Appendix B: Documentation

	Equation	Units	Documentation
SIR component			
asymptomatic	MAX(recently_infected_population*ratio_of_asymptomatic/average_incubation_time, 0)	person/day	"asymptomatic" flow is the rate at which recently infected individuals leave the stock through multiplication with (ratio of asymptomatic) after an average incubation time of 1 day (material delay). The MAX function is to ensure the flow is more than 0.
asymptomatic_infection_acquired_immunity_waning	MAX(0, recovered_asymptomatic_population/average_asymptomatic_infection_acquired_immunity_period-vaccination_recovered_asymptomatic)	person/day	"asymptomatic infection acquired immunity waning" flow is the rate at which recovered asymptomatic individuals leave the stock after an average asymptomatic infection acquired immunity period of 6 months (material delay). The MAX function is to ensure the flow is more than 0. The flow also minus the vaccination flow once the intervention is activated.
asymptomatic_population(t)	asymptomatic_population(t - dt) + (asymptomatic - recovered_from_asymptomatic - vaccination_asymptomatic) * dt	person	"asymptomatic population" are cholera infected individuals who show no symptom. Asymptomatic individuals who shifted to the "asymptomatic population" stock then leave after an average duration of asymptomatic illness of 5 days and flow towards "recovered from asymptomatic population" stock. The "asymptomatic population" is assumed to be 0 initially.
average_asymptomatic_infection_acquired_immunity_period	180	day	Subclinical infections, or infections confirmed by positive stool culture but unaccompanied by diarrhea, have been documented. Leung and Matrajt (2021) study highlights the difference between protection from infection and protection from disease. They identified 3 challenge studies in which most participants were reported among the participants without diarrhea on initial challenge developed symptoms upon rechallenge (3 to 12 months) (Leung & Matrajt, 2021)
average_duration_of_illness_asymptomatic	5	day	The shedding of bacteria typically ends within 7 to 10 days.
average_duration_of_illness_symptomatic	9	day	The symptomatic infectious period ranges from 7 to 14 days (Chao et al., 2011; Nelson et al., 2009). Médecins Sans Frontières (2018) similarly reports bacteria shedding of bacteria among symptomatic patients typically ends within 7 to 10 days. The "average duration of illness symptomatic" uses 9 days.

average_duration_of_recovery_under_treatment	5	day	Findings indicate that antibiotics reduced volume of stool output by 8–92%, duration of diarrhea by 50–56%, and duration of positive bacterial culture by 26–83% (CDC, 2020). However, mass administration of antibiotics is not recommended, as it has no proven effect on the spread of cholera may contribute to antimicrobial resistance (WHO, 2021). A patient with severe dehydration or complications may remain hospitalised 4 to 5 days (MSF, 2018).Hence, the "average duration of recovery under treatment" uses 5 days.
average_incubation_time	1	day	The incubation period of cholera can range from several hours to 5 days (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018; Nelson et al., 2009). The "average incubation time" uses 1 day as the symptomatic individuals will then progress to either mild or severe disease stage with "time to progress to next stage".
average_symptomatic_infection_acquired_immunity_period	3*365	day	Studies found that clinical cholera conferred protection against subsequent cholera for at least 3 years (Kaper, Morris, & Levine, 1995; Leung & Matrajt, 2021)
bacteria_shedding_from_asymptomatic	0.67	1	Some patients can even be infected with V. cholerae and yet show no symptoms but then tend to shed the organism into the environment, even for only a few days, explaining why vibrios can be isolated in wastewater effluents in a non-Vibrio and/or non-cholera epidemic area (Okoh et al., 2015). According to Kaper, Morris, and Levine (1995), doses of 10^11 CFU of V. cholerae were required to consistently cause diarrhea in healthy North American volunteers when the inoculum was given in buffered saline (pH 7.2). When stomach acidity was neutralized with 2 g of sodium bicarbonate immediately prior to administration of the inoculum, attack rates of 90% were seen with an inoculum of 10^6. Food has a buffering capacity comparable to that seen with sodium bicarbonate. Ingestion of 10^6 vibrios with food such as fish and rice resulted in the same high attack rate (100%) as when this inoculum is administered with buffer. For Yemen context, the model uses 10^6 vibrios as the amount to cause an infection. 10^6 vibrios is normalized to 1. An asymptomatic infected individual can shed vibrios in the stool in low but potentially infectious concentrations (10^3 to 10^5 V. cholerae organisms per g of stool) for several days (Kaper, Morris, & Levine, 1995). The variable "bacteria shedding from asymptomatic" uses 10^4, hence, normalized to 10^4/10^6 = 0.67

bacteria_shedding_from_mildly_infected	1.33	1	According to Nelson et al. (2013), a symptomatic, mildly infected individual can shed vibrios in the stool in low but potentially infectious concentrations, up to 10^8 V. cholerae organisms per g of stool. For Yemen context, the model uses 10^6 vibrios as the amount to cause an infection. 10^6 vibrios is normalized to 1. The variable "bacteria shedding from a mildly infected individual" uses 10^8, hence, normalized to 10^8/10^6 = 1.23
bacteria_shedding_from_severely_infected	2	1	According to Kaper, Morris, and Levine (1995), individual with acute cholera excretes 10^7 to 10^8 V. cholerae organisms per g of stool; for patients who have 5 to 10 liters of diarrheal stool, total output of V. cholerae can be in the range of 10^11 to 10^13 CFU. Even after cessation of symptoms, patients who have not been treated with antibiotics may continue to excrete vibrios for 1 to 2 weeks. For Yemen context, the model uses 10^6 vibrios as the amount to cause an infection. 10^6 vibrios is normalized to 1.The variable "bacteria shedding from severely infected" uses 10^12, hence, normalized to 10^12/10^6 = 2 (Kaper, Morris, & Levine, 1995).
become_severe_infected	(mildly_infected_population/time_progress_to_next_stage-rehydration_care)*normal_ratio_of_severe_disease	person/day	"become severe infected" flow is the rate at which part of the mildly infected individuals leave the stock through multiplication with the normal ratio of severe disease after the time progress to next stage - 1 day (material delay).
connectedness_of_aquifers	0.435	1/day	The "connectedness of aquifers" is the rate of contact with contaminated water. This is an abstract concept that in the context of this model must be related to the amount of reservoir water consumed, but is not expressed in units that include volume and has no upper or lower bounds (Pruyt, 2013). The "connectedness of aquifers" is a simplified and uncertain factor. The variable is calibrated to the historical data, amount to 43% in the base model.
data_IDP	362292	person	Data is obtained from online database from International Organization for Migration (2018) who has an IDP tracking system (DTM). Due to the intensified conflict in Al-Hudaydah from June 2018, an increase of IDP from June to November 2018 was recorded: 133830 to 362292 IDP within 6 months.
duration_IDPs_movement	180	day	Data is obtained from online database from International Organization for Migration (2018) who has an IDP tracking system (DTM). Due to the intensified conflict in Al-Hudaydah from June 2018, an increase of IDP from June to

			November 2018 was recorded: 133830 to 362292 IDP within 6 months. Hence, 180 days is used.
emergency_treatment	IF switch_data_collection =0 THEN emergency_treatment_at_hospital ELSE MAX(emergency_treatment_at_hospital, seeking_care_at_DTC) {IF switch_DTC=0 THEN severe_infected_population*fraction_severe_infected_seeking_care*effect_of_DTC_strain_on_seeking_emergency_treatment*seeking_care_at_hospital ELSE severe_infected_population*fraction_severe_infected_seeking_care*effect_of_DTC_strain_on_seeking_emergency_treatment	person /day	"treatment at DTC" flow is the rate at which severe infected individuals leave the stock by seeking treatment at DTC. The flow depends on the fraction severe infected seeking care and it is affected by the ORC strain.
emergency_treatment_at_hospital	fraction_seeking_care_at_hospital*severe_infected_population/time_progress_to_next_stage	person /day	"emergency treatment at hospital" flow is the rate at which mildly infected population seek emergency treatment at hospital.
fraction_mildly_infected_seeking_care	0.3	1	Only symptomatic infections are likely to be reported. Camacho et al. (2018) demonstrated that only 32.4% of suspect cholera cases in Yemen visited a DTC on the same day of symptom onset, while for 10.2% of patients it took two or more days to access care (Yemen report). For mildly infected individuals who may experience short period of cholera symptoms and may be clinically indistinguishable from other causes of diarrheal illness, are likely to not seek treatment. Hence, the value is assumed to be 0.1 (less than 0.32 who seek treatment in DTC).
fraction_of_Infected_IDP	0.1	1	Assuming 10% of the IDP are infected. Many IDPs live in forest, mountainous or desert areas of Hudaydah, which lack services and provide little for shelter, food or water (Ali, 2021).
fraction_seeking_care_at_hospital	0.15	1	if ORC intervention is switch off, assuming 15% of the individuals who would seek treatment at ORC resort to care at the hospital. MSF (2018) reported that approximately 15-20% of patients will seek medical care

