Simulating the Impact of Climate Change on a Waterborne Disease Outbreak

An SIWR Model of a Cholera Outbreak in Harare, Zimbabwe with Climate Forcing

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Summary

Harare, Zimbabwe has suffered periodic cholera outbreaks since 1992.(1) It is projected to experience temperature and rainfall increases due to climate change, factors associated with greater cholera incidence in similar settings.(2)(3)(4) We use an SIWR model with a climate forcing function to simulate the impact of climate change on a typical cholera outbreak in Harare. According to our model climate change will make outbreaks more explosive but not more severe.

Introduction

- Cholera is caused by the bacteria *V. cholerae*.(5) It is transmitted by the fecal-oral route through contaminated water or close contact.(6) Its chief symptoms are severe watery diarrhea and dehydration; it can be deadly if untreated.(5)
- Zimbabwe's most recent cholera outbreak was in September, 2018 when the vast majority of its 8,535 cases and 50 deaths occurred in its capital, Harare. The outbreak's sources were the contaminated wells and boreholes relied upon for water by most of the city.(7)
- Waterborne disease transmission is highly sensitive to climatic conditions; increases in temperature and rainfall increase the human-contaminated water contact rate.(8) In neighboring Zambia, a 1°C temperature increase was associated with a 5% increase in cholera incidence, while a 50 mm rainfall increase was associated with a 2% increase.(2) We used these findings to derive a climate forcing function to simulate the dynamics of cholera outbreaks in 2050 and 2090 with and without climate change.

Residents of Epworth wait to fetch water at a borehole in Harare Credit: AP Photo/Tsvangirayi Mukwazhi *from The Telegraph*

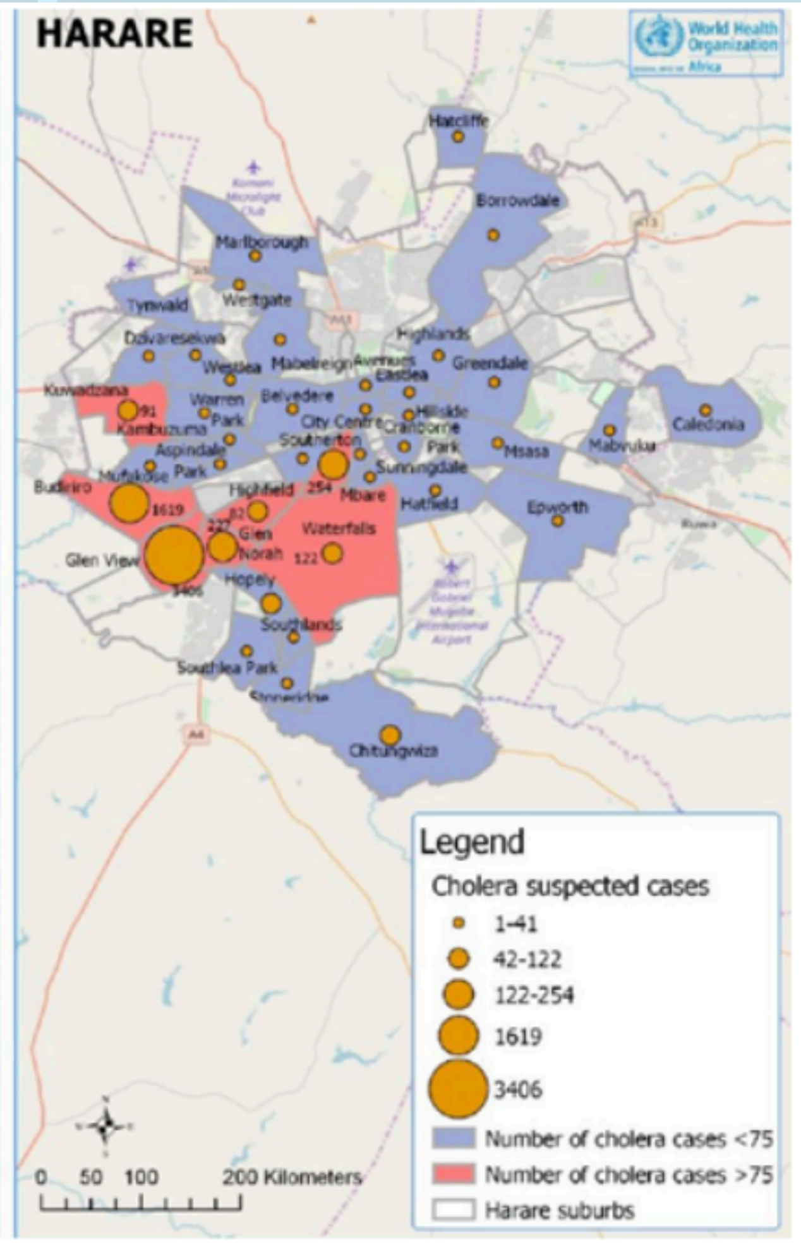

Figure 1. Map of 2018 Harare cholera outbreak.(7)

