

## Supplementary Information

### Overview

The main aim of the current study is to evaluate the epidemiological impact of cholera vaccination for 37 countries that requested cholera vaccines from the stockpile from July 2013 to December 2025 [1]. We constructed a mathematical model which captures both direct and indirect effects of vaccination, considering age structure, transmission and climate dynamics. With the model, we simulated different vaccination scenarios considering varying time lags, as well as the number of available doses and timing of vaccination.

### Mathematical model of cholera transmission

We developed an age-structured dynamic model that includes cholera transmission dynamics (person-to-person transmission) and vaccination (Fig. S1). The model also tracks the concentration of *Vibrio cholerae* in water to simulate the water-to-person transmission (Fig. S1).

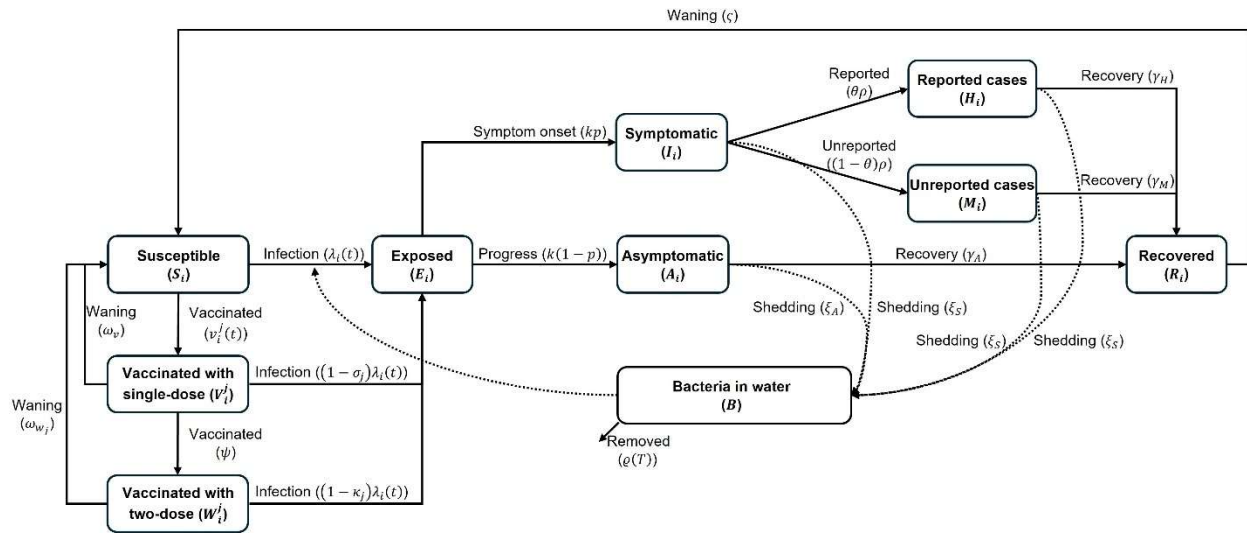


**Fig. S1. Model diagram for cholera transmission and vaccination.** For clarity, the notations for natural birth and death were omitted.

The model categorized the population into three age brackets:  $i = 1$  for those aged 0-4 years,  $i = 2$  for those aged 5-14 years, and  $i = 3$  for those older than 15 years. Births are accounted for by adding

susceptible individuals to the youngest age group with birth rate  $b_i$  (where  $b_1 > 0$  and  $b_2 = b_3 = 0$ ), while deaths are modeled by removing individuals from all age groups with age-specific death rates ( $d_i$ ). We assumed that the age distribution had reached a steady state, and the population size approaches the exponential growth or decay of the form  $e^{qt}$  where  $q$  denotes growth rate [2]. Cohorts are aged by moving individuals into the net older age compartment at age-specific rates  $c_i = \frac{d_i + q}{\exp\{ageb_{i*(d_i+q)}\} - 1}$ , where  $ageb_{i*(d_i+q)}$  denotes the number of years within the age group  $i$  [2].

Individuals in each age group  $i$  were divided into different categories based on their epidemiological status, including susceptible individuals ( $S_i$ ), individuals who got vaccinated with the single-dose regimen at age group  $j$  ( $V_i^j$ ), individuals who got vaccinated with the two-dose regimen at age group  $j$  ( $W_i^j$ ), and various stages of infection such as exposed ( $E_i$ ), asymptomatic ( $A_i$ ), symptomatic ( $I_i$ ), symptomatic with reporting ( $H_i$ ), symptomatic without reporting ( $M_i$ ), and recovered ( $R_i$ ). The total population size is given by  $N(t) = \sum_{i=1}^3 N_i(t) = \sum_{i=1}^3 \left\{ S_i(t) + \sum_{j=1}^3 \left( V_i^j(t) + W_i^j(t) \right) + E_i(t) + A_i(t) + I_i(t) + H_i(t) + M_i(t) + R_i(t) \right\}$ . The concentration of *Vibrio cholerae* in water was tracked in an additional compartment  $B$ .

Susceptible individuals may become infected through direct contacts with infected individuals (person-to-person transmission) or by exposure to *Vibrio cholerae* in the environment (water-to-person transmission). The force of infection for an individual in the age group  $i$ ,  $\lambda_i(t)$ , was modeled by aggregating the effects of person-to-person transmission and water-to-person transmission:

$$\lambda_i(t) = u_i \left( \beta_h \frac{\sum_{a=1}^3 (I_a(t) + H_a(t) + M_a(t) + \epsilon A_a(t))}{N} + \beta_w \left( \frac{B(t)}{\chi + B(t)} \right) \right) \quad (S1)$$

Specifically, the person-to-person transmission is determined by age-specific susceptibility ( $u_i$ ), transmission rate per unit time ( $\beta_h$ ) and the proportion of the infectious population. Here, we hypothesized that asymptomatic individuals are less infectious than those with symptoms by  $\epsilon$ . The water-to-person transmission follows a Michaelis-Menten functional response form with age-specific susceptibility, transmission rate per unit time ( $\beta_w$ ), the concentration of *Vibrio cholerae* at that time, and a half-saturation concentration of cholera in water,  $\chi$  [3, 4].

Susceptible individuals receive a single-dose vaccine at a rate of  $v(t)$ , and for mathematical expressions, we defined  $v_i^j(t)$  as the vaccination rate for individuals in age group  $i$  who received the vaccine when they were in age group  $j$  ( $j = 1$  for those vaccinated at ages 0-4 years,  $j = 2$  for those vaccinated at ages 5-14 years, and  $j = 3$  for those vaccinated at ages 15 and older), that is,

$$v_i^j(t) = \begin{cases} v(t), & i = j \\ 0, & i \neq j \end{cases} \quad (S2)$$

If the vaccination program is a two-dose program, they receive the second dose after the delay of  $\frac{1}{\psi}$  weeks. The age-specific vaccine efficacy is modeled based on the timing of vaccination. For this, individuals vaccinated with a single dose ( $V_i$ ) or two doses ( $W_i$ ) are stratified into three compartments per age group ( $i$ ) ( $V_i^j$  and  $W_i^j$  for  $j = 1, 2$ , and  $3$ ) based on their age ( $j$ ) at the time of vaccination. Thus, vaccine-induced protection does not change abruptly when an individual ages into an older group. The effectiveness of the vaccine wanes progressively in an exponential manner over time following vaccination, independent of the individual's age. The impact of single-dose and two-dose vaccines was modeled as the decrease in infection rate among the vaccinated individuals by age-specific values  $\sigma_j$  and  $\kappa_j$ , respectively. Specifically, vaccine efficacy of two-dose vaccine ( $\kappa_j$ ) was assumed to be 31% and 62% for those vaccinated at ages 0-4 and 5+, respectively [5]. Existing clinical trials reported that vaccine efficacy for individuals aged 5 and older remained stable for 4 years in Bangladesh and for 5 years in India, while vaccine efficacy for those younger than 5 years became insignificant within 3 to 4 years since vaccination [6, 7]. Thus, the duration of protection was assumed to last for an average of 3 years for those at ages 0-4 and of 5 years for those older than 5 years before becoming susceptible again. The single-dose regimen was hypothesized to have lower vaccine efficacy rates and offer shorter protection compared to the two-dose regimen, with vaccine efficacy ( $\sigma_j$ ) of 0%, 52%, and 59% for individuals vaccinated at aged 0-4, 5-14, and 15 and older, respectively, and an average protection of two years [8]. We assumed that vaccinated individuals would have the same probability of being symptomatic and infectious as non-vaccinated individuals once infected.

Upon infection, individuals enter the category of exposed individuals, and exposed individuals progress to infectious stages after 1.4 days on average [9]. We assumed that 21% of individuals who become infectious exhibit symptoms, while the remainder are asymptomatic [10]. After one day on average, individuals with symptoms are reported with a country-specific reporting probability ( $\theta$ ) and transition to reported cases compartment  $H$ , while the unreported cases move to compartment  $M$ . Finally, asymptomatic and symptomatic individuals with reporting or without reporting recover at rates of  $\gamma_A$ ,  $\gamma_H$ , and  $\gamma_M$ , respectively, and get natural immunity after clearing the infection. Recovered individuals experience a decline in their immunity against *Vibrio cholerae* after an average of three years and transition into susceptible categories [11]. The number of deaths was determined by multiplying the total number of symptomatic cases by case fatality rate.

The dynamics of the population are described using ordinary differential equations (ODEs). For simplicity and clarity in mathematical expressions, we introduced several dummy variables to maintain consistency across equations. Specifically, we define  $S_0, V_0^j, W_0^j, E_0, I_0, A_0, H_0, M_0, R_0$  and  $c_0$  as dummy variables, each assigned a value of zero. The system of ODE for each age group  $i$  ( $i = 1, 2$ , and  $3$ ) is then formulated as follows:

$$\begin{aligned} \frac{dS_i}{dt} = & b_i N(t) + c_{i-1} S_{i-1}(t) + \omega_v \sum_{j=1}^3 V_i^j(t) + \sum_{j=1}^3 \omega_{w_j} W_i^j(t) + \varsigma R_i(t) \\ & - \left( \lambda_i(t) + \sum_{j=1}^3 v_i^j(t) + d_i + c_i \right) S_i(t), \end{aligned} \quad (S3)$$

$$\frac{dV_i^j}{dt} = c_{i-1} V_{i-1}^j(t) + v_i^j(t) S_i(t) - \left( (1 - \sigma_j) \lambda_i(t) + \psi + \omega_v + d_i + c_i \right) V_i^j(t), \quad (S4)$$

$$\frac{dW_i^j}{dt} = c_{i-1} W_{i-1}^j(t) + \psi V_i^j(t) - \left( (1 - \kappa_j) \lambda_i(t) + \omega_{w_j} + d_i + c_i \right) W_i^j(t), \quad (S5)$$

$$\frac{dE_i}{dt} = c_{i-1} E_{i-1}(t) + \lambda_i(t) \left( S_i(t) + \sum_{j=1}^3 \left( (1 - \sigma_j) V_i^j(t) + (1 - \kappa_j) W_i^j(t) \right) \right) - (k + d_i + c_i) E_i(t), \quad (S6)$$

$$\frac{dI_i}{dt} = c_{i-1} I_{i-1}(t) + kp E_i(t) - (\rho + d_i + c_i) I_i(t), \quad (S7)$$

$$\frac{dA_i}{dt} = c_{i-1} A_{i-1}(t) + k(1 - p) E_i(t) - (\gamma_A + d_i + c_i) A_i(t), \quad (S8)$$

$$\frac{dH_i}{dt} = c_{i-1} H_{i-1}(t) + \theta \rho I_i(t) - (\gamma_H + d_i + c_i) H_i(t), \quad (S9)$$

$$\frac{dM_i}{dt} = c_{i-1} M_{i-1}(t) + (1 - \theta) \rho I_i(t) - (\gamma_M + d_i + c_i) M_i(t), \quad (S10)$$

$$\frac{dR_i}{dt} = c_{i-1} R_{i-1}(t) + \gamma_A A_i(t) + \gamma_M M_i(t) + \gamma_H H_i(t) - (\varsigma + d_i + c_i) R_i(t). \quad (S11)$$

