Cholera in Zimbabwe

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Abstract

By the end of December 2008, alarming reports and articles concerning the cholera outbreak in Zimbabwe received plenty of international media coverage. By that time nearly 30000 cases of cholera infections and 1600 cholera deaths had been reported. In the first week of January 2009, a System Dynamics simulation model related to this cholera epidemic was created which was subsequently turned into a 'hot' testing/teaching case. Although the model contains some bold assumptions which require further research, the issue and dynamics are sufficiently important and interesting to be presented here. This case is a System Dynamics study with a special focus on exploring dynamics and uncertainties.

Keywords: Cholera, Epidemics, Zimbabwe, System Dynamics

1 Introduction

1.1 The 2008-2009 Cholera Outbreak in Zimbabwe

The deterioration of the Zimbabwean sanitary and health infrastructures over the past years has lead to a lack of safe drinking water and health services, especially in and around the cities, which lead to a cholera outbreak in August 2008.

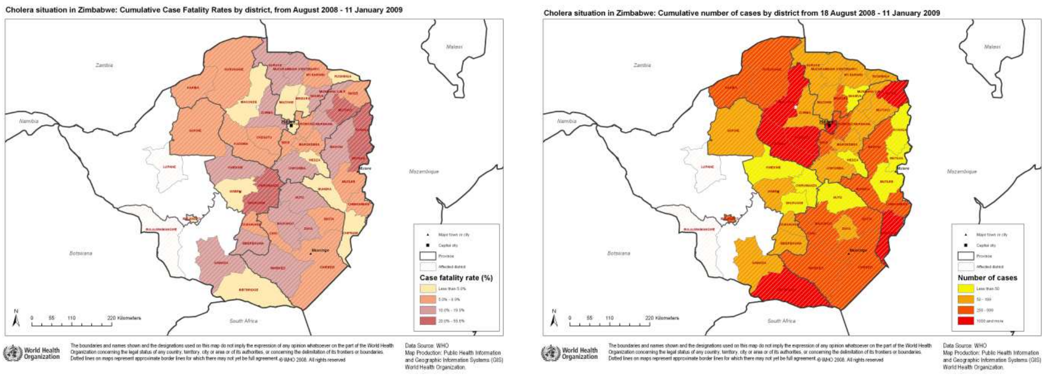
According to the World Health Organization (2009c):

> 'Cholera is an acute enteric infection caused by the ingestion of bacterium Vibrio cholerae present in faecally contaminated water or food. [... It] is characterized in its most severe form by a sudden onset of acute watery diarrhoea that can lead to death by severe dehydration. The extremely short incubation period –two hours to five days– enhances the potentially explosive pattern of outbreaks, as the number of cases can rise very quickly. About 75% of people infected with cholera do not develop any symptoms. However, the pathogens stay in their faeces for 7 to 14 days and are shed back into the environment, possibly infecting other individuals. Cholera is an extremely virulent disease that affects both children and adults. Unlike other diarrhoeal diseases, it can kill healthy adults within hours. Individuals with lower immunity, such as malnourished children or people living with HIV, are at greater risk of death if infected by cholera.'

Cholera may be epidemic but also endemic. Outbreaks are often associated/triggered by season- or climate-related factors –such as heavy rainfalls, floods and droughts– which may disrupt the supply of safe drinking water, aggravate hygiene conditions, and increase (per capita) water contamination (Codeco 2001).

The Zimbabwean Ministry of Health and Child Welfare (MoHCW) reported a total of 26497 cholera cases and 1518 cholera deaths between August 2008 and 25 December 2008 (World Health

Organization 2008a), a total of 79613 cases and 3731 deaths between August 2008 and 18 February 2009 (World Health Organization 2009a), a total of 91164 cases with 4037 deaths between August 2008 and 17 March 2009 (World Health Organization 2009b), and a total of 98522 cases with 4282 deaths between August 2008 and 8 June 2009. The spread on 11 January 2009 is depicted in Figure 1.



(a) Cumulative CFR by district, Zimbabwe, August 2008 until 11 January 2009

(b) Cumulative number of cases by district, Zimbabwe, 18 August 2008 until 11 January 2009

Figure 1: Geographic information related to the Cholera Outbreak in Zimbabwe. Source: WHO 14/Jan/2009 – `http://gamapserver.who.int/mapLibrary/app/searchResults.aspx`

Cholera can be prevented by taking precautionary hygienic measures and/or a good sanitary infrastructure. In case of a fast and appropriate treatment, the (weekly) Case Fatality Rate [CFR] is usually low, below 1%. That percentage was –and still is– much higher in Zimbabwe: the average weekly CFR peaked near 6% in January and stood at 2.3% in the second week of March (World Health Organization 2009b), with a much higher CFR outside of cholera treatment facilities (in remote areas of Zimbabwe) peaking at 62% and declining to 33% (World Health Organization 2009b).