			during the peak week (less for rural settings, more for crowded urban settings). However, if ORC and DTC is unavailable, infected individuals are assumed to seek healthcare services at hospitals. Spiegel et al. (2018) and Qadri, Islam, and Clemens (2017) highlighted that delivery of health care has been limited by the destruction by air strikes of approximately half the health sector facilities, including hospitals and clinics in Yemen. Hence, "seeking care at hospital" uses 0.15.
fraction_severe_infected_seeking_care	0.4	1	Only symptomatic infections are likely to seek treatment and be reported. Camacho et al. (2018) demonstrated that only 32.4% of suspect cholera cases in Yemen visited a DTC on the same day of symptom onset, while for 10.2% of patients it took two or more days to access care (Yemen report). This parameter uses 0.4.
immunity_waning_treated_population	recovered_immune_treated_population/average_symptomatic_infection_acquired_immunity_period	person/day	"immunity waning treated population" flow is the rate at which all recovered immune treated individuals leave the stock after an average symptomatic infection acquired immunity period of 3 years (material delay) and flow back to the susceptible population.
immunity_waning_untreated_population	MAX(recovered_immune_untreated_population/average_symptomatic_infection_acquired_immunity_period, 0)	person/day	All recovered symptomatic individuals leave recovered immune untreated population stock after an average symptomatic infection acquired immunity period of 3 years and flow as "immunity waning untreated population" back to the susceptible population. The MAX function is to ensure the flow is more than 0. The flow also minus the vaccination flow once the intervention is activated.
indicated_ratio_of_severe_disease	normal_ratio_of_severe_disease*effect_of_ORC_strain_on_fraction_of_severe_disease	1	The "indicated ratio of severe disease" shows the value of normal ratio of severe disease under the effect of ORC strain on fraction of severe disease. An increase in ORC health services strain leads to a decrease care quality. Hence, more mildly infected individuals progress to severe infected stage.
indirect_degree_of_infection	connectedness_of_aquifers*smoothed_fraction_of_contaminated_water	1/day	Studies have shown that Cholera is most commonly acquired from drinking water in which V. cholerae is found naturally or that has been contaminated by the faeces of an infected individual (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018; Nelson et al., 2009). Food may be contaminated when prepared with contaminated water or kitchen utensils, or mixed with other contaminated food, or handled by infected persons in unhygienic conditions. Okoh et al. claimed that V. cholera presence in wastewater, therefore, could be dependent on the number of infected people in the population contributing to the wastewater flow.

			Once these vibrios get into environmental water, they convert to conditionally viable environmental cells within 24 h (Nelson et al. 2008). Such vibrios are infectious on reintroduction into a human body. This becomes a major public health problem in underdeveloped areas like the ECP where, as of 2011, about 36 % of the population still got their drinking water directly from rivers and streams (Okoh, 2015). According to WHO–UNICEF statistics, in 2014 only 55% had access to drinking water from improved water sources (Qadri, Islam, and Clemens, 2017). Therefore, in this model, the "indirect rate of infection" equals the product of following two factors: the smoothed fraction of contaminated water and the connectedness of aquifers (Pruyt, 2013). Although cholera can be transmitted through direct faecal-oral contamination. For example, by eating food that has come into contact with human faeces. This model only incorporates indirect transmission through contaminated water: indirect contamination is assumed to occur much more often than direct contamination (Pruyt, 2013).
Infected_IDP	DELAY (PULSE(data_IDP, "time_IDPs_increase_to_Al-hudaydah", 0), duration_IDPs_movement)*fraction_of_Infected_IDP	person /day	A spike in internal displaced persons (IDPs) from August 2018 due to intensified conflict in Al-hudaydah. Pulse function is used to show the increase of IDP that is DELAY over 5 months: to represent the displacement of IDP over time in Al-Hudaydah.
infections	susceptible_population *indirect_degree_of_infection	person /day	"infections" flow is the product of the susceptible population and the indirect infection rate. When individuals from the susceptible population become infected with cholera, they shift to the recently infected population.
initial_recently_infected_population	500	person	OCHA (2017) recorded 21 suspected and confirmed cases in 2017. The health seeking ratio in the beginning is 10% of the symptomatic individuals, assuming that there is a lack of DTC and ORC, and perceived of threat among the public. Symptomatic is 25% of total infected individuals (MSF, 2018). Hence, the estimated total infected individuals is 840 in April. The calibration of the model to historical data resulted as 500 as initial value of recently infected population, it is within a reasonable range.
mildly_infected	MAX(recently_infected_population*(1-ratio_of_asymptomatic	person /day	"mildly infected" flow is the rate at which recently infected individuals leave the stock through multiplication with (1 minus the ratio of asymptomatic) after an average

	)/average_incubation_time, 0)		incubation time of 1 day (material delay). The MAX function is to ensure the flow is more than 0.
mildly_infected_population(t)	mildly_infected_population(t - dt) + (mildly_infected - rehydration_care - become_severe_infected - remain_untreated_mildly_infected) * dt	person	"midly infected population" are mild cases of V. cholerae infection that may be clinically indistinguishable from other causes of diarrheal illness (LaRocque & Harris, 2020). Mildly infected individuals who shifted to the "mildly infected population" stock then leave after the time progress to next stage - 1 day, and flow to 3 directions: "treated mildly infected population", "untreated mildly infected population" and "severe disease population" stocks. The "asymptomatic population" is assumed to be 0 initially.
normal_ratio_of_severe_disease	0.3	1	The "normal ratio of severe disease" is the ratio of mildly infected population progress into severe disease. Among patients who seek treatment, 25-30% of patients will have severe dehydration, 30-40% some dehydration, and 30-40% no dehydration (Médecins Sans Frontières, 2018). Kaper, Morris, and Levine (1995) report that, among all cholera infection (including asymptomatic), 11% of patients with classical infections develop severe disease while 15% of classical infections result in moderate illness (defined as cases detected and managed in outpatient clinics). Hence, the "normal ratio of severe disease" is 0.3 in this model, from the symptomatic mildly infected population.
ratio_of_asymptomatic	0.75	1	Depending on the strain involved, 75% of infections remain clinically unapparent while the remaining 25% develop mild to severe symptoms. For example, stomach cramps and vomiting followed by diarrhoea, which may progress to fluid losses of up to 1 litre per hour (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018).
recently_infected_population(t)	recently_infected_population(t - dt) + (infections + Infected_IDP - mildly_infected - asymptomatic) * dt	person	Infected individuals who shifted to the "recently infected population" stock then leave after an average incubation time of 1 day and flow towards "mildly infected population" and "asymptomatic population" stocks. The World Health Organization estimates that officially reported cases of cholera represent only 5–10% of the actual number occurring annually worldwide because of inadequate laboratory and epidemiological surveillance systems and economic, social and political disincentives to case reporting (CDC, 2020). Historical data (OCHA, 2017) shows 40 cases in April 2017. Assuming that those are tested symptomatic severe cases and taking into consideration of under-reporting, the "recently infected population" is assumed to be 1000.

recovered_asymptomatic_population(t)	recovered_asymptomatic_population(t - dt) + (recovered_from_asymptomatic - asymptomatic_infection_acquired_immunity_waning - vaccination_recovered_asymptomatic) * dt	person	"recovered asymptomatic population" are asymptomatic individuals who recover and become immune because of natural infection. Asymptomatic individuals who shifted to the "recovered asymptomatic population" stock then leave after mild infection-acquired immunity waning of 6 months and flow back to "susceptible population" stock. The "recovered asymptomatic population" is assumed to be 0 initially.
recovered_from_asymptomatic	MAX(asymptomatic_population/average_duration_of_illness_asymptomatic-vaccination_asymptomatic, 0)	person /day	"recovered from asymptomatic" flow is the rate at which asymptomatic individuals leave the stock after an average duration of illness asymptomatic of 5 days (material delay). The MAX function is to ensure the flow is more than 0. The flow also minus the vaccination flow once the intervention is activated.
recovered_from_treated_mild_infection	treated_mildly_infected_population*(1-indicated_ratio_of_severe_disease)/average_duration_of_illness_symptomatic	person /day	"recovered from treated mild infection" flow is the rate at which part of the treated mildly infected individuals, through multiplication with (1 minus indicated ratio of severe disease), leaves the stock after an average duration of illness asymptomatic of 9 days (material delay).
recovered_from_treated_severely_infection	treated_severe_infected_population/average_duration_of_recovery_under_treatment-treated_death	person /day	"recovered from treated severely infection" flow is the rate at which most of the treated severe disease individuals leave the stock after an average duration of illness asymptomatic of 9 days (material delay) and flow as "recovered from treated severely infection" to the recovered immune treated population after minus the treated death flow.
recovered_from_untreated_mild_infection	untreated_mildly_infected_population/average_duration_of_illness_symptomatic	person /day	"recovered from untreated mild infection" flow is the rate at which all of the untreated mildly infected individuals leaves the stock after an average duration of illness symptomatic of 9 days (material delay).
recovered_from_untreated_severe_disease	untreated_severe_infected_population/average_duration_of_illness_symptomatic-untreated_deaths	person /day	"recovered from untreated severe infection" flow is the rate at which all of the untreated severe infected individuals leaves the stock after an average duration of illness symptomatic of 9 days (material delay). The flow also minus the untreated deaths flow.
recovered_immune_treated_population(t)	recovered_immune_treated_population(t - dt) + (recovered_from_treated_mild_infection + recovered_from_treated_severely_infection -	person	"recovered immune treated population" are symptomatic individuals who recover and become immune because of natural infection with treatment. Treated symptomatic individuals, both mild and severe disease, who shifted to the "recovered a immune treated population" stock then leave after average symptomatic infection acquired immunity period of 3 years and flow back to "susceptible