The environmental compartment was designed by considering the biological characteristics of the *Vibrio cholerae*, the shedding of *Vibrio cholerae* into the environment by humans, and the impact of precipitation and temperature on the concentration and survival of *Vibrio cholerae* in the environmental reservoir. Precipitation impacts the concentration of bacteria, while temperature affects the mortality rate of bacteria. Specifically, symptomatic and asymptomatic infected individuals shed bacteria at rate of  $\xi_I$  and  $\xi_A$ , respectively, and precipitation accelerates shedding with a non-linear impact determined by coefficient parameter  $\tau$  and exponent parameter  $\phi$  [12]. The net death rate for *Vibrio cholerae*, denoted

as  $\varrho(T(t))$ , is assumed to have a linear relationship with temperature, that is,  $\varrho(T(t)) = \bar{\varrho} \left( 1 - \varepsilon \frac{T(t) - \bar{T}}{T_{max} - \bar{T}} \right)$ , where  $T(t)$  represents the temperature in degrees Celsius,  $\bar{\varrho}$  denotes the average death rate of the *Vibrio cholerae*,  $\varepsilon$  indicates the temperature dependence, and  $\bar{T}$  and  $T_{max}$  denote the mean and maximum temperature of each country from 1990 to 2030 (including calibration and simulation period), respectively [13]. To address the uncertainty of the impact of climate change, we generated 100 sets for climate-related parameters ( $\tau, \phi, \bar{\varrho}$  and  $\varepsilon$ ) using Latin hypercube sampling (LHS). The bacterial concentration is computed using the following ODE:

$$\frac{dB}{dt} = (1 + \tau r(t)^\phi) \sum_{i=1} \{ \xi_s (I_i(t) + M_i(t) + H_i(t)) + \xi_A A_i(t) \} - \varrho(T(t)) B(t). \quad (S12)$$

Baseline values of epidemiological parameters employed in the simulation are given in Table S1.

**Table S1. Baseline values of epidemiological parameters used in the simulation.**

| Param         | Description                                                | Values                                                 | References |
|---------------|------------------------------------------------------------|--------------------------------------------------------|------------|
| $b_i$         | Birth rate (1/week)                                        | Country-specific estimates<br>$b_1 > 0, b_2 = b_3 = 0$ | [14]       |
| $c_i$         | Aging rate (1/week)                                        | Country-specific estimates                             | -          |
| $d_i$         | Natural death rate (1/week)                                | Country-specific estimates                             | [14]       |
| $q$           | Growth rate (1/week)                                       | Country-specific estimates                             | -          |
| $\epsilon$    | Relative infectiousness for asymptomatic infection         | $10^{-3}$                                              | [15]       |
| $1/\varsigma$ | Average duration of natural immunity (weeks)               | 156                                                    | [11]       |
| $1/k$         | Latent period (weeks)                                      | 0.20                                                   | [9]        |
| $p$           | Proportion of symptomatic infection                        | 0.21                                                   | [10]       |
| $\theta$      | Proportion of reported cases among symptomatic individuals | Table S2                                               | [16]       |
| $\rho$        | Delay rate from symptom onset to case detection (1/week)   | 7                                                      | Assumed    |
| $\gamma_A$    | Recovery rate for asymptomatic cases (1/week)              | 1.40                                                   | [17]       |
| $\gamma_H$    | Recovery rate for reported symptomatic cases (1/week)      | 1.75                                                   | [17]       |

|              |                                                                                                |                                                           |       |
|--------------|------------------------------------------------------------------------------------------------|-----------------------------------------------------------|-------|
| $\gamma_M$   | Recovery rate for unreported symptomatic cases (1/week)                                        | 1.75                                                      | [17]  |
| $\kappa$     | Half saturation concentration of <i>Vibrio cholerae</i> (cell/ml)                              | $10^5$                                                    | [18]  |
| $\xi_S$      | Rate of excretion of <i>Vibrio cholerae</i> , symptomatic infection (cells/(ml*person*week))   | 7                                                         | [18]  |
| $\xi_A$      | Rate of excretion of <i>Vibrio cholerae</i> , asymptomatic infection (cells/(ml*person*week))  | 0.07                                                      | [18]  |
| $v(t)$       | Time-dependent vaccination rate (1/week)                                                       | Derived from the number of vaccine recipients             | [1]   |
| $\sigma_j$   | Age-specific vaccine efficacy of single-dose regimen for those who vaccinated at age group $j$ | 0 for $j = 1$ ;<br>0.52 for $j = 2$ ;<br>0.59 for $j = 3$ | [8]   |
| $\kappa_j$   | Age-specific vaccine efficacy of two-dose regimen for those who vaccinated at age group $j$    | 0.31 for $j = 1$ ;<br>0.62 for $j = 2$ and 3              | [6]   |
| $1/\omega_v$ | Average duration of vaccine-induced immunity of single-dose (weeks)                            | NA for $j = 1$ ;<br>104 for $j = 2$ and 3                 | [8]   |
| $1/\omega_w$ | Average duration of vaccine-induced immunity of two-dose (weeks)                               | 156 for $j = 1$ ;<br>260 for $j = 2$ and 3                | [5-7] |
| $1/\psi$     | Time interval between the first dose and the second dose (weeks)                               | 2.29                                                      | [19]  |
| $\beta_h$    | Transmission rate (person-to-person) (1/week)                                                  | Calibrated                                                | -     |
| $u_i$        | Age-specific susceptibility                                                                    | Calibrated                                                | -     |
| $\beta_w$    | Transmission rate (environmental infection) (1/week)                                           | Assumed to be $\beta_h/10^3$                              | -     |
| $\bar{T}$    | Average of temperature                                                                         | Country-specific data                                     | [20]  |
| $T_{max}$    | Maximum of temperature                                                                         | Country-specific data                                     | [20]  |
| $T(t)$       | Temperature at time $t$                                                                        | Country-specific data                                     | [20]  |
| $r(t)$       | Precipitation at time $t$                                                                      | Country-specific data                                     | [20]  |

|               |                                                               |                                   |          |
|---------------|---------------------------------------------------------------|-----------------------------------|----------|
| $\bar{q}$     | Average decay rate of <i>Vibrio cholerae</i> at $T = \bar{T}$ | Sampled from range of [7/41, 7/3] | [18, 21] |
| $\varepsilon$ | Coefficient parameter for temperature                         | Sampled from range of [0, 0.05]   | Assumed  |
| $\tau$        | Coefficient parameter for precipitation                       | Sampled from range of [0, 0.05]   | Assumed  |
| $\phi$        | Exponent parameter for precipitation                          | Sampled from range of [0, 0.05]   | Assumed  |

## Country-specific data and parameterization for the dynamic model

The model was calibrated for each country using country-specific demographic, epidemiological, and climate-related data to ensure that it accurately reflects the local context. Country-specific data used in calibration and simulation are listed in Table S2. The model was fitted to match the country-specific incidence rates during the baseline period, following a burn-in period from 1990 to 2009. The impact of cholera vaccination was estimated by simulating the model from January 1, 2013, to December 31, 2030.

- **Demographic and climate-related data and parameters**

The total population size for each country was obtained from the estimates provided by the Institute for Health Metrics and Evaluation (IHME) [22]. Since the simulation begins in 2013, the initial population size used in the model was set to the country-specific population size for 2013, allowing the population to follow an exponential growth or decay pattern based on a growth rate  $q$ . To estimate at-risk population, we multiplied the proportion of the at-risk population from a previous typhoid study [23] by the total population size, presuming that typhoid and cholera diseases share some of the common risk factors such as drinking water sources, hygiene facilities, and population density. The birth rate ( $b_i$ ) and age-specific death rates ( $d_i$ ) were derived from the country-specific averaged fertilities and deaths per 1,000 population from 2013 to 2023 obtained from the Population Division of the United Nations [14]. The country-specific value of  $q$  was calculated based on the birth and death rates, and the age distribution of the population was determined to satisfy the Lotka characteristic equation with growth rate  $q$  [2].

For incorporating the potential impact of climate change on cholera into the model, we collected daily temperature and precipitation data from the ERA5 single-level reanalysis dataset provided by the Copernicus Climate Data Store from January 01, 1990 to December 31, 2025, and spatially averaged at the

country level based on latitude and longitude [20]. Future climate data were generated by calculating the daily average values from 2021 to 2025. Climate-related data were averaged on a weekly basis to align with the simulation timeline.

- **Country- and age-specific incidence**

Due to the scarcity of data, it was challenging to obtain comprehensive cholera incidence data for each country. We calculated country- and age-specific annual incidence rates using available data, including the number of cholera-related deaths, age distribution of cases, and case fatality rates. Specifically, we obtained the number of deaths and population from the 2023 Global Burden of Disease (GBD) study from 2013 to 2023 [22]. The country-specific case fatality rates (CFR) were extracted from WHO [16]. For years with missing data, CFRs were imputed using the most recent available value (or the nearest available year when earlier values were missing), and the resulting CFRs for each year were applied to each country for the period 2000–2023. Using the number of cholera-related deaths and case fatality rates, the country-specific incidence rates by year were calculated. Age-specific incidence rates were then derived by applying the age distribution of cholera cases from a multi-country surveillance study to the country-specific total incidence [24] - 18.4% for age cohorts 0-4, 21.4% for age cohorts 5-14, 60.2% for age cohorts 15+. Finally, the average incidence from 2013 to 2023 was calculated and used as the country-specific baseline incidence.

- **Reporting probability**

The country-specific reporting probability was calculated by dividing the total number of reported cholera cases by the total number of cases estimated from the annual incidence for each country from 2000 to 2023. Reported case data were obtained from the World Health Organization (WHO) [16].