Several international aid organisations offered to provide the necessary medical and sanitary facilities, safe water, and programmes to train aid workers to deal with and prevent cholera. At first, Mugabe refused international aid, but by mid December 2008, he allowed international aid organisations to provide clean drinking water. By that time, half of the population was undernourished ...

1.2 State of the Art of Cholera Models

Although cholera is an 'old disease' which is –with the exception of some underdeveloped regions– under control, the modeling of cholera outbreaks could still be improved substantially. Possible improvements may be the inclusion of the loss of immunity (flow from recovered to susceptible population), of new insights related to the survival of V. cholerae in aquatic environments, of the detailed submodels related to the indirect infection via aquatic environments (often modelled with an abstract R_0 factor), and the consideration of the long term dynamics.

Although some recently published models explicitly take the role of aquatic reservoirs of V. cholerae (Islam 1997; Colwell and Huq 1994; Codeco 2001), hyper-infective vibrios in water reserves (D. M. Hartley and Smith 2006), or the age-structures of populations (Agheksanterian and Gobbert 2007) into account, most of these models are too complex in terms of the mathematics used, too theoretical/abstract, insufficiently focussed on the exploration of the remaining uncertainties[1], and of too low a level of aggregation to inform and be helpful for policy-makers.

[1] For example: Strongly different extinction rates of toxigenic V. cholerae in aquatic environments have been observed (Feachem, Bradley, Garelick, and Mara 1983; Colwell and Huq 1994). It has even been shown that V.

Codeco (2001) proposes for example a formal mathematical SIR model of a *hypothetical* population of 10000 individuals with an explicit cholera reservoir –but without a return flow from recovered individuals to susceptible individuals– in order to explore the role of the aquatic reservoir on the persistence of endemic cholera and to define minimum conditions for the development of cholera.

Here, we present a model with a submodel of the V. cholerae reservoir –be it of a higher level than the one in (Codeco 2001)– and with a return flow from the recovered population to the susceptible population. Uncertainties will also be focussed on.

1.3 Organisation

In this paper, we present a simple System Dynamics simulation model of cholera outbreaks in section 2 and a high-level causal loop diagram in section 3. The behaviour of the base model is analysed in section 4. Validity, sensitivity, and uncertainties are explored in section 5. Model use is discussed in section 6 where policy measures are tested and a teaching/testing case based on the model is briefly presented. Further research and concluding remarks are distilled in section 7. Appendix A contains the 'hot' testing/teaching case description. And appendix B contains the equations of the simulation model.

2 System Dynamics Simulation Model of Cholera Outbreaks

All explicit causal relationships of the base model are described in subsections 2.1 and 2.2. Implicit and bold assumptions are further discussed in subsection 2.3. The Stock-Flow Diagram of the base model is depicted in Figure 2.

The model is in fact a SIR model extended with loss of immunity (a return flow from recovered to susceptible after an average of 6 to 10 years), with different degrees of illness, mortality, and an explicit –but boldly assumed– infection loop with a reservoir to harbor the V.cholerae. The formulation of this 'SIRS with infectious reservoir' model is kept simple: it contain a few lookup/graph, max, smoothing and delay functions (see appendix B).

The model is kept as simple as possible: it contains, consequently, many implicit assumptions and many possibly relevant factors are omitted. For example, the model does not incorporate births, deaths (other than cholera-caused deaths), detailed geographic/spatial information (dispersion, information related to aquifers and cholera reservoirs), climate/season related variables, HIV/AIDS[2], etc. It contains a homogeneous population (no age structure), homogenous infection (no difference in amounts of V.cholerae and infectivity), fixed incubation and delay times, mainly first-order delays, and several highly aggregated structures.

2.1 Susceptible, Infected, Recovered and Immune Populations

When individuals from the *susceptible population* become infected (*cholera infections*), they shift to the *recently infected population.* The number of *cholera infections* is the product of the *susceptible population* and the *indirect infection rate.* Those shifted to the *recently infected population* leave that stock after an *average incubation time* of only 1 day and flow:

- as *mildly infected* to the *mildly infected population* if they show mild or moderate symptoms, or if they are infected but do not show any symptoms at all (all asymptomatic cases);
- as *heavily infected* to the *heavily infected population* in case of severe symptoms.

In the model, the fraction of the *recently infected population* getting only *mildly infected* depends on the *average health condition* of the average Zimbabwean. The fraction used in the base model

cholerae populations may also decay into a non-culturable state and survive for more than 15 months, living in association with aquatic organisms (Islam 1997). The mechanisms driving V. cholerae dynamics in water are still poorly known (Codeco 2001) and are therefore often omitted.