Methods and Model

Figure 2. Modified Tien et al. SIWR model for waterborne diseases with a compartment for deaths.(9)(10)

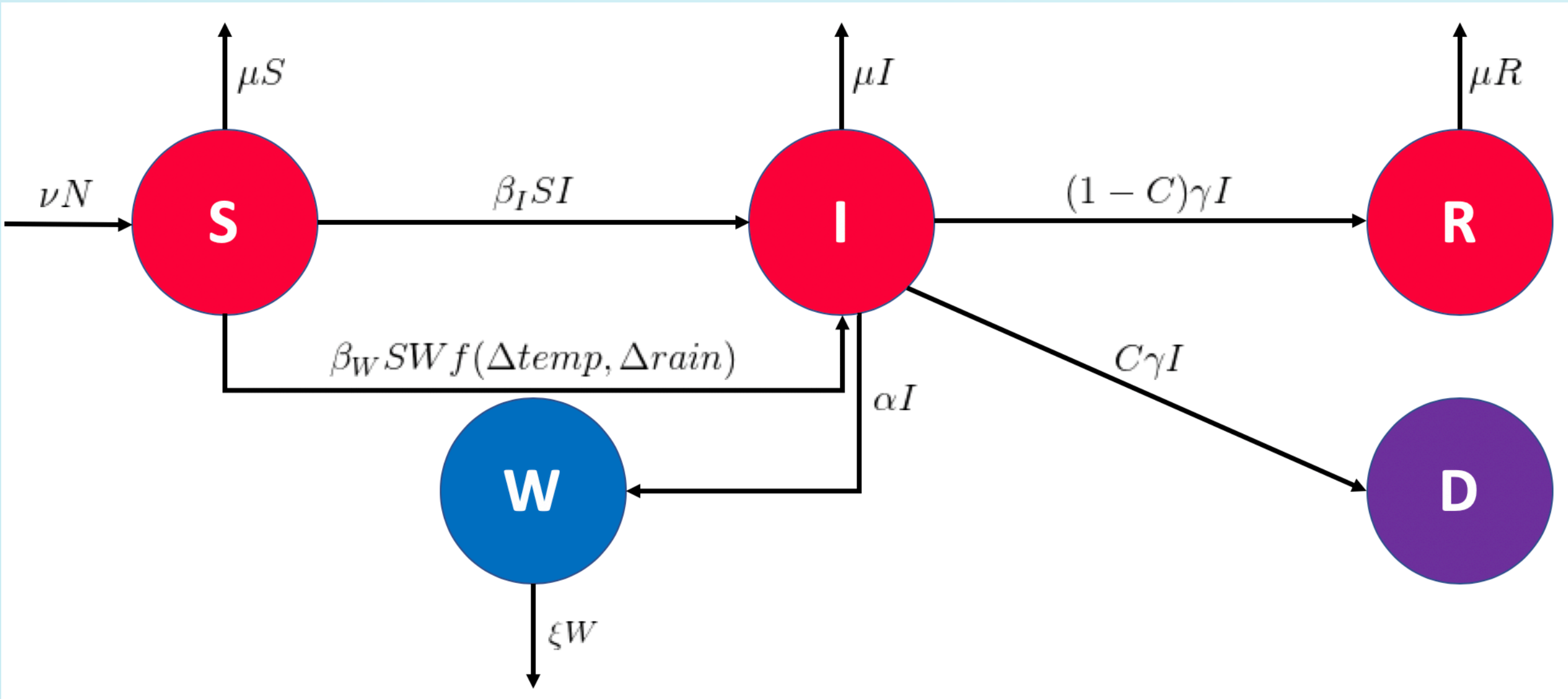

Figure 3. Differential equations for modified SIWR model with a compartment for deaths.