**Table S2. Country-specific data and number of calibrated set of parameters**

| Country                          | ISO3 code | Population at risk (2013) | Incidence rate (per 1000 people) |       |       |       | Number of parameters set | Reporting probability (%) |
|----------------------------------|-----------|---------------------------|----------------------------------|-------|-------|-------|--------------------------|---------------------------|
|                                  |           |                           | Overall                          | 0-4   | 5-14  | 15+   |                          |                           |
| Angola                           | AGO       | 19,203,961                | 4.96                             | 5.01  | 3.71  | 5.61  | 68                       | 3.63                      |
| Bangladesh                       | BGD       | 14,876,535                | 0.31                             | 0.56  | 0.32  | 0.27  | 33                       | 1.12                      |
| Burundi                          | BDI       | 1,035,639                 | 2.56                             | 2.70  | 1.96  | 2.82  | 98                       | 0.85                      |
| Cameroon                         | CMR       | 2,463,843                 | 2.61                             | 2.90  | 2.07  | 2.79  | 71                       | 4.21                      |
| Chad                             | TCD       | 1,652,504                 | 3.58                             | 3.13  | 2.50  | 4.45  | 94                       | 2.54                      |
| Comoros                          | COM       | 71,565                    | 0.62                             | 0.87  | 0.53  | 0.60  | 95                       | 40.27                     |
| Congo                            | COG       | 3,132,114                 | 0.56                             | 0.70  | 0.47  | 0.56  | 49                       | 7.97                      |
| Cote d'Ivoire                    | CIV       | 2,086,083                 | 0.87                             | 1.02  | 0.74  | 0.89  | 59                       | 2.71                      |
| Democratic Republic of the Congo | COD       | 52,589,353                | 1.37                             | 1.50  | 1.07  | 1.49  | 72                       | 11.64                     |
| Dominican Republic               | DOM       | 634,155                   | 1.79                             | 3.50  | 2.13  | 1.49  | 44                       | 9.75                      |
| Ethiopia                         | ETH       | 16,573,584                | 1.61                             | 1.94  | 1.24  | 1.70  | 60                       | 1.46                      |
| Ghana                            | GHA       | 2,731,735                 | 0.58                             | 0.77  | 0.53  | 0.56  | 47                       | 12.83                     |
| Guinea                           | GIN       | 4,072,366                 | 0.25                             | 0.26  | 0.19  | 0.28  | 43                       | 10.85                     |
| Haiti                            | HTI       | 1,098,322                 | 6.90                             | 9.91  | 6.67  | 6.39  | 98                       | 66.8                      |
| Iran (Islamic Republic of)       | IRN       | 39,638,778                | 0.04                             | 0.08  | 0.05  | 0.03  | 31                       | 0.95                      |
| Iraq                             | IRQ       | 17,786,760                | 2.27                             | 3.33  | 2.05  | 2.15  | 48                       | 1.82                      |
| Kenya                            | KEN       | 38,383,496                | 2.17                             | 2.97  | 1.76  | 2.18  | 80                       | 2.51                      |
| Lao People's Democratic Republic | LAO       | 390,478                   | 2.53                             | 4.08  | 2.60  | 2.25  | 78                       | 0.07                      |
| Lebanon                          | LBN       | 2,192,476                 | 1.66                             | 3.37  | 2.17  | 1.34  | 66                       | 3.27                      |
| Malawi                           | MWI       | 1,593,257                 | 1.19                             | 1.33  | 0.88  | 1.30  | 72                       | 11.64                     |
| Mozambique                       | MOZ       | 6,866,699                 | 14.74                            | 15.13 | 10.85 | 16.74 | 75                       | 2.61                      |
| Myanmar                          | MMR       | 3,059,513                 | 1.46                             | 2.79  | 1.66  | 1.23  | 53                       | 0.06                      |
| Nepal                            | NPL       | 2,859,344                 | 2.86                             | 5.17  | 2.89  | 2.52  | 48                       | 0.14                      |
| Niger                            | NER       | 1,833,094                 | 2.73                             | 2.38  | 1.91  | 3.39  | 64                       | 1.29                      |
| Nigeria                          | NGA       | 61,603,358                | 1.91                             | 2.01  | 1.48  | 2.10  | 94                       | 1.98                      |
| Pakistan                         | PAK       | 146,557,990               | 6.72                             | 8.71  | 5.59  | 6.74  | 100                      | 0.03                      |
| Philippines                      | PHL       | 5,975,192                 | 3.37                             | 5.91  | 3.44  | 2.96  | 39                       | 0.56                      |

|                             |     |            |       |       |      |       |    |       |
|-----------------------------|-----|------------|-------|-------|------|-------|----|-------|
| Sierra Leone                | SLE | 5,196,744  | 0.45  | 0.58  | 0.38 | 0.45  | 53 | 6.61  |
| Somalia                     | SOM | 4,913,884  | 4.91  | 4.73  | 3.72 | 5.60  | 98 | 3.31  |
| South Sudan                 | SSD | 3,270,126  | 10.48 | 13.22 | 8.20 | 10.89 | 99 | 1.99  |
| Sudan                       | SDN | 10,427,924 | 2.35  | 3.23  | 2.04 | 2.28  | 43 | 4.65  |
| Syrian Arab Republic        | SYR | 11,684,320 | 1.49  | 2.96  | 1.36 | 1.35  | 55 | 6.81  |
| Uganda                      | UGA | 10,642,352 | 3.79  | 3.92  | 2.78 | 4.31  | 87 | 0.79  |
| United Republic of Tanzania | TZA | 13,009,783 | 1.34  | 1.50  | 1.06 | 1.44  | 41 | 3.87  |
| Yemen                       | YEM | 13,870,819 | 0.33  | 0.39  | 0.26 | 0.35  | 50 | 100*  |
| Zambia                      | ZMB | 11,523,628 | 1.76  | 1.81  | 1.32 | 1.97  | 51 | 3.97  |
| Zimbabwe                    | ZWE | 4,173,830  | 1.12  | 1.38  | 0.92 | 1.15  | 46 | 12.35 |

\* Because the calculated reporting probability was greater than 100%, a value of 100% was assumed for the analysis.

## Model calibration

Using the estimated annual incidence rates, we calibrated the model to the country- and age-specific annual incidence by adopting the least-squares method which adjusts three parameters (transmission rate  $\beta_h$  and relative susceptibility of those aged 0-4 ( $u_1$ ) and 5-14 ( $u_2$ ) compared to those aged 15 and over, with setting  $u_3 = 1$ ) for each of the 100 parameter samples of climate-related parameters ( $\tau, \phi, \bar{q}$  and  $\varepsilon$ ) for each country. To calculate the annual incidence from the model, we initially simulated the model from 1990 to 2009 to reach equilibrium (burn-in period) and then continued with simulations from 2010 to 2012 to calculate the average annual incidence. For calibration, we assumed that the population size in each country remained constant over time to maintain simplicity and clear identification of the model. To achieve this, the birth rate of each country was adjusted to satisfy the Lotka characteristic equation with a growth rate of zero ( $q = 0$ ) [2]. Through this calibration process, we were able to obtain reliable estimates which match the simulated annual incidence and data, ranging from 31 to 100 sets of parameters out of a total of 100 samples.

## Reproduction number

The basic reproduction number ( $\mathcal{R}_0$ ) is typically defined as the average number of new infections caused by one infected person within a fully susceptible population during the infectious period. In our model,  $\mathcal{R}_0$  was supposed to be time-dependent (i.e.,  $\mathcal{R}_0(t)$ ) as it included time-varying environmental variables and the environmental compartment  $B$ . However, to estimate epidemic dynamics by multiplying  $\mathcal{R}_0$  by multipliers (more details below), we defined the representative reproduction number,  $\bar{\mathcal{R}}_0$  which was calculated using fixed population size ( $N_i(t) = N_i$ ) and averaged temperature and precipitation ( $r(t) = \bar{r}$  and  $T(t) = \bar{T}$ ).

Similar to the vector-host model, we can consider the aquatic environment,  $B$ , as a vector, and use the next-generation method to calculate  $\bar{\mathcal{R}}_0$  by defining the matrices  $\mathcal{F}$  and  $\mathcal{P}$  using the new infection and transition terms:

$$\mathcal{F} = \begin{bmatrix} \lambda_1(t)S_1(t) \\ \lambda_2(t)S_2(t) \\ \lambda_3(t)S_3(t) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ (1 + \tau\bar{r}^\phi) \sum_j \left\{ \xi_S \left( I_j(t) + M_j(t) + H_j(t) \right) + \xi_A A_j(t) \right\} \end{bmatrix} \quad (\text{S13})$$

and

$$\mathcal{P} = \begin{bmatrix} (k + d_1 + c_1)E_1(t) \\ -c_1E_1(t) + (k + d_2 + c_2)E_2(t) \\ -c_2E_2(t) + (k + d_3 + c_3)E_3(t) \\ -kpE_1(t) + (\rho + d_1 + c_1)I_1(t) \\ -c_1I_1(t) - kpE_2(t) + (\rho + d_2 + c_2)I_2(t) \\ -c_2I_2(t) - kpE_3(t) + (\rho + d_3 + c_3)I_3(t) \\ -k(1 - p)E_1(t) + (\gamma_A + d_1 + c_1)A_1(t) \\ -c_1A_1(t) - k(1 - p)E_2(t) + (\gamma_A + d_2 + c_2)A_2(t) \\ -c_2A_2(t) - k(1 - p)E_3(t) + (\gamma_A + d_3 + c_3)A_3(t) \\ -\theta\rho I_1(t) + (\gamma_H + d_1 + c_1)H_1(t) \\ -c_1H_1(t) - \theta\rho I_2(t) + (\gamma_H + d_2 + c_2)H_2(t) \\ -c_2H_2(t) - \theta\rho I_3(t) + (\gamma_H + d_3 + c_3)H_3(t) \\ -(1 - \theta)\rho I_1(t) + (\gamma_M + d_1 + c_1)M_1(t) \\ -c_1M_1(t) - (1 - \theta)\rho I_2(t) + (\gamma_M + d_2 + c_2)M_2(t) \\ -c_2M_2(t) - (1 - \theta)\rho I_3(t) + (\gamma_M + d_3 + c_3)M_3(t) \\ \varrho(\bar{T})B(t) \end{bmatrix} \quad (\text{S14})$$

By linearizing the matrices  $\mathcal{F}$  and  $\mathcal{P}$  at disease-free equilibrium, we can obtain matrices  $F$  and  $P$ , respectively, and  $\bar{\mathcal{R}}_0$  can be calculated by the spectral radius of the next generation matrix  $FP^{-1}$  [25]. First, we defined some notations used in calculation:

- $\mathbf{D}_{n \times n}$  is  $n \times n$  identity matrix.
- $\mathbf{k}_{m \times n}$  is  $m \times n$  matrix where all elements are  $k$ .
- $\text{diag}(a_1, a_2, \dots, a_n)$  is diagonal matrix where the main diagonal entries are  $a_1, a_2, \dots, a_n$  with size  $n \times n$ .