	immunity_waning_treated_population) * dt		population" stock. The "recovered immune treated population" is assumed to be 0 initially.
recovered_immune_untreated_population(t)	recovered_immune_untreated_population(t - dt) + (recovered_from_untreated_mild_infection + recovered_from_untreated_severe_disease - immunity_waning_untreated_population) * dt	person	"recovered immune untreated population" are symptomatic individuals who recover and become immune because of natural infection without any treatment. Untreated symptomatic individuals, both mild and severe disease, who shifted to the "recovered a immune untreated population" stock then leave after average symptomatic infection acquired immunity period of 3 years and flow back to "susceptible population" stock. The "recovered immune untreated population" is assumed to be 0 initially.
rehydration_care	IF switch_data_collection =0 THEN rehydration_care_at_hospital ELSE MAX(rehydration_care_at_hospital, seeking_care_at_ORC)	person /day	"treatment at ORC" flow is the rate at which mildly infected individuals leave the stock by seeking treatment at ORC. The flow depends on the fraction mildly infected seeking care and it is affected by the ORC strain. If there is no ORC, infected individuals would need to rely on the current health facilities. Hence, a MAX function is used.
rehydration_care_at_hospital	(mildly_infected_population/time_progress_to_next_stage)*fraction_seeking_care_at_hospital	person /day	"rehydration care at hospital" flow is the rate at which mildly infected population seek rehydration care at hospital.
remain_untreated_mildly_infected	mildly_infected_population/time_progress_to_next_stage-rehydration_care-become_severe_infected	person /day	"remain untreated mildly infected" flow is the rate at which mildly infected individuals leave the stock through multiplication with (1 minus the normal ratio of severe disease) after the time progress to next stage - 1 day (material delay). The MAX function is to ensure the flow is more than 0. The flow also minus the treatment at ORC rate once the intervention is activated.
remain_untreated_severe_infected	MAX((severe_infected_population/time_progress_to_next_stage)-emergency_treatment, 0)	person /day	"remain untreated severe infected" flow is the rate at which severe infected individuals leave the stock through multiplication with (1 minus the untreated fatality ratio) after the time progress to next stage - 1 day (material delay). The MAX function is to ensure the flow is more than 0. The flow also minus the treatment at DTC rate once the intervention is activated.
seeking_care_at_DTC	effect_of_DTC_strain_on_seeking_emergency_treatment*fraction_severe_infected_seeking_care*severe_infected_population/time_progress_to_next_stage	person /day	"rehydration care at DTC" flow is the rate at which severe infected population seek emergency care at DTC.

seeking_care_at_ORC	(mildly_infected_population/time_progress_to_next_stage)*fraction_mildly_infected_seeking_care*effect_of_ORC_strain_on_people_seeking_hydration_care	person/day	"seeking care at ORC" flow is the rate at which mildly infected population seek rehydration care at ORC.
severe_infected_population(t)	severe_infected_population(t - dt) + (become_severe_infected - remain_untreated_severe_infected - emergency_treatment) * dt	person	"severe infected population" are severe cases of V. cholerae infection that is characterized by a sudden onset of acute voluminous watery diarrhoea described as 'rice water stools' and vomiting leading to rapid volume depletion and death if left untreated (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018). Mildly infected individuals who shifted to the "severe infected population" stock then leave after the time progress to next stage - 1 day, and flow to 3 directions: "treated severe infected population", "untreated severe infected population" and "untreated cholera death" stocks. The "severe infected population" is assumed to be 0 initially.
smoothed_fraction_of_contaminated_water	(SMTH3(total_bacteria_shedding_from_the_fraction_of_infected,time_to_affect_water_in_aquifers)*effect_of_sanitary_on_contaminated_water)	1	The "smoothed fraction of contaminated water" smoothes the (third order) effect of the fraction of infected on the fraction of contaminated water with a delay of 14 days. This structure is refering to cholera model by Pruyt (2013). A third order delay is used to account for the fact that there are many stages in the process between bacteria shedding by the infected individuals to contaminating the water. (Sterman, Business Dynamics: Systems Thinking and Modeling for a Complex World, 2000) Igbinosa et al. (2011) found that South Africa has been plagued by outbreaks of Vibrio-related waterborne infections that are suspected to be linked to inefficiently treated effluents discharge from wastewater treatment facilities (cited from Okoh et al., 2015). Effluent is sewage that has been treated in a septic tank or sewage treatment plant.
susceptible_population(t)	susceptible_population(t - dt) + (immunity_waning_untreated_population + vaccination_acquired_immunity_waning + immunity_waning_treated_population + asymptomatic_infection_acquired_immunity_waning + stop_receiving_clean_water - infections -	person	Total population in Al Hudaydah governorate, Yemen in 2017 was 3,238,199 (OCHA, 2017). For models that simulate an outbreak within a short period of time (e.g. two years in this model), one can ignore the dynamics of population growth (birth rate and death rate, gray arrows) and assume a constant population. It is assumed the total population as susceptible to cholera as the first cholera case only reported in September 2016.

	vaccination_susceptible - receiving_clean_water) * dt		
"time_IDPs_increase_to_Al-hudaydah"	540	day	The conflict in Al-Hudaydah intensified from June 2018. Hence, the starting day is 540,000. Although IDP present in Al-Hudaydah even before June 2018, the impact from IDP is less compared to the drastic increase of IDP from June 2018. Hence, only IDP from June 2018 is captured in the model.
time_progress_to_next_stage	1	day	The incubation period of cholera can range from several hours to 5 days (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018; Nelson et al., 2009). Similar to the "average incubation time", "time to progress to next stage" uses 1 day as the symptomatic individuals will then progress to either mild or severe disease stage.
time_to_affect_water_in_aquifers	3	day	The "time to affect water in aquifers" has an assumptive value of 5 days delayed. According to Nevondo and Cloete (2001), survival of vibrios in the aquatic environment relates sharply to various chemical, biological and physical characteristics of the aquatic milieu, with V. cholerae known to remain viable in surface waters for periods ranging from 1 h to 13 days (cited from Okoh, 2015).
total_asymptomatic_shedding	(recently_infected_population+asymptomatic_population)*bacteria_shedding_from_asymptomatic	person	"total asymptomatic shedding" is the total bacteria shed by number of asymptomatic population and recently infected population
total_bacteria_shedding_from_the_fraction_of_infected	(total_asymptomatic_shedding+total_mildly_shedding+total_severe_infected_not_in_DTC_shedding)/Total_Population	1	"fraction of infected" is the fraction of infected individuals who are contributing to the concentration of V. cholerae in the environment. This is a product of the number of infected individuals and the bacteria shedding in the stool over the total population. This compound parameter is depending on severity of infection as the bacteria shedding is different (Kaper, Morris, & Levine, 1995). Okoh et al. claimed that V. cholera presence in wastewater, therefore, could be dependent on the number of infected people in the population contributing to the wastewater flow.
total_mildly_shedding	(mildly_infected_population+untreated_mildly_infected_population+treated_mildly_infected_population)*bacteria_	person	"total mildly shedding" is the total bacteria shed by number of treated mildly infected, mildly infected and untreated mildly infected population.