$$\frac{dS}{dt} = \nu N - \beta_W SW f(\Delta temp, \Delta rain) - \beta_I SI - \mu S$$

$$\frac{dI}{dt} = \beta_W SW f(\Delta temp, \Delta rain) + \beta_I SI - \gamma I - \mu I$$

$$\frac{dW}{dt} = \alpha I - \xi W$$

$$\frac{dR}{dt} = (1-C)\gamma I - \mu R$$

$$\frac{dD}{dt} = C\gamma I$$

Figure 4. Climate forcing function. Coefficients from associations between temperature/rainfall and incidence in Zambia. Modified to work through water-person transmission incidence term. (8)(2)

$$f(\Delta temp, \Delta rain) = 1 + .05\Delta temp \frac{\beta_W SW + \beta_I SI}{\beta_W SW} + .02\Delta rain \frac{\beta_W SW + \beta_I SI}{\beta_W SW}$$

Table 1. Parameter values.(12)(10)(7)(8)(11)

Parameter	Value
ν (Birth rate)	8.49×10^{-5} (day^{-1})
μ (Natural death rate)	2.19×10^{-5} (day^{-1})
γ (Recovery rate)	1/3 (day^{-1})
C (Case fatality rate)	.006
α (Pathogen "shedding" rate)	10 (cells/ml*person*day)
ξ (Pathogen decay rate in water)	.0242 (day^{-1})
R_0 (Basic reproduction number)	1.52
β (Total transmission rate)	- ($people^{-1}day^{-1}$)
β_W (Water-person transmission rate)	- (ml/cells*day)
β_I (Person-person transmission rate)	- ($people^{-1}day^{-1}$)

Figure 5. R0 and proportion of water-person vs. person-person transmission formulas.(11)

$$R_0 = \frac{N_0 \beta}{\gamma + \mu}$$

$$\beta_W = .25\beta$$

$$\beta_I = .75\beta$$

Table 2. Harare population projections.(13)

Year	Population (Projected)
2050	4,532,010
2090	10,006,857

Table 3. Climate change projections. 2050- based on median probability scenarios for 2040-2059. 2090- based on 1/20 probability scenarios for 2080-2099. (3)(4)

Parameter	Value
Δtemp (Change in temperature)	2°C/1°C (2050)
	8°C/1°C (2090)
Δrain (Change in rainfall)	73 mm/50 mm (2050)
	200 mm/50 mm (2090)

Table 4. Variable starting values. In our model virtually all susceptibles get infected. Initial susceptibles are calculated from the proportion of the city's population that was infected in the 2018 outbreak. W set to simulate water contamination.(7)

Variable	Value (Initial)
S (Susceptible)	15,235 (people, 2050)
	33,640 (people, 2090)
I (Infected)	0 (people)
W (Pathogen concentration in water)	1 (cells/ml)
R (Recovered)	0 (people)
D (Dead)	0 (people)
N (Total Population)	15,235 (people, 2050)
	33,640 (people, 2090)

Results

Figure 6.