The matrices  $F$  and  $P$  are given by

$$F = \begin{bmatrix} \mathbf{0}_{3 \times 3} & X_1 & \epsilon X_1 & X_1 & X_1 & x_2 \\ \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{1 \times 3} & \xi_S x_3 & \xi_A x_3 & \xi_S x_3 & \xi_S x_3 & 0 \end{bmatrix} \quad (S15)$$

and

$$P = \begin{bmatrix} Y_1 & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ -kp\mathbf{D}_{3 \times 3} & Y_2 & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ -k(1-p)\mathbf{D}_{3 \times 3} & \mathbf{0}_{3 \times 3} & Y_3 & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{3 \times 3} & -\theta\rho\mathbf{D}_{3 \times 3} & \mathbf{0}_{3 \times 3} & Y_4 & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{3 \times 3} & -(1-\theta)\rho\mathbf{D}_{3 \times 3} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 3} & Y_5 & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{1 \times 3} & \mathbf{0}_{1 \times 3} & \mathbf{0}_{1 \times 3} & \mathbf{0}_{1 \times 3} & \mathbf{0}_{1 \times 3} & \varrho \end{bmatrix}, \quad (S16)$$

where,

$$A = \begin{bmatrix} 0 & 0 & 0 \\ -c_1 & 0 & 0 \\ 0 & -c_2 & 0 \end{bmatrix}, \quad (S17)$$

$$X_1 = \left[ \frac{\beta_h u_1 N_1}{N} \quad \frac{\beta_h u_2 N_2}{N} \quad \frac{\beta_h u_3 N_3}{N} \right]^T * \mathbf{1}_{1 \times 3}, \quad (S18)$$

$$x_2 = \left[ \frac{\beta_w u_1 N_1}{\chi} \quad \frac{\beta_w u_2 N_2}{\chi} \quad \frac{\beta_w u_3 N_3}{\chi} \right]^T, \quad (S19)$$

$$x_3 = (1 + \tau \bar{r}^\phi) \mathbf{1}_{1 \times 3}, \quad (S20)$$

$$Y_1 = \text{diag}(k + d_1 + c_1, k + d_2 + c_2, k + d_3 + c_3) + A, \quad (S21)$$

$$Y_2 = \text{diag}(\rho + d_1 + c_1, \rho + d_2 + c_2, \rho + d_3 + c_3) + A, \quad (S22)$$

$$Y_3 = \text{diag}(\gamma_A + d_1 + c_1, \gamma_A + d_2 + c_2, \gamma_A + d_3 + c_3) + A, \quad (S23)$$

$$Y_4 = \text{diag}(\gamma_H + d_1 + c_1, \gamma_H + d_2 + c_2, \gamma_H + d_3 + c_3) + A, \quad (S24)$$

$$Y_5 = \text{diag}(\gamma_M + d_1 + c_1, \gamma_M + d_2 + c_2, \gamma_M + d_3 + c_3) + A. \quad (S25)$$

Due to its analytic complexity, the  $FP^{-1}$  and corresponding reproduction number were numerically determined.

## Modeling cholera outbreaks and vaccination strategies

To model cholera outbreaks and evaluate vaccination strategies, we utilized the data on the requested, approved, and delivered OCV doses globally from July 2013 until December 2025. The data were extracted from the GTFCC OCV Dashboard [1] and included the detailed information on the timelines of requests, approvals, and deliveries; the number of doses requested, approved, and delivered; the request type (preventive/reactive); and the status of approval. To address abnormal or missing data, we

preprocessed the data concerning the dates of requests or deliveries, as well as the number of requested or delivered doses, based on the results from a review paper on the global cholera vaccine use [26]:

- A delivery date precedes a request date: the delivery date was assumed to be 13 days after the decision date.
- Request approved but not delivered: The delivery date was set to 18 days after the request date, and the number of doses delivered was assumed to match the requested doses.
- Request and decision approved but not delivered: The delivery date was set to 13 days after the decision date, and the number of delivered doses was assumed to match the approved doses.
- Delivery and decision recorded, but no request reported: The request date was set to 5 days before the decision date, and the number of requested doses was assumed to match the approved doses.
- Delivery recorded, but no request or decision reported: The request date was set to 18 days before the delivery date, and the number of requested doses was assumed to match the number of delivered doses.

Ideally, simulating outbreaks using complete time-series data for all countries would allow for a comprehensive examination of the potential impacts of vaccination, but unfortunately, such data are scarce. Thus, for reactive vaccination campaigns, we created three outbreak scenarios (outbreak 1, outbreak 2, and outbreak 3, with outbreak 1 representing the most severe scenario) under the assumption that countries requested vaccines from the stockpile in response to outbreak occurrences. Specifically, we assumed that three weeks before the request date for reactive vaccines coincided with the onset of an outbreak occurrence and modeled the outbreak by increasing the reproduction number. To achieve this, we calculated the representative reproduction number ( $\bar{\mathcal{R}}_0$ ) of the outbreak by multiplying the endemic  $\bar{\mathcal{R}}_0$  by an “R0 multiplier”. The corresponding transmission rate,  $\beta_h$ , was computed based on the adjusted reproduction number. The value of  $\beta_h$  was increased at the onset of an outbreak and maintained during the outbreak period which was assumed to be 12 weeks [27]. After the outbreak duration, we decreased  $\beta_h$  to the level corresponding to the endemic state. The magnitude of an outbreak was defined based on the proportion of vaccine recipients for each request across all target countries which was derived from the number of the requested doses relative to the at-risk population. If the proportion for a single request ranked in the top 25% among all requests, outbreak 1 was assumed for this country at that time; if in the bottom 25%, outbreak 3 was assumed; otherwise, outbreak 2 was assumed. The “R0 multiplier” for each outbreak scenario was determined by comparing the reported cases of data with model simulations (Figs. S2-S12, Table S3). For this, we collected weekly reported cases for the following countries: Cameroon,

Chad, Congo, Cote d'Ivoire, Democratic Republic of Congo, Ghana, Guinea, Niger, Nigeria, and Sierra Leone (data obtained from [28, 29]), and Haiti (data obtained from [12, 30]).

## Cameroon

|            | Data                                |                                                      | Simulation                          |                                                      |
|------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|            | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 3 | 330                                 | 0.37                                                 | 484 (329-681)                       | 0.54                                                 |

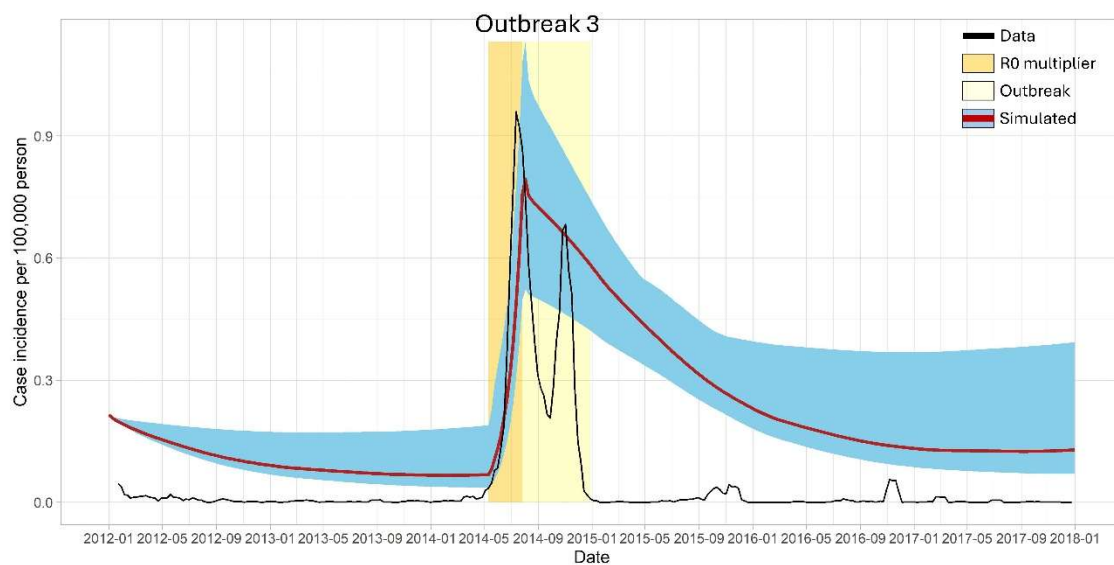


**Fig. S2. Case incidence per 100,000 population in the case of Cameroon: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Chad

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 1-1 | 19                                  | 0.06                                                 | 19 (2-235)                          | 0.06                                                 |
| Outbreak 1-2 | 156                                 | 0.37                                                 | 181 (19-612)                        | 0.43                                                 |

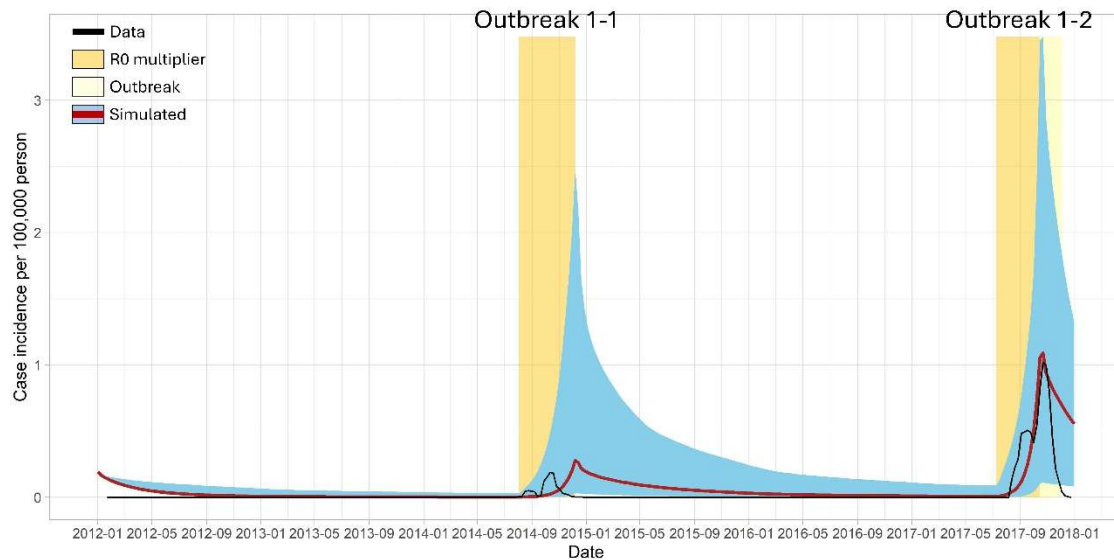


**Fig. S3. Case incidence per 100,000 population in the case of Chad: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Congo

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 3-1 | 743                                 | 0.94                                                 | 751 (199-935)                       | 0.95                                                 |
| Outbreak 3-2 | 31                                  | 0.97                                                 | 693 (224-818)                       | 1.27                                                 |