	shedding_from_mildly_infected		
total_severe_infected_not_in_DTC_shedding	(severe_infected_population+untreated_severe_infected_population)*bacteria_shedding_from_severely_infected	person	Severity affects the intensity of shedding, and so the average contribution of an infectious person to transmission may change systematically with time as the distribution of infectious doses changes (Kaper, Morris, & Levine, 1995; Nelson et al., 2013). The "severe infected not in DTC" excludes treated severe infected population because at DTC, the sewage system is in place with disinfection. Hence, it is assumed that all patients at DTC do not attribute their bacteria shedding back into the environment.
total_symptomatic_bacteria_shedding	total_mildly_shedding+total_severe_infected_not_in_DTC_shedding	person	"total symptomatic bacteria shedding" is a product of both mild and severely infected bacteria shedding.
treated_cholera_death(t)	treated_cholera_death (t - dt) + (treated_death) * dt	person	"treated cholera death" are the deaths result from severe infected individuals who have received treatment.
treated_death	treated_severe_infected_population*fatality_fraction/average_duration_of_illness_symptomatic	person /day	"treated deaths" flow is the rate at which severe infected individuals leave the stock through multiplication with the treated fatality fraction after an average duration of illness symptomatic of 9 days (material delay).
treated_mild_become_severe_infected	treated_mildly_infected_population*indicated_ratio_of_severe_disease/time_progress_to_next_stage	person /day	"treated mild become severe infected" flow is the rate at which treated mildly infected individuals leave the stock after the time to progress to next stage - 1 day (material delay) into treated severe infected population. The flow depends on the indicated ratio of severe disease which is lower if the capacity of the ORC is not strained. The ORC aims to treat mildly infected individuals at an early stage as a prevention from deteriorating into severe infected stage. The strained ORC will affected the quality of treatment among the mildly infected individuals where the rate "treated mild become severe infected" is higher. Médecins Sans Frontières (2018) reports that the initial clinical state can rapidly deteriorate (or not improve) if: – the volume of fluid prescribed on admission is insufficient: degree of dehydration underestimated or error in calculation. The volume is not administered within the correct time frame: rehydration too slow or too fast, interruptions in treatment (empty IV bags or ORS cups). On-going fluid losses (continued diarrhoea) are not adequately compensated by additional ORS or RL. Frequent vomiting persists: IV therapy may be needed for those who systematically vomit all ORS, even in patients with some dehydration.

treated_mildly_infected_population(t)	treated_mildly_infected_population(t - dt) + (rehydration_care - recovered_from_treated_mild_infection - treated_mild_become_severe_infected) * dt	person	"treated mildly infected population" are mild cases of V. cholerae infection that are treated. Mildly infected individuals who shifted to the "treated mildly infected population" stock then leave after an average duration of illness symptomatic 9 days, and flow to "recovered immune treated population" and "treated severe infected population" stocks. The "treated mildly infected population" is assumed to be 0 initially.
treated_severe_infected_population(t)	treated_severe_infected_population(t - dt) + (emergency_treatment + treated_mild_become_severe_infected - recovered_from_treated_severely_infection - treated_death) * dt	person	"treated severe infected population" are severe cases of V. cholerae infection that are treated. Severe infected individuals who shifted to the "treated severe infected population" stock then leave after an average duration of illness symptomatic 9 days, and flow to "recovered immune treated population" and "treated cholera death" stocks. The "treated severe infected population" is assumed to be 0 initially.
untreated_cholera_death(t)	untreated_cholera_death(t - dt) + (untreated_deaths) * dt	person	"untreated cholera death" are the deaths result from severe infected individuals who left untreated.
untreated_deaths	untreated_severe_infected_population*untreated_fatality_fraction/average_duration_of_illness_symptomatic	person/day	"untreated deaths" flow is the rate at which severe infected individuals leave the stock through multiplication with the untreated fatality fraction after an average duration of illness symptomatic of 9 days (material delay).
untreated_fatality_fraction	0.01	1	Case fatality rate is 0.19% in 2017 in Al-hudaydah governorate (OCHA, 2017). "untreated fatality fraction" uses 0.004 assuming that the fatality fraction is higher than the case fatality rate with treated death fraction of 0.0021. McCrickard et al. (2016) reports that more than half of the records of cholera deaths in Dar es Salaam were missing from the existing surveillance system, which only captured patients who arrived at DTCs. Deaths that occurred in other treatment locations or in the community were not reported. Underreporting of deaths during cholera epidemics, a phenomenon not unique to Tanzania poses a threat to global health security.
untreated_mildly_infected_population(t)	untreated_mildly_infected_population(t - dt) + (remain_untreated_mildly_infected - recovered_from_untreated_mild_infection) * dt	person	"untreated mildly infected population" are mild cases of V. cholerae infection that are not treated. Mildly infected individuals who shifted to the "untreated mildly infected population" stock then leave after an average duration of illness symptomatic 9 days, and flow to "recovered immune untreated population" stock. The "untreated mildly infected population" is assumed to be 0 initially.

untreated_severe_infected_population(t)	untreated_severe_infected_population(t - dt) + (remain_untreated_severe_infected - recovered_from_untreated_severe_disease - untreated_deaths) * dt	person	"untreated severe infected population" are severe cases of V. cholerae infection that are not treated. Severe infected individuals who shifted to the "untreated severe infected population" stock then leave after an average duration of illness symptomatic 9 days, and flow to "recovered immune untreated population" stock. The "untreated severe infected population" is assumed to be 0 initially.
vaccinated_population(t)	vaccinated_population(t - dt) + (vaccination_susceptible + vaccination_recovered_asymptomatic + vaccination_asymptomatic - vaccination_acquired_immunity_waning) * dt	person	"vaccinated population" has the vaccinated individuals from recovered asymptomatic population, asymptomatic population, and susceptible population. Since there is no mass screening to filter the indviduals with infection acquired immunity, it is assumed that the health workers vaccinate those who seemed healthy and never been treated for cholera the past 1 year.
vaccination_acquired_immunity_waning	vaccinated_population //average_duration_of_protection	person /day	All vaccinated individuals leave vaccinated population stock after an average duration of protection (depending on 1 or 2 doses of vaccines) and flow as "vaccination acquired immunity waning" back to the susceptible population.
vaccination_asymptomatic	asymptomatic_population*indicated_fractional_vaccination	person /day	"vaccination asymptomatic" flow is the rate at which asymptomatic individuals leave the stock through multiplication with indicated fractional vaccination.
vaccination_recently_infected_population	recently_infected_population*indicated_fractional_vaccination	person /day	Vaccination on recently infected population is assumed to be no impact. Hence, the flow is not attached to any stock. This is used
vaccination_recovered_asymptomatic	recovered_asymptomatic_population*indicated_fractional_vaccination	person /day	"vaccination recovered asymptomatic" flow is the rate at which recovered asymptomatic individuals leave the stock through multiplication with indicated fractional vaccination.
Health_sector:			
beds	50	person /centre	2,531 beds were reported in 54 Diarrhoea treatment centres DTCs (EOC, 2018). "beds" is assumed to have 50 patients capacity in each DTC. MSF (2018) guideline shows that one DTC has the capacity from 50 to 200 beds.
building_DTC_start_time	80	day	"building DTC start time" is the day when DTC started to be built.
building_ORC_start_time	90	day	"building ORC start time" is the day when ORC started to be built.

data_number_of_DTC	18	centre	Emergency Operations Center (2017) reported 18 functioning DTC. The population in Al-hudaydah was in need of 44 ORC.
data_number_of_ORC	144	centre	Emergency Operations Center (2017) reported 142 functioning ORC. The population in Al-hudaydah was in need of 422 ORC.
desired_DTC_capacity	IF switch_data_collection =0 THEN 0 ELSE (IF switch_DTC=1 THEN (0+STEP(data_number_of_DTC*beds, indicated_building_DTC_start_time)) ELSE IF switch_DTC=2 THEN (0+STEP(desired_number_of_DTC*beds, indicated_building_DTC_start_time)) ELSE 0)	person	"desired DTC capacity" is adjusted according to the number of severely infected individuals from the cholera prevalence (simulation). The variable input is a graphical function that has included the intervention historical data in 2017. It can be changed to test the policy impacts when the switch is turned to 2. "desired DTC capacity" also includes the implementation limitation from the effect of new DTC added.
desired_number_of_DTC	18	centre	"desired number of DTC" is adjusted according to the number of severely infected individuals from the cholera prevalence (simulation). It can be changed to test the policy impacts when the switch is turned to 2.
desired_number_of_ORC	144	centre	"desired number of ORC" is adjusted according to the number of severely infected individuals from the cholera prevalence (simulation). It can be changed to test the policy impacts when the switch is turned to 2.
desired_ORC_capacity	IF switch_data_collection =0 THEN 0 ELSE (IF switch_ORC=1 THEN (0+STEP(data_number_of_ORC*patient_treated, indicated_building_ORC_start_time))ELSE IF switch_ORC=2 THEN (0+STEP(desired_number_of_ORC*patient_treated, indicated_building_ORC_start_time)) ELSE 0)	person	"desired ORC capacity" is adjusted according to the number of symptomatic individuals from the cholera prevalence (simulation). The variable input is a graphical function that has included the intervention historical data in 2017. It can be changed to test the policy impacts when the switch is turned to 2. "desired ORC capacity" also includes the implementation limitation from the effect of new ORC added.
DTC_capacity(t)	DTC_capacity(t - dt) + (DTC_capacity_building) * dt	person	People who are severely dehydrated may need intravenous fluids and hospitalisation. In these cases, they should be admitted to a Diarrhoea Treatment Centre (DTC). Without treatment, the mortality rate can reach 50