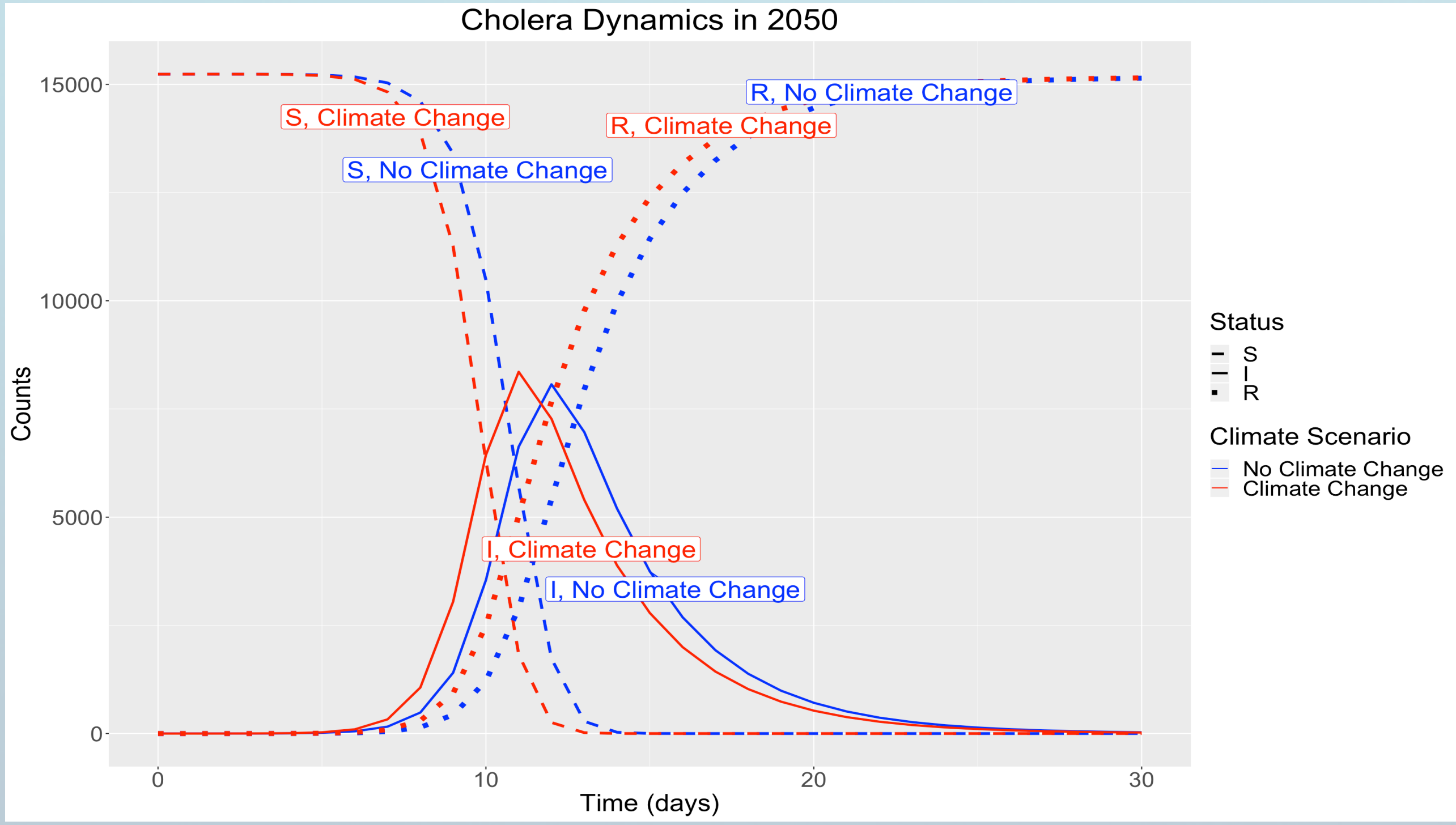

Table 5. Cholera dynamics in 2050 with vs. without climate change

	No Climate Change	Climate Change	Change	Percent change
Total cases (Period prevalence)	15,270 (337 per 100,000 per month)	15,270 (337 per 100,000 per month)	~0 (~0 per 100,000 per month)	~0% (~0%)
Deaths	91	91	~0	~0%
Peak number of cases (Peak prevalence)	8,070 (178 per 100,000)	8,358 (184 per 100,000)	+288 (+6 per 100,000)	+3.57% (+3.57%)
Timing of peak	Day 12	Day 11	1 day earlier	8.33% earlier

Figure 7.