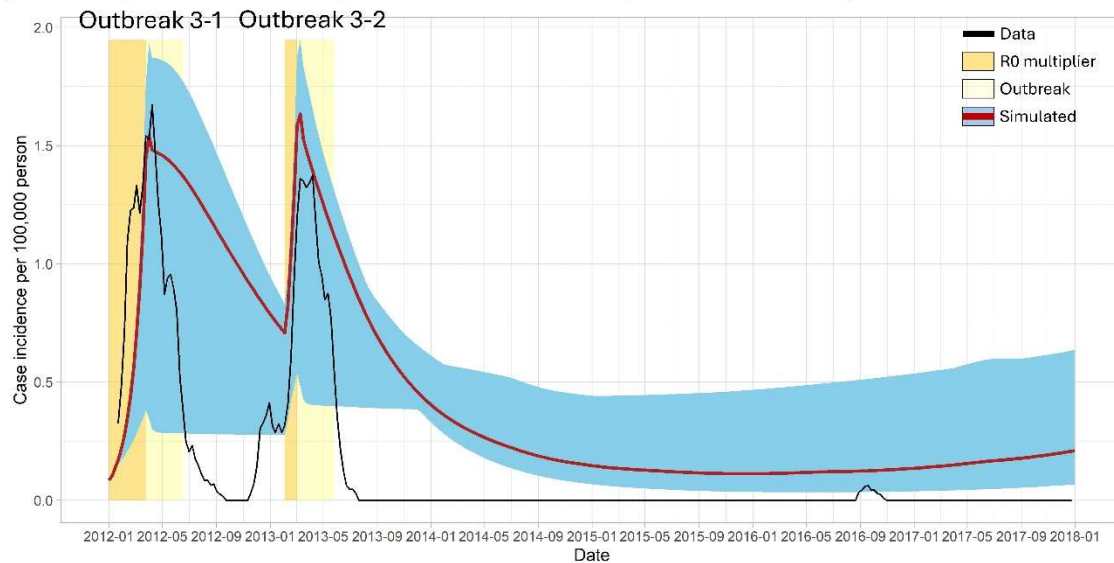


**Fig. S4. Case incidence per 100,000 population in the case of Congo: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Cote d'Ivoire

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 3-1 | 30                                  | 0.08                                                 | 37 (28-45)                          | 0.10                                                 |
| Outbreak 3-2 | 29                                  | 0.09                                                 | 46 (31-66)                          | 0.15                                                 |

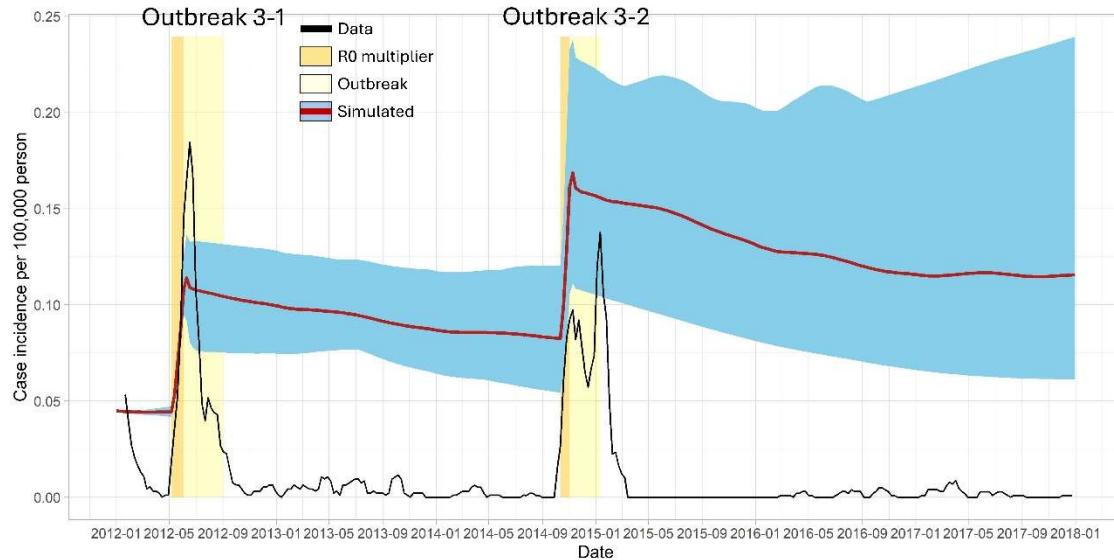


**Fig. S5. Case incidence per 100,000 population in the case of Cote d'Ivoire: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Democratic Republic of the Congo

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 3-1 | 13644                               | 0.96                                                 | 14252 (7297-21957)                  | 1.01                                                 |
| Outbreak 3-2 | 4985                                | 0.95                                                 | 4831 (2743-7017)                    | 0.92                                                 |
| Outbreak 3-3 | 28592                               | 1.84                                                 | 28141 (11325-49568)                 | 1.81                                                 |

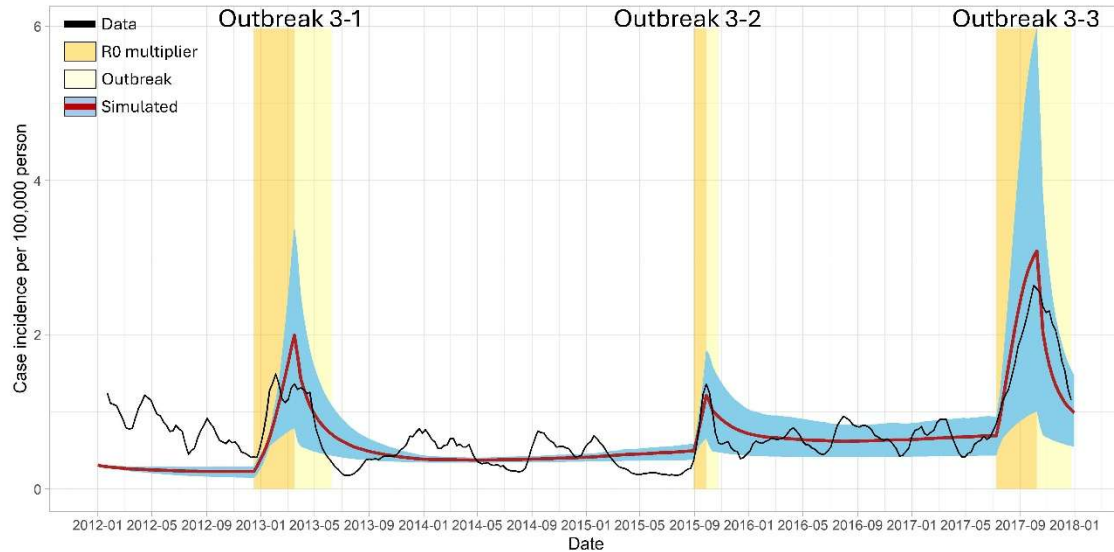


**Fig. S6. Case incidence per 100,000 population in the case of Democratic Republic of the Congo: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Ghana

|            | Data                                |                                                      | Simulation                          |                                                      |
|------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|            | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 3 | 935                                 | 0.85                                                 | 880 (337-1123)                      | 0.80                                                 |
| Outbreak 1 | 2880                                | 3.89                                                 | 3242 (1088-3758)                    | 4.38                                                 |

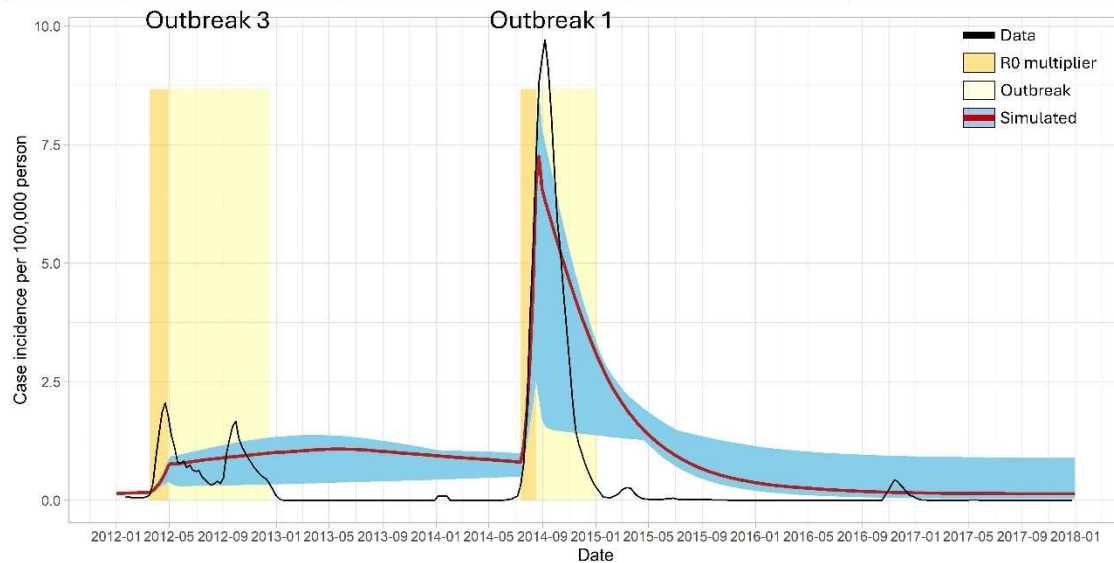


**Fig. S7. Case incidence per 100,000 population in the case of Ghana: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Guinea

|            | Data                                |                                                      | Simulation                          |                                                      |
|------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|            | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 1 | 2547                                | 2.57                                                 | 2201 (1032-2964)                    | 2.22                                                 |

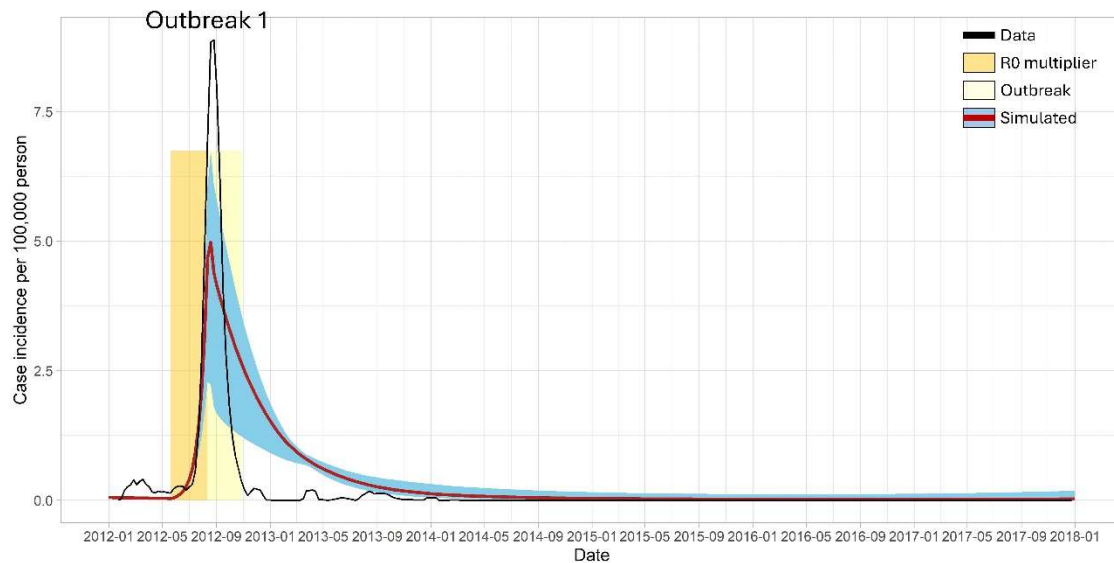


**Fig. S8. Case incidence per 100,000 population in the case of Guinea: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Haiti

|            | Data                                |                                                      | Simulation                          |                                                      |
|------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|            | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 2 | 30121                               | 101.42                                               | 30360 (13321-34845)                 | 102.19                                               |
| Outbreak 1 | 21890                               | 58.26                                                | 18002 (11718-37549)                 | 47.93                                                |