			per cent; with adequate care, it's less than 2 per cent (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018; Nelson et al., 2009). A DTC is set up outside of the main hospital to prevent the spread of the disease and is fully autonomous. In open settings, with spread-out populations, treatment needs to be as close as possible to affected populations. "DTC capacity" expressed as number of severely infected individuals that can be treated at ORC in Al-hudaydah. The stock has an initial value of 0.
DTC_capacity_building	(desired_DTC_capacity-DTC_capacity)//time_to_build_DTC	person/day	"DTC capacity building" is a goal seeking function at which the current capacity to treat severely infected individuals is closing the gap with desired DTC capacity over the time to build DTC (first order delay).
DTC_need	people_in_need_DTC//beds	centre	"DTC need" is a demand of beds relative to supply of beds ratio.
DTC_strain	treated_severe_infected_population*ratio_severe_disease_in_DTC//DTC_capacity	1	Strain on DTC services capacity, level of overloading, from ratio of treated severe infected population to DTC capacity.
effect_of_DTC_strain_on_seeking_emergency_treatment	GRAPH(DTC_strain) Points(11): (0.000, 1.296), (0.500, 1.222), (1.000, 1.128), ...	1	The graphical function shows that when the DTC strain is high, it affects the health seeking behavior among the infected individuals. More data/expert input is required for this parameter.
effect_of_ORC_strain_on_fraction_of_severe_disease	GRAPH(ORC_strain) Points(18): (0.000, 0.503346425462), (0.0882352941176, 0.505994142063), (0.176470588235, 0.510691654066), ...	1	By helping to reduce the severity of dehydration of patients who require health facility services, ORCs reduce stress and overcrowding at health facilities (UNICEF, 2013). Besides, when mildly infected individuals receive early treatment, it can help prevent the symptoms deteriorates to severely infected stage that requires DTC treatment. Médecins Sans Frontières (2018) also reports that the initial clinical state can rapidly deteriorate (or not improve) if: The volume of fluid prescribed on admission is insufficient (degree of dehydration underestimated or error in calculation). In addition, when the volume is not administered within the correct time frame (rehydration too slow or too fast, interruptions in treatment). In this model, the graphical function shows that when the ORC strain is high, it affects the quality and availability of care to mildly infected individuals. Hence, the ORC has less effect on preventing individuals flow into "treated severe infected population".
effect_of_ORC_strain_on_people_seeking_hydration_care	GRAPH(ORC_strain) Points(11): (0.000, 1.296), (0.500, 1.222), (1.000, 1.128), ...	1	The graphical function shows that when the ORC strain is high, it affects the health seeking behavior among the infected individuals. More data/expert input is required for this parameter.

fatality_fraction	service_strain_fatality_fraction+(treated_fatality_fraction-service_strain_fatality_fraction)/(1+DTC_strain^service_capacity_sensitivity)	1	According to Médecins Sans Frontières (2018), the case fatality rate (CFR) is is used for assessing the quality of healthcare services (case management) at treatment centres. The standard indicator for adequate case management is a CFR < 1%. In this model, the "fatality fraction" on treated death is affected by the strain on DTC services capacity. The formula includes the sensitivity of care quality to health services strain. The negative exponent indicates an inverse relationship, whereby an increase in health services strain leads to a decrease care quality. Hence, an increase in fatality fraction.
indicated_building_DTC_start_time	IF switch_data_collection =2 THEN building_DTC_start_time + (response_time_to_update_system) ELSE building_DTC_start_time	day	"indicated building DTC start time" includes the delay from surveillance system.
indicated_building_ORC_start_time	IF switch_data_collection =2 THEN building_ORC_start_time + (response_time_to_update_system) ELSE building_ORC_start_time	day	"indicated building ORC start time" includes the delay from surveillance system.
initial_DTC_capacity	50	person	The initial DTC is assumed to be 50 persons. This is an assumption as the cholera cases were reported since September 2016.
initial_ORC_capacity	200	person	The initial ORC is assumed to be 200 persons. This is an assumption as the cholera cases were reported since September 2016.
ORC_capacity(t)	ORC_capacity(t - dt) + (ORC_capacity_building) * dt	person	Cholera is relatively simple to treat in people with mild to moderate forms usually able to recover through treatment with fluids and oral rehydration salts, which are easy to administer (Kaper, Morris, & Levine, 1995; Médecins Sans Frontières, 2018; Nelson et al., 2009). Care is decentralised to smaller-scale Oral Rehydration Centres (ORCs) known as cholera treatment units and oral rehydration solution points, supported by mobile teams."ORC capacity" expressed as number of people that can be treated at ORC in Al-hudaydah. The stock has an initial value of 0.

ORC_capacity_building	(desired_ORC_capacity - ORC_capacity)//time_to_build_ORC	person/day	"ORC capacity building" is a goal seeking function at which the current capacity to treat mildly infected individuals is closing the gap with desired ORC capacity over the time to build ORC (first order delay).
ORC_need	(people_in_need_ORC) //patient_treated	centre	"ORC need" is a demand of care relative to supply of care ratio.
ORC_strain	people_in_need_ORC// ORC_capacity	1	Strain on services capacity, level of overloading, from ratio of mildly and severely infected population to ORC capacity.
other_AWD_cases	7000	person	AWD case that is not easy to be differentiated from cholera patients. Most cases of acute, watery diarrhea are caused by viruses (viral gastroenteritis). The most common ones in children are rotavirus and in adults are norovirus (this is sometimes called "cruise ship diarrhea" due to well publicized epidemics) (Ochoa and Surawicz, 2012). This is an assumption number of 7000 persons. More data/expert input is required for this parameter.
patient_treated	50	person/centre	Michas (2020) reports majority physicians see 20 patients per day, only 1.3% of physicians saw between 51 and 60 patients per day. Assuming doctors in an emergency setting can see 50 patients. "patient tested" is assumed to be 50 patients per day.
people_in_need_DTC	treated_severe_infected_population*ratio_severe_disease_in_DTC	person	"people in need DTC" is number of severely infected individuals who need DTC treatment. Some severely infected individuals can be treated at ORC.
people_in_need_ORC	(treated_severe_infected_population*(1-ratio_severe_disease_in_DTC)+treated_mildly_infected_population+other_AWD_cases)	person	"people in need DTC" is number of mildly infected individuals who need ORC treatment. This include other AWD case that is not easy to be differentiated from cholera patients.
ratio_severe_disease_in_DTC	0.7	1	Some severely infected individuals can be treated at ORC while some of them require treatment at DTC. It is assumed that 0.2 of all severely infected individuals need treatment at DTC.
service_capacity_sensitivity	2	1	"service capacity sensitivity" indicates the sensitivity of care quality to health services strain.
service_strain_fatality_fraction	0.01	1	Case fatality rate is 0.19% in 2017 in Al-hudaydah governorate (OCHA, 2017). "treated fatality fraction" uses 0.004 assuming that the fatality fraction is higher than the case fatality rate with treated death fraction of 0.0019 when minimally treated due to overwhelmed, chaotic health care.

