Florida, USA (Lucey & Gostin, 2016).

The biology and ecology of *Ae. aegypti* and *Ae. albopictus* are important for understanding the role of water insecurity on mosquito populations. *Ae. aegypti* is an urban mosquito, breeding predominantly around dense human settlements (Couret et al., 2014). Urban populations of *Ae. aegypti* show a high-fidelity preference, up to 99%, for human hosts based on blood meal analysis (Ponlawat & Harrington, 2005). In contrast, *Ae. albopictus* shows more varied host preference even in urban environments (Niebylski et al., 1995) and prefers habitats at the peripheries. Both species have evolved to develop in small volumes of water and are well adapted for utilizing human-made containers as larval habitat. Uncontrolled and unplanned urbanization, population growth, poverty, and ineffective vector control services and abatement strategies are critical factors that can foster local mosquito populations (Gubler, 2010; Guzman et al., 2010; Kraemer et al., 2019). Climate projections indicate that year-round conditions conducive to these mosquitoes will extend throughout the southern United States, with seasonal spread of *Ae. aegypti* possible into the Midwest and Mid-Atlantic while *Ae. albopictus* is already present in the Northeast (Kraemer et al., 2019). Figure 1 shows the dynamic interactions between climatic and anthropogenic factors and effects on water insecurity and mosquito biology leading to vector-borne diseases.

3. Case Study: Oaxaca de Juarez, Mexico

The spread of dengue is a significant public health crisis in Mexico. Human demographic trends and insufficient mosquito management are major factors contributing to increases in dengue transmission, and climatic conditions conducive to the survival and expansion of *Ae. aegypti* also contribute (Baez-Harnandez et al., 2017; Dick et al., 2012). Human migration, population density, and inadequate water management facilitate residential mosquito populations, particularly in arid regions where they were previously absent (Akanda & Hossain, 2012). Water management and abatement programs remain the most immediate solution for vector-borne disease spread (Machado-Machado, 2012). Integrating sociopolitical drivers into hydroclimatic models are essential for modeling the distribution and spread of *Ae. aegypti*-borne infections for Mexico's arid regions (Okuneye et al., 2017).

Oaxaca offers an opportunity to examine the interaction of the hydroclimatic variance and sociopolitical forces driving the *Aedes* mosquitoes' northward migration. The climate of Oaxaca can be classified as warm subtropical, with about 750 mm of annual rainfall and a very dry winter period from November through March. Oaxaca thus exists in a state of water insecurity, particularly during the dry season. The impact of climate change is anticipated to exacerbate water insecurity in the region. By 2025, between 20% and 40% of the state's population will experience water insecurity (INEGI, 2011). Historically, two rivers, the *Jalatlaco* and *Atoyac*, supplied water to the city's central valley. Unplanned urbanization coupled with watershed impacts have resulted in decline in flow as well as contamination of the Atoyac, which runs through the city. The Jalatlaco River has been largely paved over; what remains runs beneath the city. Most of the city lacks piped water; water is trucked in and stored in large roof tanks, with multi-family buildings housing multiple large storage tanks. Alternate water storage includes several categories of rain catchment systems, from cisterns to sophisticated catchment systems to open-air rock-lined pits. Purchased water from a neighboring community, Etla, travels 11 km via open aqueduct and fails to meet city demands.

Few resources exist to improve water security, particularly in poor neighborhoods, creating a disincentive to invite surveillance for disease (INEGI, 2011). These infrastructural limitations, including inadequate sewage and clogged drainage systems, facilitate creation of larval habitats; *Ae. aegypti* may be found in septic and drainage systems. Despite a World Bank project addressing water distribution in Oaxaca, municipal governments are tasked with securing water resources and sanitation services, resulting in disaggregated and fractured water governance.

Oaxaca is experiencing a change in the distribution and frequency of dengue cases. Historic distribution of dengue within the state is concentrated in tropical coastal regions and the Isthmus region near the Veracruz