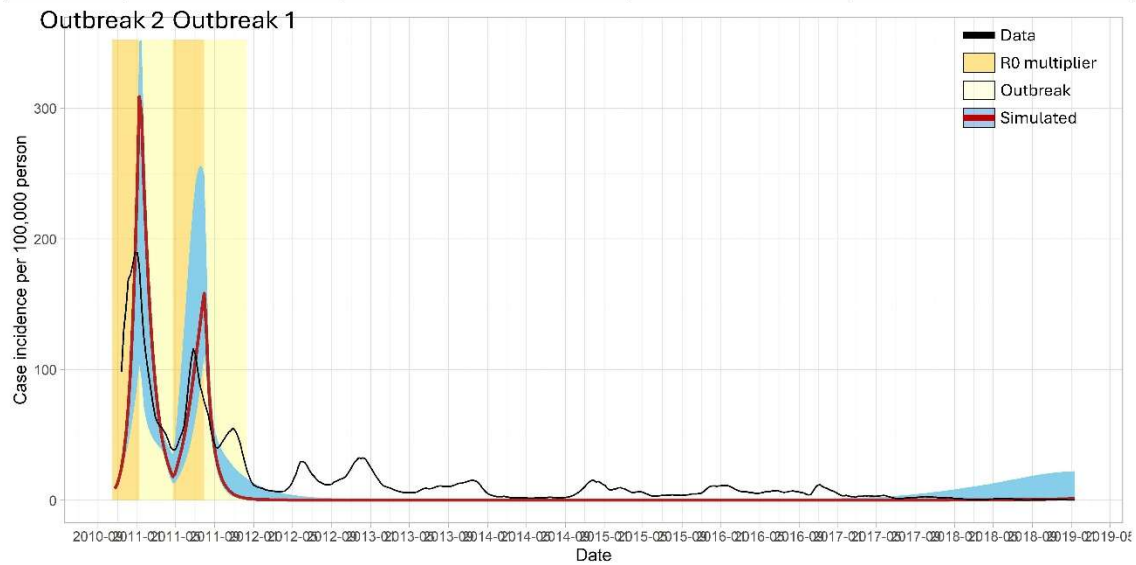


**Fig. S9. Case incidence per 100,000 population in the case of Haiti: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Niger

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 2-1 | 324                                 | 0.73                                                 | 329 (173-385)                       | 0.74                                                 |
| Outbreak 2-2 | 174                                 | 0.52                                                 | 214 (143-247)                       | 0.64                                                 |
| Outbreak 1   | 176                                 | 0.21                                                 | 111 (3-1000)                        | 0.13                                                 |

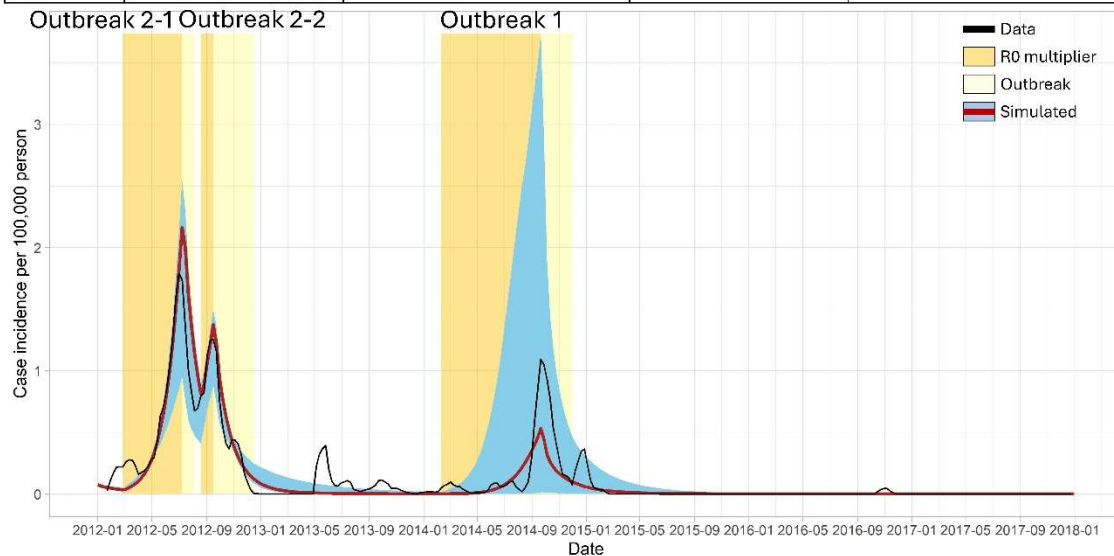


**Fig. S10. Case incidence per 100,000 population in the case of Niger: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Nigeria

|              | Data                                |                                                      | Simulation                          |                                                      |
|--------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|              | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 2-1 | 8065                                | 0.47                                                 | 8957 (2822-16025)                   | 0.52                                                 |
| Outbreak 2-2 | 3752                                | 0.25                                                 | 3715 (1800-5572)                    | 0.25                                                 |
| Outbreak 2-3 | 1930                                | 0.20                                                 | 2286 (1115-3278)                    | 0.24                                                 |

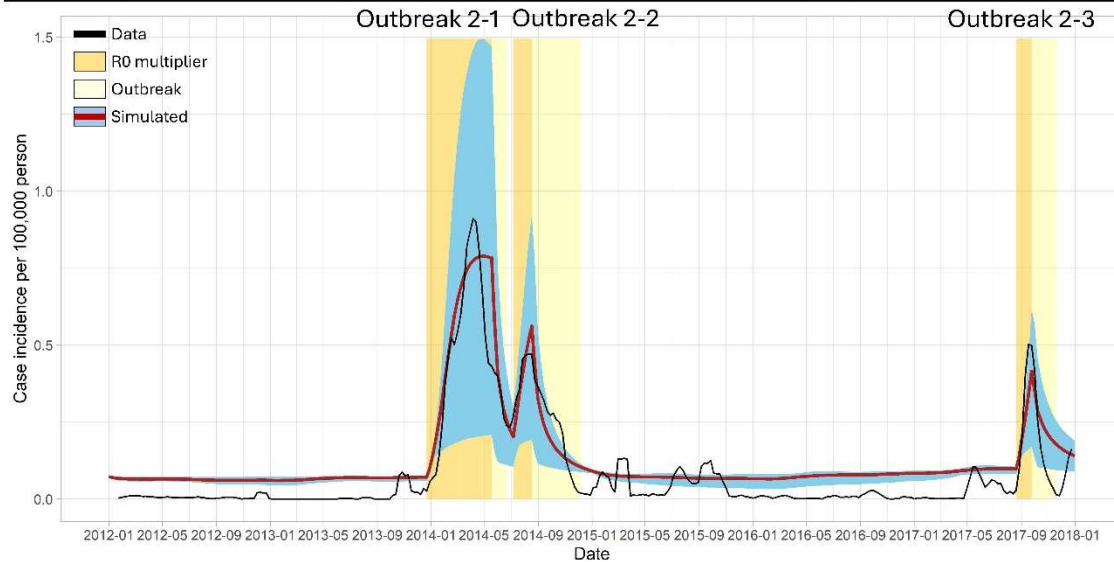


**Fig. S11. Case incidence per 100,000 population in the case of Nigeria: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

## Sierra Leone

|            | Data                                |                                                      | Simulation                          |                                                      |
|------------|-------------------------------------|------------------------------------------------------|-------------------------------------|------------------------------------------------------|
|            | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) | Cumulative number of reported cases | Mean of case incidence (per 100,000 people per week) |
| Outbreak 1 | 14643                               | 8.99                                                 | 13710 (962-21645)                   | 8.41                                                 |

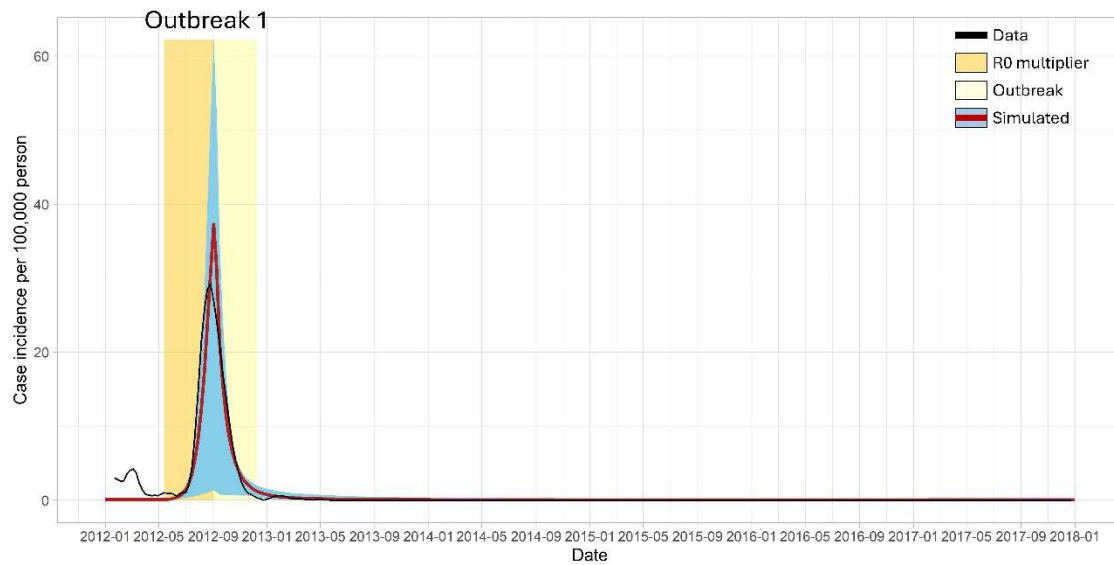


**Fig. S12. Case incidence per 100,000 population in the case of Sierra Leone: comparison between data and simulation results.** The black line represents the observed reported data, while the red line with the blue shaded area represents the simulated results. The yellow shaded area indicates the period during which the R0 multiplier was applied, and the light-yellow shaded area marks the duration of an outbreak.