switch_DTC	1	1	A switch to activate and deactivate the intervention
switch_ORC	1	1	A switch to activate and deactivate the intervention
time_to_build_DTC	120	day	"time to build DTC" is an assumptive duration (days) needed to increase the current capacity to meet the need from "desired desired DTC capacity".
time_to_build_ORC	30	day	"time to build ORC" is an assumptive duration (days) needed to increase the current capacity to meet the need from "desired desired ORC capacity".
treated_fatality_fraction	0.0021	1	Case fatality rate is 0.21% in 2017 in Al-hudaydah governorate (OCHA, 2017). "treated fatality fraction" uses 0.001 assuming that the fatality fraction is lower than the case fatality rate with treated death fraction of 0.0019 when the quality of healthcare services is good.
National_cholera_surveillance_system:			
data_updated_in_cholera_surveillance_system	IF switch_data_collection =2 THEN SMTH3("recorded_suspected_and_confirmed_cases_(cummulative)", normal_time_to_update_system+response_time_to_update_system) ELSE SMTH3("recorded_suspected_and_confirmed_cases_(cummulative)", normal_time_to_update_system)	person	
including_unreported(t)	including_unreported(t - dt) + (including_unreported_flow) * dt	person	"including unreported" is the stock of all infected individuals.
including_unreported_flow	asymptomatic+mildly_infected*0.8	person /day	"including unreported flow" is the rate of all infected individuals in the model per day.
normal_time_to_update_system	14	day	"normal time to update system" is a desired duration (days) needed to collect and update data of the surveillance system.
"recorded_suspected_and_confirmed_cases_(	"recorded_suspected_and_confirmed_cases_(cummulative)"(t - dt) + ("recorded_suspected_	person	In areas where an epidemic is under way, a suspected case of cholera is defined as acute watery diarrhea, with or without vomiting, in a patient over 5 years of age. According the study by Camacho (2018), Yemen Health

cummulative)"(t)	and_confirmed_cases_(rate)") * dt		Authorities set up a national cholera surveillance system to collect information on suspected cholera cases presenting at health facilities (no mass screening, the data depends on the availability of ORC, DTC, and health seeking ratio). Individual variables included symptom onset date, age, severity of dehydration, and rapid diagnostic test result. Suspected cholera cases were confirmed by culture, and a subset of samples had additional phenotypic and genotypic analysis. "cumulative cholera cases (suspected and confirmed cases)" is a stock with recorded cases from ORC and DTC.
"recorded_suspected_and_confirmed_cases_(rate)"	rehydration_care+emergency_treatment	person /day	According the study by Camacho (2018), Yemen Health Authorities set up a national cholera surveillance system to collect information on suspected cholera cases presenting at health facilities. Individual variables included symptom onset date, age, severity of dehydration, and rapid diagnostic test result. Suspected cholera cases were confirmed by culture, and a subset of samples had additional phenotypic and genotypic analysis. "recorded cholera cases" flow is the rate of individuals seeking treatment at ORC and DTC.
response_time_to_update_system	0	day	"normal time to update system" is an assumptive duration (days) needed to collect and update data of the surveillance system.
switch_data_collection	1	1	A switch to activate and deactivate the intervention
Sanitation_condition:			
added_latrine_capacity(t)	added_latrine_capacity (t - dt) + (latrine_construction) * dt	person	"added latrine capacity" is expressed as number of people that can be provided with latrine facility.
average_sewered_population	Total_Population*ratio_sewered_population	person	"average sewered population" is the product of total population multiply with ratio sewered population.
building_capacity_to_do_treatment	((desired_sewage_plant_treatment-capacity_to_treat_sewage_plant)/time_to_increase_treatment_capacity)*effect_of_maximum_support_on_building_capacity	person /day/day	"building capacity to do treatment" is a goal seeking function at which the current capacity to treat sewage plant is closing the gap with desired desired sewage plant treatment over the time to increase treatment capacity (first order delay).
building_latrine_start_time	0	day	"building latrine start time" is the day when latrines started to be built.

capacity_to_treat_sewage_plant(t)	capacity_to_treat_sewage_plant(t - dt) + (building_capacity_to_do_treatment) * dt	person/day	Taking into the implementation challenges such as delay in building capacity in treating and maintaining sewage plants, "capacity to treat sewage plant" expressed as number of people that can be covered by the treated sewage plant.
current_max_latrine_need	Total_Population*current_ratio_open_defecation	person	"current max latrine need" is the maximum capacity reduces with the additional capacity (and likewise) overtime.
current_ratio_open_defecation	ratio_open_defecation-(added_latrine_capacity/Total_Population)	1	Ratio of people practicing open defecation in urban area of Yemen after the intervention.
data_sewage_treatment_plant_support	GRAPH(TIME) Points(728): (0.0, 0), (1.00412654746, 0), (2.00825309491, 0), ...	person/day	
degradation	sewage_treatment_plant_supported/degradation_time	person/day	"degradation' flow is the rate that describes how quickly the sewage treatment plant are in need of treatment and maintenance again.
degradation_time	30	day	"degradation time" is assumed to be 30 days, assuming a sewage treatment plant needs maintenance after 30 days. More data/expert input is required for this parameter.
desired_latrine_construction	IF switch_data_collection =0 THEN 0 ELSE (IF switch_latrine=2 THEN STEP(desired_number_of_new_latrine, indicated_building_latrine_start_time)*people_per_latrine*effect_of_maximum_new_latrine ELSE 0)	person	Once the switch is changed to value 2, "desired latrine construction" has a pulse function of the product of desired number of new latrine, people per latrine, and building latrine start time. It also includes the effect of maximum new latrine as the implementation limitation.
desired_number_of_new_latrine	0	latrine	"desired number of new latrine" is adjusted according to the maximum new latrine capacity needed. It can be changed to test the policy impacts when the switch is turned to 2.
desired_sewage_plant_treatment	GRAPH(IF switch_data_collection =2 THEN TIME + (response_time_to_update_system) ELSE TIME) Points(730): (0.0,	person/day	"desired sewage plant treatment" is adjusted according to the number of individuals covered by treated sewage plant. The variable input is a graphical function that has included the intervention historical data in 2017. It can be changed to test the policy impacts. The intervention start time include response time (delay) from the surveillance system.

	0), (1.00137174211, 0), (2.00274348422, 0), ...		
effect_from_latrine_intervention	normal_sanitary_condition*weight_of_latrine_use*effect_of_additional_latrine_on_sanitary_condition	1	
effect_from_other_infrastructure_conditions	normal_sanitary_condition*weight_of_other_sanitary_interventions*Other_infrastructure_states	1	
effect_from_sewage_plant_intervention	normal_sanitary_condition*weight_of_sewage_plant_support*effect_of_sewage_plant_treatment_on_sanitary_condition	1	
effect_of_additional_latrine_on_sanitary_condition	GRAPH(latrine_need) Points(20): (0.000, 2.000), (0.0526315789474, 1.978), (0.105263157895, 1.949), ...	1	Latrine intervention includes additional latrine and maintenance during the epidemic. The "effect of additional latrine on sanitary condition" has a graphical function of S-shape decay.When the latrine need is value 1 (no intervention), the effect is 1 (no effect to the normal sanitary condition). The maximum effect is limited at 2 in order to constrain the sanitary condition at its maximum at 100%.
effect_of_maximum_new_latrine	GRAPH(latrine_need) Points(11): (0.0000, 0.000), (0.0300, 0.237185670755), (0.0600, 0.423017710815), ...	1	The "effect of maximum new latrine" has a graphical function of logarithmic growth. Assuming that when the latrine need is closer to 0, the effect decreases increasingly towards 0 because there is a lack of need to add more latrine.
effect_of_maximum_support_on_building_capacity	GRAPH(sewage_treatment_plant_need) Points(11): (0.0000, 0.000), (0.0300, 0.212119217174), (0.0600, 0.385094456986), ...	1	The "effect of maximum support on building capacity" has a graphical function of logarithmic growth. Assuming that when the sewage treatment plant need is closer to 0, the effect decreases increasingly towards 0 because there is a lack of need to support the sewage plant treatment.
effect_of_sanitary_on_contaminated_water	GRAPH(indicated_sanitary_conditions) Points(13): (0.000, 0.7503), (0.0833333333333, 0.7144),	1	"effect of sanitary on contaminated water" represents the sanitation states that impact the population in accessing clean water. When the indicated sanitary conditions is close to 1, from the range of 0 to 1, (poor to good sanitary condition), the effect (values) on the contaminated water decreases decreasingly towards zero: It reduces the water

	(0.166666666667, 0.6755), ...		contamination level. The maximum effect (minimum value) is limited at 0.2 as good infrastructure cannot promise 0 water contamination. There are other factors on the water contamination.
effect_of_sewage_plant_treatment_on_sanitary_condition	GRAPH(sewage_treatment_plant_need) Points(20): (0.000, 2.000), (0.0526315789474, 1.967), (0.105263157895, 1.929), ...	1	Sewage plant support intervention includes additional treatment and maintenance to the sewage plants during the epidemic. Hence, this is additional treatment to the usual maintenance routines in the governorate. The "effect of sewage plant treatment on sanitary condition" has a graphical function of S-shape decay.When the sewage treatment plant need is value 1 (no intervention), the effect is 1 (no effect to the normal sanitary condition). The maximum effect is limited at 2 in order to constrain the sanitary condition at its maximum at 100%.
indicated_building_latrine_start_time	IF switch_data_collection =2 THEN building_latrine_start_time + (response_time_to_update_system) ELSE building_latrine_start_time	day	"building latrine start time" includes the delay from surveillance system.
indicated_sanitary_conditions	effect_from_sewage_plant_intervention+effect_from_other_infrastructure_conditions+effect_from_latrine_intervention	1	"indicated sanitary conditions" represents the sanitation states that impact the population in accessing clean water. It multiplies the effect of sewage plant treatment on sanitary, effect of additional latrine on sanitary condition, and effect of other infrastructure states on the indicated sanitary conditions. Most of Yemen's major water and sanitation systems have sustained damage, and refuse collection services have been severely impaired. That there has not been a complete collapse is down to the resourcefulness of the population. “In some of the large cities, it is the business community that has come together, raised funds, and arranged solid waste collection campaigns that have been very successful” (Burki, 2016).
initial_latrine_capacity_needed	(Total_Population*ratio_open_defecation)	person	"initial latrine capacity needed" is the initial need of latrine capacity by looking at the current number of population who are openly defecating.
latrine_construction	MAX((desired_latrine_construction-added_latrine_capacity)/time_to_build_latrine, 0)	person/day	"latrine construction" is a goal seeking function at which the added latrine capacity is closing the gap with desired latrine construction over the time to build latrine (first order delay).