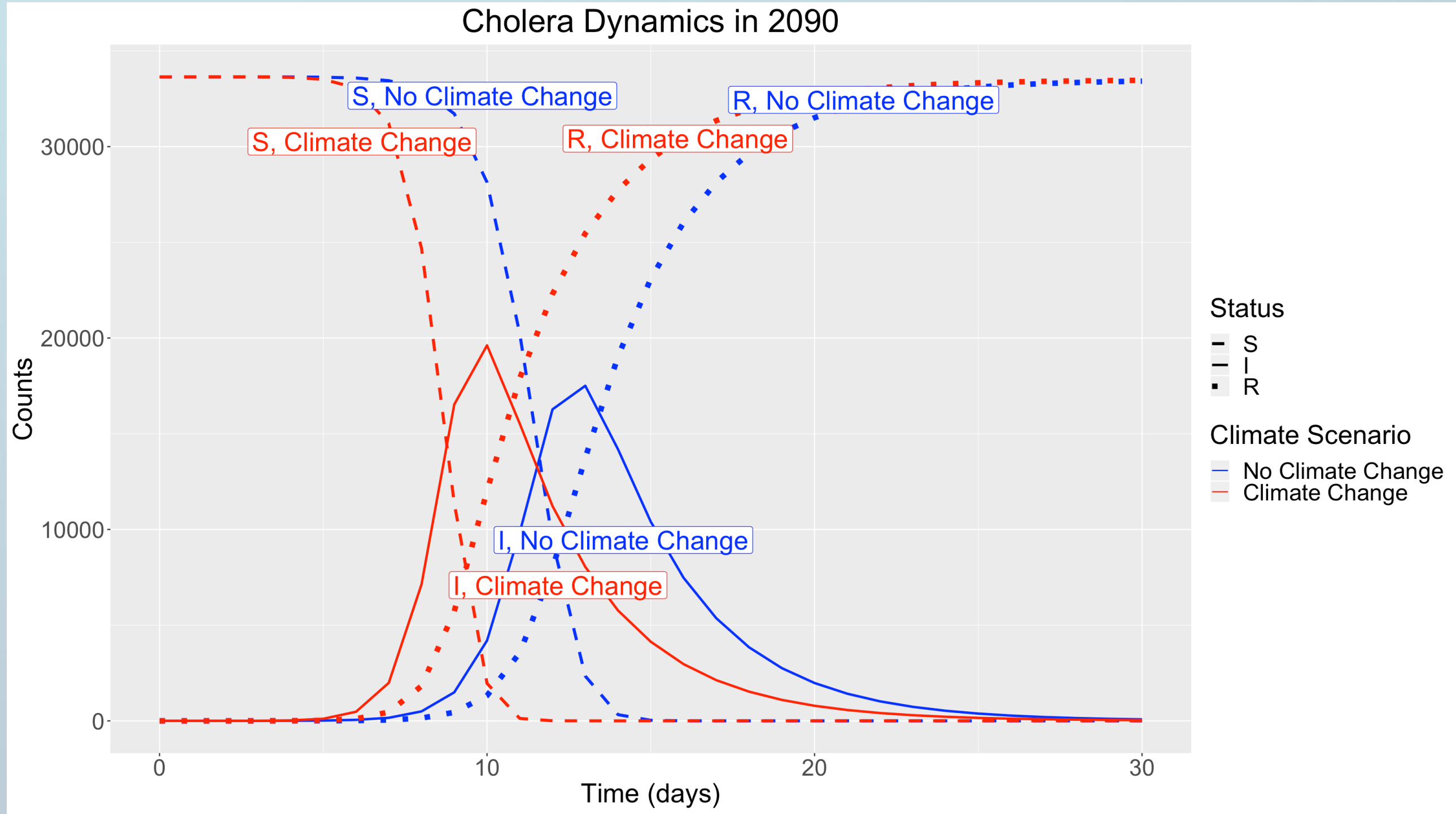

Table 6. Cholera dynamics in 2090 with vs. without climate change

	No Climate Change	Climate Change	Change	Percent change
Total cases (Period prevalence)	33,717 (744 per 100,000 per month)	33,719 (744 per 100,000 per month)	+2 (~0 per 100,000 per month)	+.01% (~0%)
Deaths	202	202	~0	~0%
Peak number of cases (Peak prevalence)	17,506 (175 per 100,000)	19,618 (196 per 100,000)	+2,112 (+21 per 100,000)	+12.1% (+12.1%)
Timing of peak	Day 13	Day 10	3 days earlier	23% earlier

Conclusions

- According to our simulations the severity of a cholera outbreak, measured in total cases/period prevalence and deaths, in Harare will not increase under a moderate climate change scenario in 2050 nor an extreme scenario in 2090.
  - This is expected given our model under which virtually all susceptibles get infected regardless of climate scenario and case fatality rate is held constant.
- However, the explosiveness of a cholera outbreak, measured in peak cases/prevalence and timing, will increase marginally under a moderate scenario in 2050 and somewhat more so in an extreme scenario in 2090.
  - This is expected given our climate forcing function increasing water-person transmission and incidence.
- Although these results suggest climate change will not make cholera outbreaks more severe, their increased explosiveness may make them more difficult to contain.
- Our model assumes a linear climate-cholera relationship like that observed in Zambia.(2) But this relationship may be different in Zimbabwe, and could very well be nonlinear under extreme climate scenarios, as is projected for other health impacts of climate change.(14)
- More broadly, much uncertainty exists in predicting the impacts of climate change on human health.(15)

Policy Recommendations

1. **Decarbonization** to minimize climate change and prevent more explosive cholera outbreaks.
2. **Improve drinking water sources** to reduce the chance of future outbreaks.
3. Maintaining stockpiles of **vaccines** for rapid deployment at the onset of potentially more explosive outbreaks.

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