**Table S3. The value of the R0 Multiplier**

| Country                          | R0 Multiplier |            |            |
|----------------------------------|---------------|------------|------------|
|                                  | Outbreak 1    | Outbreak 2 | Outbreak 3 |
| Cameroon                         | -             | -          | 1.2        |
| Chad                             | 1.4           | -          | -          |
| Congo                            | -             | -          | 1.2        |
| Cote d'Ivoire                    | -             | -          | 1.2        |
| Democratic Republic of the Congo | -             | -          | 1.2        |
| Ghana                            | 1.4           | -          | 1.2        |
| Guinea                           | 1.4           | -          | -          |
| Haiti                            | 1.4           | 1.3        | -          |
| Niger                            | 1.4           | 1.3        | -          |
| Nigeria                          | -             | 1.3        | -          |
| Sierra Leone                     | 1.4           | -          | -          |
| <b>Used in simulation</b>        | <b>1.4</b>    | <b>1.3</b> | <b>1.2</b> |

**Table S4. Simulation scenarios**

| Scenario | Constraint   |                               |                            |
|----------|--------------|-------------------------------|----------------------------|
|          | No time lags | Sufficient doses as requested | Two-dose scheme throughout |
| 1        | ✗            | ✗                             | ✗                          |
| 2        | ✓            | ✗                             | ✗                          |
| 3        | ✗            | ✓                             | ✓                          |
| 4        | ✓            | ✓                             | ✓                          |

**Table S5. Cost of illness by country**

| <b>ISO3 code</b> | <b>2023 US\$</b> | <b>2023 International\$</b> |
|------------------|------------------|-----------------------------|
| AGO              | 224.94           | 752.36                      |
| BDI              | 101.76           | 466.91                      |
| BGD              | 67.65            | 242.60                      |
| CIV              | 153.56           | 428.75                      |
| CMR              | 158.93           | 499.81                      |
| COD              | 136.24           | 357.12                      |
| COG              | 164.48           | 454.70                      |
| COM              | 150.60           | 367.90                      |
| DOM              | 117.32           | 285.18                      |
| ETH              | 148.47           | 430.44                      |
| GHA              | 226.16           | 716.88                      |
| GIN              | 181.62           | 506.00                      |
| HTI              | 192.99           | 372.42                      |
| IRN              | 98.82            | 370.24                      |
| IRQ              | 298.04           | 732.07                      |
| KEN              | 148.64           | 483.36                      |
| LAO              | 67.11            | 301.67                      |
| LBN              | 80.09            | 289.59                      |
| MMR              | 138.86           | 670.37                      |
| MOZ              | 99.07            | 267.33                      |
| MWI              | 122.93           | 355.36                      |
| NER              | 125.26           | 367.95                      |
| NGA              | 161.93           | 659.09                      |
| NPL              | 86.36            | 337.07                      |
| PAK              | 112.72           | 498.35                      |
| PHL              | 104.63           | 302.17                      |
| SDN              | 170.87           | 518.80                      |
| SLE              | 78.78            | 349.94                      |
| SOM              | 138.39           | 360.68                      |
| SSD              | 100.51           | 176.97                      |
| SYR              | 68.17            | 374.07                      |
| TCD              | 138.58           | 394.20                      |
| TZA              | 124.19           | 407.71                      |
| UGA              | 122.72           | 379.27                      |
| YEM              | 74.14            | 270.40                      |
| ZMB              | 116.10           | 355.69                      |
| ZWE              | 213.46           | 563.13                      |

\* Adjusted from the source data [31, 32]

\*\* For countries with missing data, economic burden was imputed by taking values from countries where GDP per capita is similar and inflated based on country-specific GDP deflators. Specifically, the value for Syrian Arab Republic was taken from Chad; Myanmar from South Sudan; Yemen and Pakistan from Zambia; Haiti from Zimbabwe; and Iraq, Iran (Islamic Republic of), Dominican Republic, and Lebanon from Philippines.

## References

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## Additional Supplementary Figures