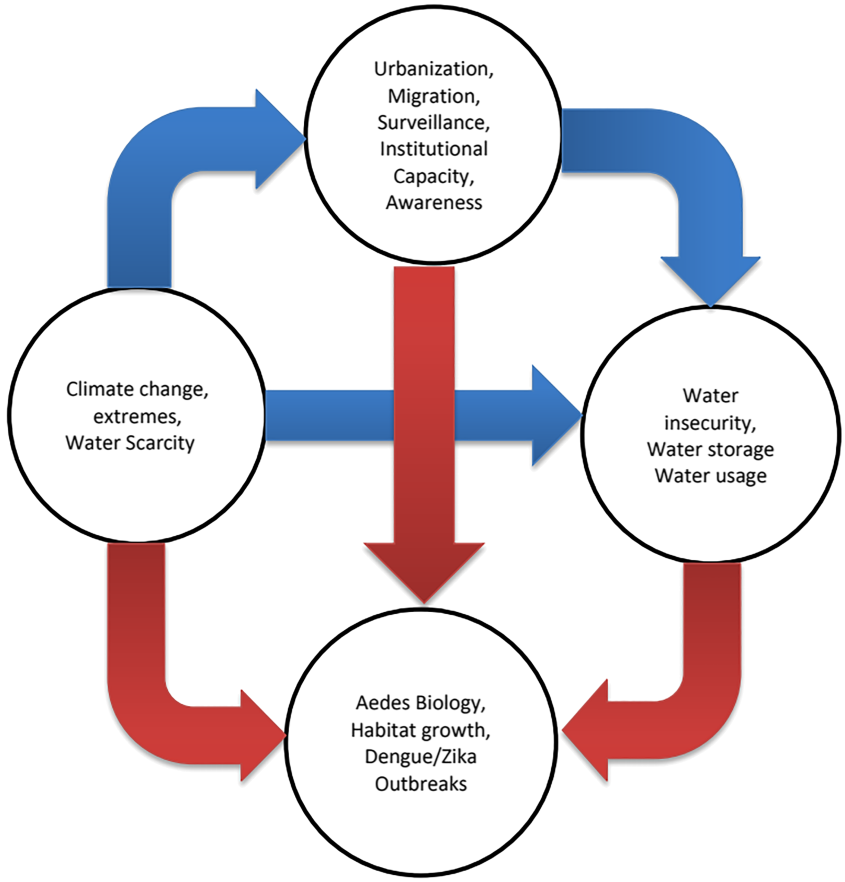

Figure 1. Interactions between hydroclimatic and sociopolitical drivers of water insecurity, mosquito biology, and vector-borne diseases (blue lines point to climatic and institutional issues that affect water practices, and red lines point to changes and issues affecting vector biology and disease burden).

border (Perez-Ramirez et al., 2009). Increasing prevalence of Dengue and diseases such as Zika and Chikungunya in Oaxaca's central valley suggest that human migration, water management, and sanitation are factors affecting patterns of disease spread (NSS Oaxaca, 2019; Torres, 2017). The valley, a densely populated urban inland region of over 650,000, is experiencing increases in vector-borne diseases, extending well into the dry season (NSS Oaxaca, 2019; Torres, 2017). Oaxaca de Juarez, with an altitude of 1,555 m above sea level, had been classified as at lower risk for *Aedes* habitats. In 2016, Chikungunya was reported in the central valley region throughout the November–May dry season (Torres, 2017). *Ae. aegypti* demonstrates remarkable adaptability; sampling of mosquito larvae between 2015 and 2017 revealed *Ae. aegypti* larvae in warmer microclimate regions of Mexico City, at an altitude of 2,250 m above sea level (Davalos-Becerril et al., 2019). Similarly, *Ae. albopictus* is well known for its strong ecological plasticity and ability to expand into newer habitats and for pushing its typical climatic thresholds (Paupy et al., 2009)

4. Challenges Facing Vector Management

Sociopolitical factors contribute to establishment of a dry season mosquito population. Oaxaca has high concentrations of poverty. Regulations supporting water access involve only licensing and delivery schedules of water delivery trucks (*Pipas*), with pricing determined by destination. Irregular and emergency delivery occurs at a premium price. Drought has exacerbated price increases over the course of the dry season and resulted in shortages; this pattern is repeated throughout Mexico, with 13 million people relying on delivery of water by *Pipas* (Rivas, 2014). Water scarcity results in “hoarding” of poor-quality refuse water, declining water quality for the poor, and frequent use of makeshift open water catchment basins and storage in population-dense areas. Pirated water from unlicensed vendors (*Pipas* are unionized in Oaxaca) renders identification of water origin, quality, and storage challenging (Fox, 2018). Disagreement over the control of a natural spring 40 km away from Oaxaca resulted in the dynamiting of a municipality dam by residents of a nearby community, serving as an illustration of the significant impact of water shortages on communities (Mexico Daily News, 2018).

The state is attempting to control mosquito habitats through insecticide application and public health education emphasizing sealing water tanks and repairing failing infrastructure and drainage (NSS Oaxaca, 2019). Substantial expenses associated with water distribution incentivize the reuse and storage of wastewater around homes. Compliance with remediation efforts and sanitation practices for improved household water management is contingent on local-scale infrastructure and governance improvements that guarantee access to quality water and on eliminating water insecurity. Mexico does enjoy national health care and a robust established dengue surveillance system. Without substantial improvements to water governance and access, preventative measures are limited in their efficacy.

5. Conclusion

Oaxaca de Juarez offers a contemporary example of how the interactions of water insecurity enable the establishment of mosquito infestation. Social and behavioral changes in water management will require addressing governance, policy, and infrastructure failures. Similar challenges with water infrastructure are echoed throughout the region; the 2017–2018 water crisis in Mexico City mirrored the distribution and sanitation challenges regularly observed in Oaxaca. *Pipas*, bucket-based water distribution, and water hoarding exist during drought, while flooding occurs during major rain events. Vector-borne disease management and mosquito abatement are heavily influenced by access to water and management of water resources at the local scale, particularly in population-dense environments. Effective water distribution, access, and maintenance systems remain a fundamental factor driving mosquito habitat expansion, limiting the efficacy of educational and treatment-based interventions that lack these elements alone. Greater emphasis should be put on improved water management, vector surveillance, and disease awareness among the most vulnerable and migrant populations.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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