latrine_need	current_max_latrine_need/INIT(current_max_latrine_need)	1	"latrine need" is the current ratio open defecation relative to the initial ratio open defecation. If the value is 1, it indicates 100% need. If there is intervention, the need of latrine reduces, causes the value to be less than 1; hence, a reduced need and an effect of intervention on sanitary conditions.
normal_sanitary_condition	0.5	1	Under conflict affected context, the value of "normal sanitary condition" is assumed to be 0.5 functioning. According to WHO–UNICEF statistics, in 2014 only 53% of the population used improved sanitation facilities (cited from (Qadri, Islam, and Clemens, 2017).
number_of_latrine_constructed	added_latrine_capacity/people_per_latrine	latrine	"number of latrine constructed" is obtained from dividing added latrine capacity with people per latrine.
Other_infrastructure_states	1	1	"Other infrastructure states" are represented by household and personal level sanitation that is different than community level interventions on sewage treatment plant and latrines. Under conflict affected context, the value of other infrastructures is assumed to be 0.5 functioning. Therefore, the value for this parameter is 1. No intervention means no effect to the normal sanitary condition. Personal and household sanitation conditions play an important role on fecal-oral cholera transmission that is not within the boundary of this model. Hence, it is represented as constant values in this model.
people_per_latrine	20	person/latrine	Gunther (2012) research findings recommend that not more than four households (or 20 individuals) should share a toilet stance to ensure long-term hygienic and sustainable use. MSF (2018) and Spiegel et al. (2018) also report a minimum of one latrine for 20 people. Hence, the value 20 is used for each latrine.
ratio_open_defecation	0.01	1	Worldbank (2021) reports 1% of people practicing open defecation in urban area of Yemen in 2017. Open defecation included cases where feces are disposed in fields, water, and other open spaces and unimproved sanitation includes disposing feces in latrines without a platform, hanging latrines, or bucket latrines.
ratio_sewered_population	0.693	1	Average sewered population in Al-hudaydah is 69.3% (Ministry of Electricity and Water, 2003).
sewage_treatment_plant(t)	sewage_treatment_plant(t - dt) + (degradation - treatment) * dt	person	Sewage plant treatment removes contaminants from sewage to produce an effluent that is suitable for discharge to the surrounding environment or an intended reuse application. Non-functional sewage plants leads to contamination of the shallow aquifers and wells, where local civilians and private tankers collect drinking water.

			Sewage plant support intervention includes additional treatment and maintenance to the sewage plants during the epidemic (UNICEF, 2018). Initial value of the stock is "average sewered population" in Al-hudaydah.
sewage_treatment_plant_need	sewage_treatment_plant/INIT(sewage_treatment_plant)	1	"sewage treatment plant need" is the stock sewage plant treatment relative to the initial sewage plant treatment. If the value is 1, it indicates 100% need. If there is intervention, the stock reduces, causes the value to be less than 1; hence, a reduced need and an effect of intervention on sanitary conditions.
sewage_treatment_plant_supported(t)	sewage_treatment_plant_supported(t - dt) + (treatment - degradation) * dt	person	"sewage treatment plant supported" is the stock where the number of individuals covered by treatment and maintenance of the sewage plants.
switch_latrine	0	1	A switch to activate and deactivate the intervention
switch_treatment	1	1	A switch to activate and deactivate the intervention
time_to_build_latrine	30	day	"time to build latrine" is an assumptive duration (days) needed to increase the current capacity to meet the need from "desired latrine construction".
time_to_increase_treatment_capacity	14	day	"time to increase treatment capacity" is an assumptive duration (days) needed to increase the current capacity to meet the need from "sewage treatment plant". More data/expert input is required for this parameter.
treatment	IF switch_data_collection =0 THEN 0 ELSE (IF switch_treatment=1 THEN data_sewage_treatment_plant_support ELSE IF switch_treatment=2 THEN capacity_to_treat_sewage_plant ELSE 0)	person /day	Sewage treatment is a type of wastewater treatment which aims to remove contaminants from sewage to produce an effluent that is suitable for discharge to the surrounding environment or an intended reuse application, thereby preventing water pollution from raw sewage discharges. "treatment' flow is the rate at which individuals who leave sewage treatment plant stock to sewage treatment plant supported stock.
weight_of_latrine_use	0.15	1	"weight of latrine use" assigns the weight of latrine state in influencing the indicated sanitary condition. It is assumed to be 0.2 of the sanitary condition as open defecation can lead to contamination of the shallow aquifers and wells. Hence, the effect of functioning latrine intervention is assumed to be 0.2. More data/expert input is required for this parameter.

weight_of_other_sanitary_interventions	0.45	1	"weight of other sanitary interventions" assigns the weight of other sanitation state in influencing the indicated sanitary condition. It is assumed to be 0.45 because this parameter sanitary conditions include household and personal level sanitation that is different than community level interventions on sewage treatment plant and latrines. Although personal and household sanitation conditions play an important role on fecal-oral cholera direct transmission, this is not within the boundary of this model.
weight_of_sewage_plant_support	0.4	1	"weight of sewage plant support" assigns the weight of sewage plant state in influencing the indicated sanitary condition. It is assumed to be 0.4 of the sanitary condition as the highest numbers of cholera cases have been reported in places where sewage treatment plants are non-functional. Without working sewage treatment plants, raw sewage is often diverted to poor neighborhoods and agricultural lands (leads to contamination of the shallow aquifers and wells) where local civilians and private tankers collect drinking water. Hence, the value is conceptualised with a higher weight than latrine use and other infrastructure states. More data/expert input is required for this parameter.
Vaccination:			
"1_dose"	1	vaccine/person	1 dose of vaccine per person
"1_dose_protection"	180	day	Although OCV currently used in mass campaigns are administered according to a two-dose regimen 14 days apart, a single dose provides short-term protection, with a pooled effectiveness of 69% (95% CI 35–85%) within the first year, which has important implications for outbreak management (Pezzoli, 2020) MSF (2018) reports that immunity develops one week after administration and lasts up to 6 months after a single dose and at least 3 years after 2 doses.
"2_doses"	2	vaccine/person	2 doses of vaccines per person
"2_doses_protection"	365*3	day	Potentially facing annual epidemics, it may be necessary to revaccinate at-risk populations every 2 y given that the duration of vaccine protection is about 2.5 to 3 years (Durham el at., 1998; UNICEF, 2018) They have an average two-dose efficacy of 58% (95% confidence interval [CI], 42–69%) and effectiveness of 76%

			(95% CI, 62–85%) for at least 3 years [12], with one study showing efficacy for up to 5 years[13]. Although OCV currently used in mass campaigns are administered according to a two-dose regimen 14 days apart, a single dose provides short-term protection, with a pooled effectiveness of 69% (95% CI 35–85%) within the first year, which has important implications for outbreak management.
average_duration_of_protection	IF switch_vaccine_dose=0 THEN "1_dose_protection" ELSE IF switch_vaccine_dose=1 THEN "2_doses_protection" ELSE 0	day	"average duration of protection" depends on 1 or 2 doses vaccination.
data_vaccines	260000	person	According to UNICEF (2018) situation report, WHO and UNICEF Yemen have supported the first round of an oral cholera vaccination campaign in five districts in the northern governorates of Al-hudaydah and Ibb to protect an additional 540,595 people (over 1 years of age) against Cholera. In total 387,390 (69 per cent) persons have been vaccinated (first dose) against the total target of 561,002 people. There is no data on dis-aggregation of Al-hudaydah and Ibb governorates. Hence, among the 3 districts, 2 are withing Al-hudaydah, it is assumed that 260,000 first dose OCV distributed in Al-hudaydah with the total target of 370,000 people (from the total of 561,002 people).
desired_number_of_vaccines	260000	vaccine	"desired number of vaccines" is initiated with the value 260000 from the historical data. The value can be changed to test the policy.
fractional_vaccination	IF switch_data_collection =0 THEN 0 ELSE (IF switch_vaccination=1 THEN data_vaccines/potential_vaccine_recipients/length_of_vaccination_campaign ELSE IF switch_vaccination=2 THEN number_of_vaccinated_people /potential_vaccine_recipients/length_of_vacci	1/day	"fractional vaccination" is rate that derived from dividing the number of vaccinated people over the campaign period (either from data or policy test input) with total population. This fraction draws number of person from the targeted stocks of sub-population into the vaccinated population stock.