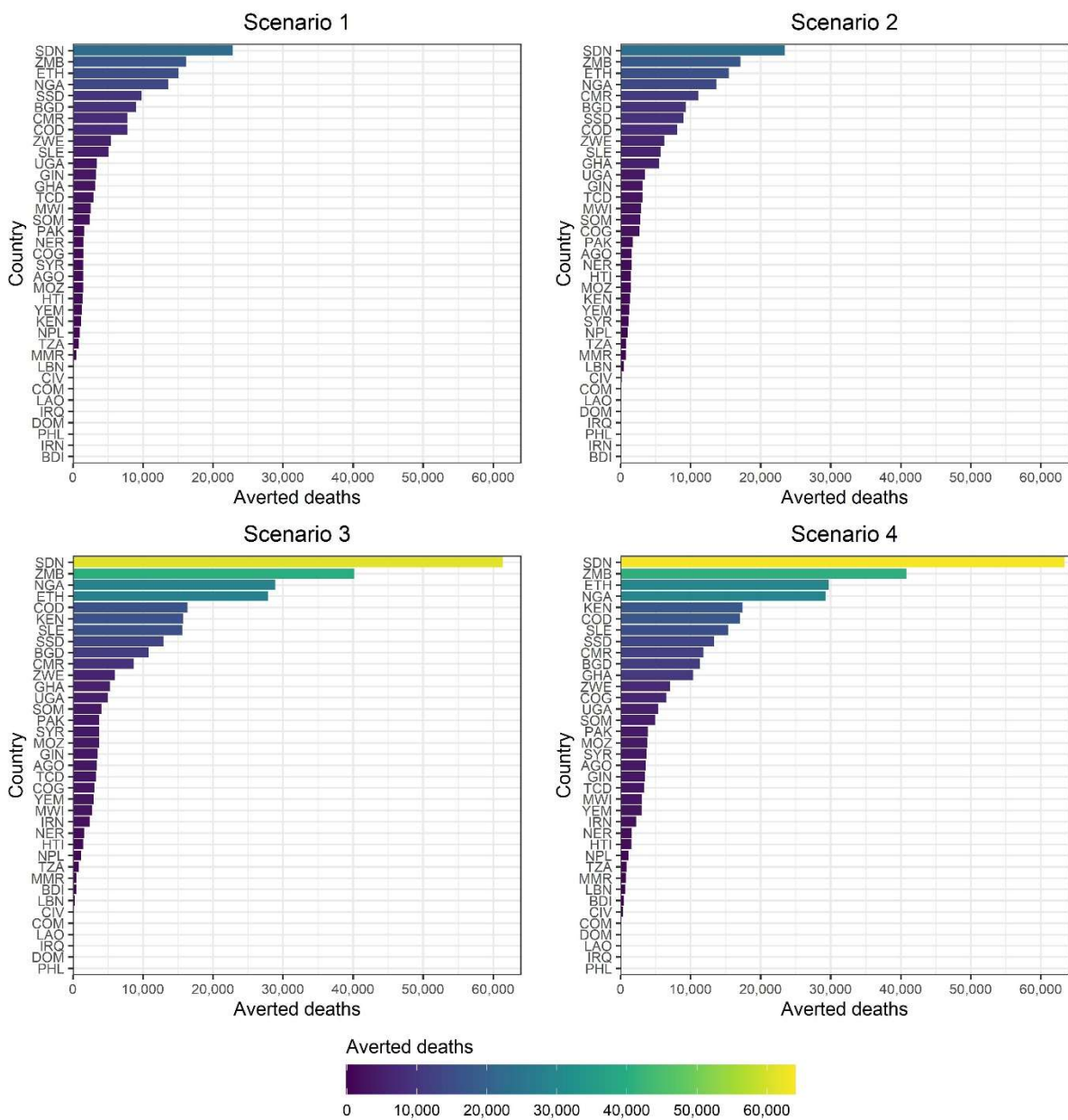


Fig. S13. Number of deaths averted by country

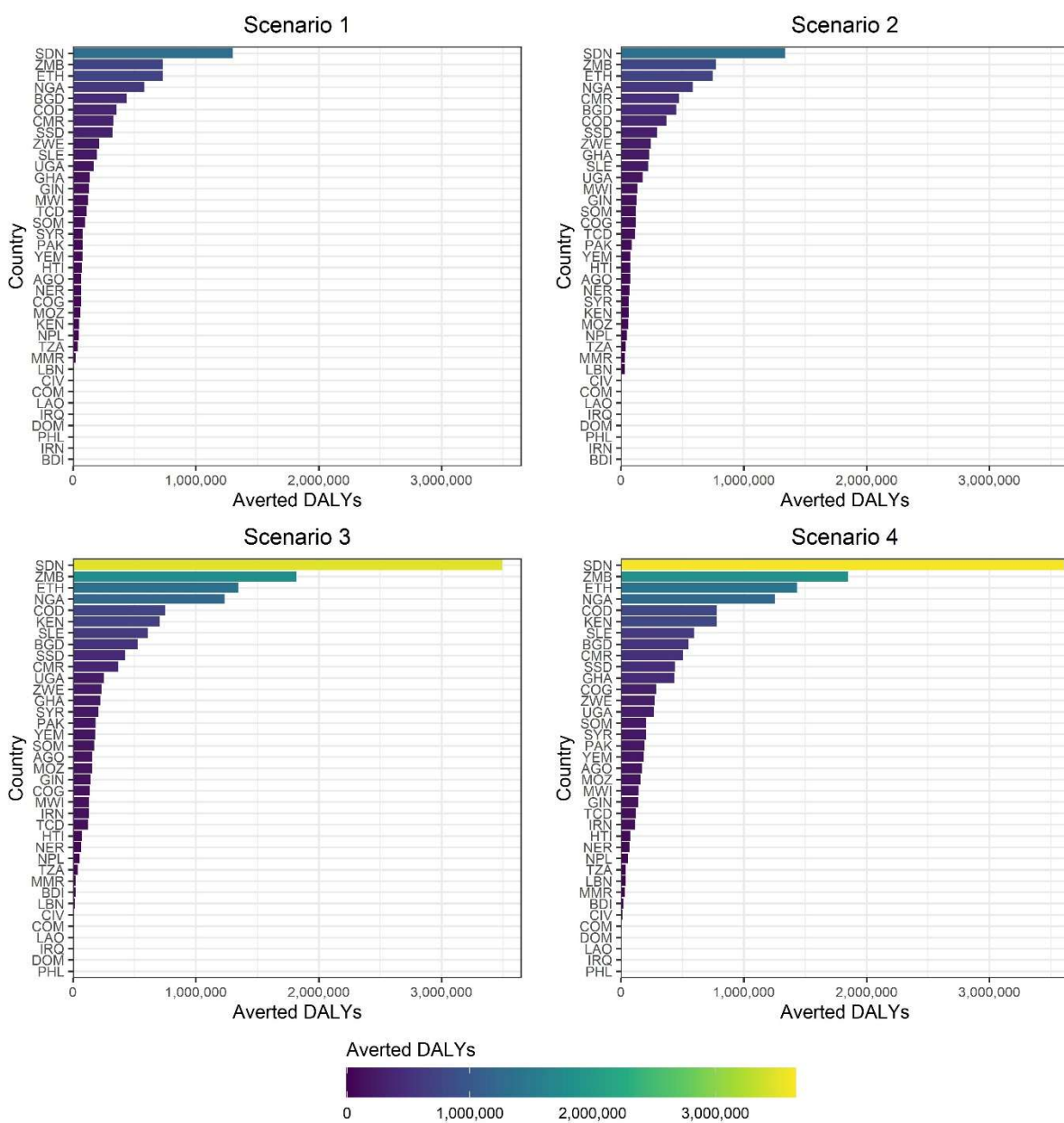


Fig. S14. Number of DALYs averted by country

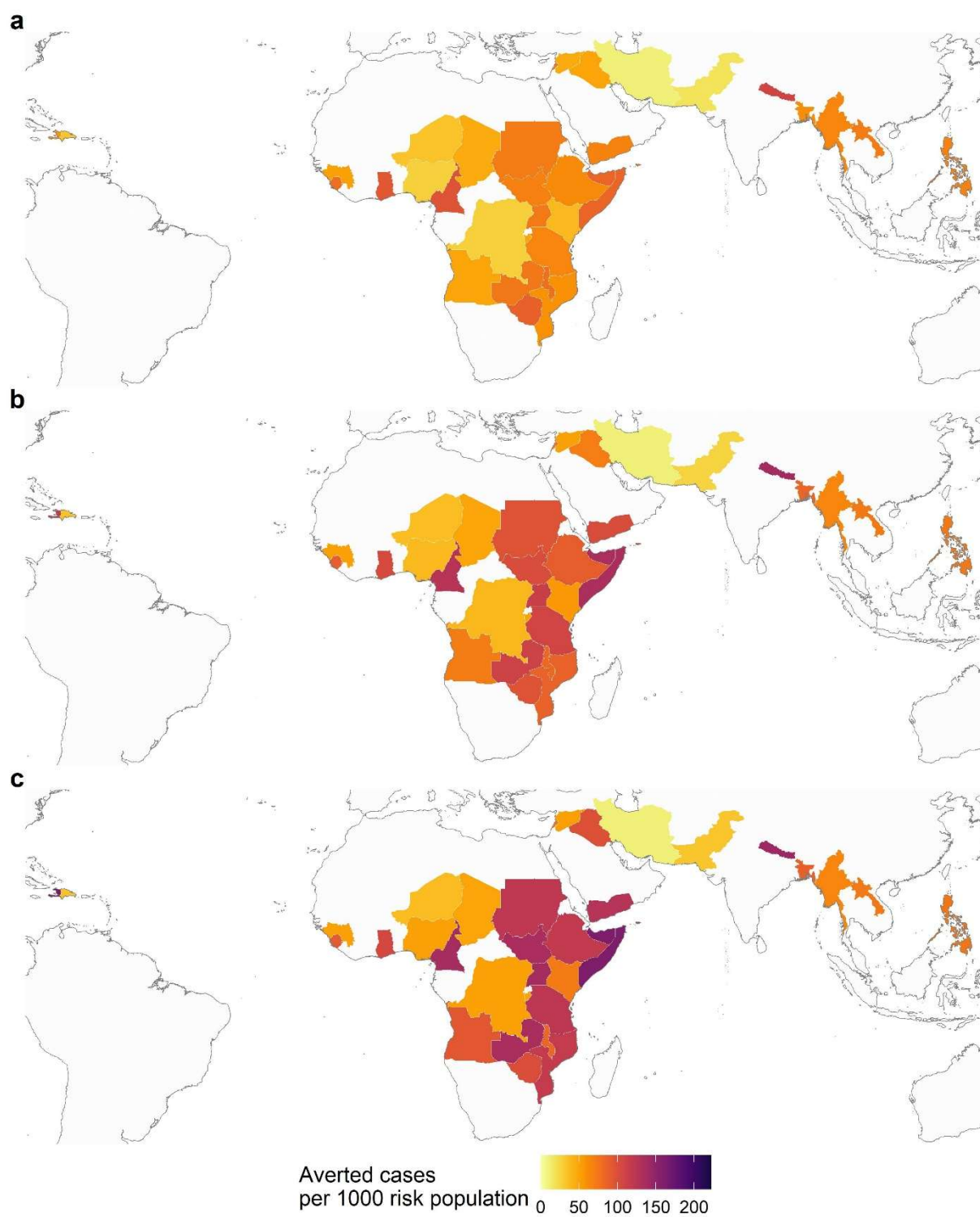


**Fig. S15. Averted cases per 1,000 risk population by varying coverage rates. a) 50%, b) 70%, and c) 90% at the time of the first outbreak event**

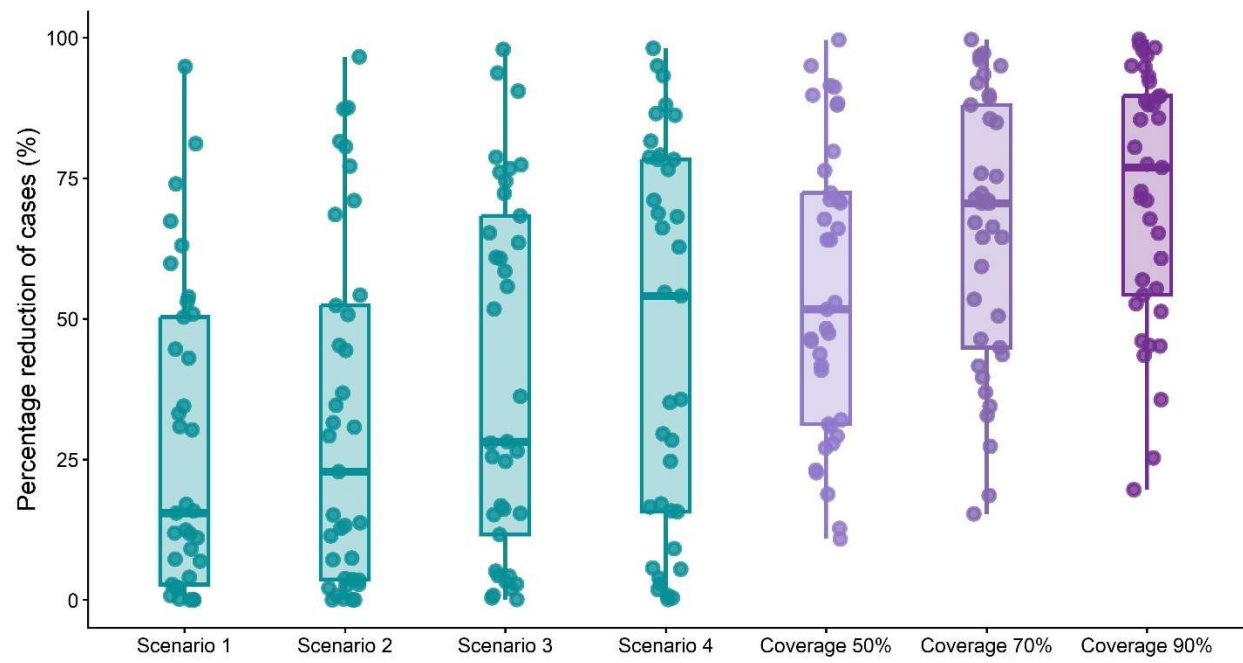


**Fig. S16.** Percentage reduction due to vaccination under scenarios 1-4, as well as one-time mass vaccination campaign with varying coverage rates

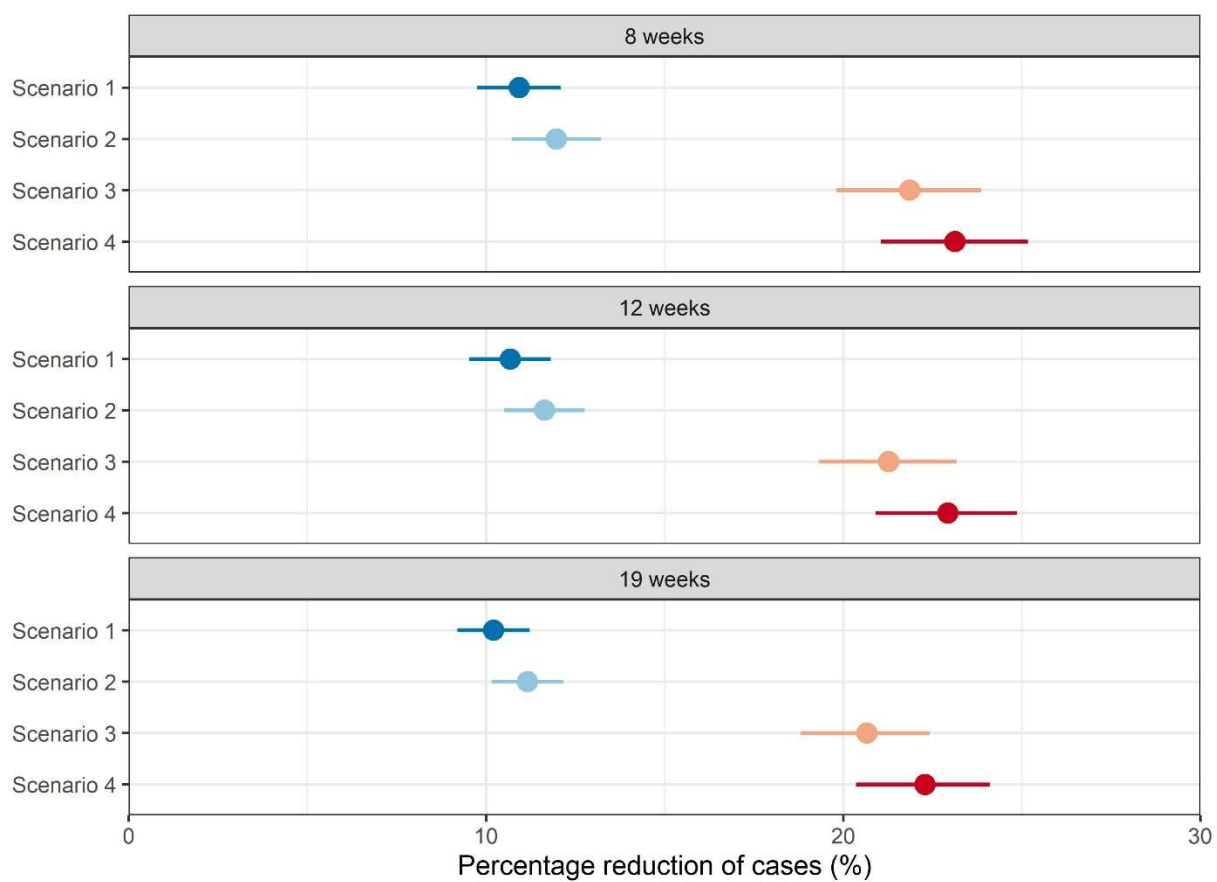


**Fig. S17. Percentage reduction with varying durations of an outbreak.** 8 weeks (shorter duration), 12 weeks (baseline), and 19 weeks (longer duration)