	nation_campaign ELSE 0)		
indicated_fractional_vaccination	(STEP(fractional_vaccination*vaccine_effectiveness, indicated_vaccination_start_time+time_to_procure_vaccines) + STEP(-fractional_vaccination*vaccine_effectiveness, vaccination_stop_time+time_to_procure_vaccines)) +(interval_for_second_round_of_vaccination//interval_for_second_round_of_vaccination)*(STEP(fractional_vaccination*vaccine_effectiveness, indicated_vaccination_start_time+time_to_procure_vaccines+interval_for_second_round_of_vaccination) + STEP(-fractional_vaccination*vaccine_effectiveness, vaccination_stop_time+time_to_procure_vaccines+interval_for_second_round_of_vaccination))	1/day	"indicated fractional vaccination" is a rate that depends on both the vaccination start time (policy initiation) and the time to procure vaccines (delay). Step function is used to enable the flows of individuals from the targeted stocks of sub-population into the vaccinated population stock.
indicated_vaccination_start_time	IF switch_data_collection =2 THEN vaccination_start_time + (response_time_to_update_system) ELSE vaccination_start_time	day	"vaccination start time" is the day when the campaign starts.
interval_for_second_round_of_vaccination	0	day	
length_of_vaccination_campaign	6	day	"length of vaccination campaign" can be adjusted according to the health workers capacity. The value is set at a 6 days campaign in Al-hudaydah (UNICEF, 2018).

number_of_vaccinated_people	IF switch_vaccine_dose=0 THEN desired_number_of_vaccines/"1_dose" ELSE IF switch_vaccine_dose=1 THEN desired_number_of_vaccines/"2_doses" ELSE 0	person	Number of people vaccinated depends on the vaccine dose policy (switch)
potential_vaccine_recipients	recovered_asymptomatic_population + asymptomatic_population + susceptible_population + recently_infected_population	person	Individuals who are perceived as potential recipients of vaccines are individuals who were not previously infected with cholera. Besides susceptible individuals, this population includes asymptomatic individuals (both currently infected and recovered) and recently infected individuals because they cannot be differentiated by healthcare providers since there is no test before inoculation.
switch_vaccination	1	1	A switch to activate and deactivate the intervention
switch_vaccine_dose	0	1	A switch for 1 or 2 doses OCV policy. 1 as 1 dose; 2 as 2 doses
time_to_procure_vaccines	26	day	"time to procure vaccines" is the delay from the day to request vaccines from global vaccine stockpile, to the day the vaccines delivered to the health workers before the vaccination campaigns. According to Pezzoli (2020), in emergency settings, the longest delay was from the occurrence of the emergency to requesting OCV (median: 26 days). The parameter uses 26 days.
vaccination_start_time	600	day	"vaccination start time" is the day when the campaign starts.
vaccination_stop_time	indicated_vaccination_start_time+length_of_vaccination_campaign	day	"vaccination stop time" is the day after the campaign ends.
vaccination_susceptible	susceptible_population*indicated_fractional_vaccination/1	person/day	"vaccination susceptible" flow is the rate at which susceptible individuals leave the stock through multiplication with indicated fractional vaccination.
vaccine_effectiveness	0.76	1	Not everyone vaccinated will be immune to infection. A recent meta-analysis of seven randomized trials and six observational studies estimates the mean effectiveness of standard two-dose killed oral cholera vaccination at 76% with protection lasting for at least 3 years (Shim and Galvani, 2012). Also, Fung (2014) summarized five models

			on the Haitian cholera epidemic model parameters in Table (Appendix).
Water_provision:			
building_capacity_to_distribute_water	(desired_water_distribution_capacity-capacity_to_distribute_water)/time_to_increase_distribution_capacity	person/day/day	"building capacity to distribute water" is a goal seeking function at which the current capacity to distribute water is closing the gap with desired water distribution capacity over the time to increase distribution capacity (first order delay).
capacity_to_distribute_water(t)	capacity_to_distribute_water(t - dt) + (building_capacity_to_distribute_water) * dt	person/day	Taking into the implementation challenges such as delay in building capacity in supply side limitations, "capacity to distribute water" is expressed as number of people that can be provided with clean water.
Data_clean_water_provision	GRAPH(TIME) Points(364): (0.0, 0), (1.00550964187, 0), (2.01101928375, 0), ...	person/day	Clean water provision intervention data were derived from OCHA (2017). The overtime data only available for 2017.
day	1	day	1 day is used because water is daily essential need for human survival.
desired_water_distribution_capacity	GRAPH(IF switch_data_collection =2 THEN TIME + (response_time_to_update_system) ELSE TIME) Points(728): (0.0, 0), (1.00412654746, 0), (2.00825309491, 0), ...	person/day	"desired water distribution capacity" is adjusted according to the number of susceptible individuals requiring clean water. The variable input is a graphical function that has included the intervention historical data in 2017. It can be changed to test the policy impacts. The intervention start time include response time (delay) from the surveillance system.
fractional_susceptible_population	susceptible_population/Total_Population	1	Fraction of population remaining susceptible to cholera.
population_with_clean_water(t)	population_with_clean_water(t - dt) + (receiving_clean_water - stop_receiving_clean_water) * dt	person	Cholera occurs in areas with poor access to sanitation and unsafe drinking water - so providing people with clean drinking water is vital to preventing and curbing any outbreaks. Clean Water Provision Intervention provides people with sachets to purify water, truck clean water in, and install, fix and clean out sanitation facilities such as toilets in affected areas. The epidemiology model by Tuite et al. (2010) simplified the cholera water provision intervention with an assumption at which 100% reduction of “contact” rate if covered by clean water provision. Hence, in this model, a similar assumption is made to represent the population with clean water. The initial value is 0. However, people who have clean water are still vulnerable to infection through other routes, such fecal-

			oral transmission (which is not within the boundary of this model).
ratio_of_clean_water_in_reducing_susceptibility	0.7	1	Compared to Tuite et al. (2011) model on 100% reduction of "contact" rate if covered by clean water provision, this model assumes only 70% of individuals who receive clean water shift into the population with clean water stock. Figure 3 below illustrates the different pathways of cholera transmission. Having clean water does not ensure a 100% reduction in susceptibility (Wolfe et al., 2018). In addition, not all the water provision goes directly to the susceptibility population. The water provision is shared among all SIR sub-populations since there is no disaggregation among the recipients in this model. Hence, only a fraction of individuals from the susceptible population stock receives clean water.
receiving_clean_water	IF switch_data_collection =0 THEN 0 ELSE (IF switch_water_provision=1 THEN Data_clean_water_provision*susceptible_population_receiving_water*ratio_of_clean_water_in_reducing_susceptibility ELSE IF switch_water_provision=2 THEN capacity_to_distribute_water*susceptible_population_receiving_water*ratio_of_clean_water_in_reducing_susceptibility ELSE 0)	person /day	"receiving clean water' flow is the rate at which a fraction of susceptible population is receiving water based on the capacity to distribute water (supply). IF switch_water_provision=1 THEN "WASH_support_(data)"*susceptible_population_receiving_water ELSE IF switch_water_provision=2 THEN capacity_to_distribute_water*susceptible_population_receiving_water ELSE 0
stop_receiving_clean_water	population_with_clean_water/day	person /day	"stop receiving clean water" flow is the rate at which individuals who had received clean water leave the stock after one day (material delay) once they no longer provided with water. They become susceptible to cholera again.
susceptible_population_receiving_water	fractional_susceptible_population	1	"susceptible population receiving water" is the fractional susceptible population. This is an assumption of water is provided to the population without knowing who are the receivers. It is unrealistic to model all water provision goes to the susceptible population. Hence, only a fraction of the intervention is able to impact the population by reducing their susceptibility to cholera.

switch_water_provision	1	1	A switch to activate and deactivate the intervention
time_to_increase_distribution_capacity	14	day	"time to increase distribution capacity" is an assumptive duration (days) needed to increase the current capacity to meet the need from "desired water distribution capacity".

Run Specs	
Start Time	0
Stop Time	730
DT	1/4
Fractional DT	True
Save Interval	0.25
Sim Duration	0
Time Units	Day
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000