[2]WHO/UNAIDS estimated the 2003 Adult HIV/AIDS prevalence to range between 21.7-27.8%.

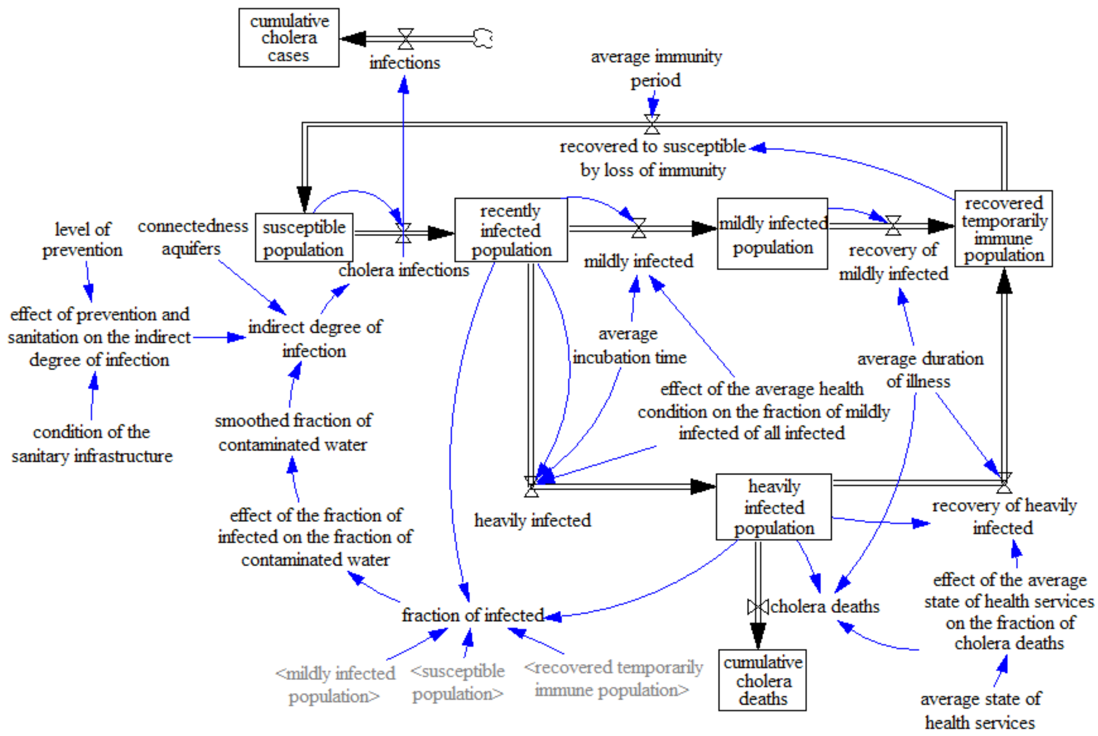


Figure 2: Stock-Flow Diagram of the Cholera Simulation Model

equals 95%. This number is a general estimate, not specific for Zimbabwe. It is derived from WHO statistics: '[a]bout 75% of people infected with cholera do not develop any symptoms, [. . . and] among people developing symptoms, 80% of episodes are of mild or moderate severity' (World Health Organization 2008b). In other words, only 5% of the *recently infected population* in the base model becomes very ill after an *average incubation time* of 1 day. This fraction will be further explored in section 5.

All sick persons belonging to the *mildly infected population* shift –after an *average duration of the illness* of 10 days– as *recovered from mild infection* towards the *recovered temporarily immune population*. The sick persons belonging to the *heavily infected population* either die (*cholera deaths*) or recover and become immune (*recovered from heavy infection*) after the same *average duration of the illness* of 10 days. The fraction of the *heavily infected population* dying or recovering depends in this model on the *effect of the average state of health services on the fraction of cholera deaths*, and hence, on the *average state of health services*.

The values of the *effect of the average state of health services on the fraction of cholera deaths* and the *average state of health services* are guestimates (their influence will be explored in section 5), based on the information that

- without treatment, as many as one in two people may die (World Health Organization 2008b),
- and with proper treatment, the fatality rate should stay below 1% (World Health Organization 2008b).

Given that –in the base model– the graph function *effect of the average state of health services on the fraction of cholera deaths* only affects the heavily infected and that the fraction of *heavily infected* is only 5% of all infections, the *effect of the average state of health services on the fraction of cholera deaths* is assumed to be 100% in case of an *average state of health services* of 0%, 50%

in case of an *average state of health services* of 25%, 20% in case of an *average state of health services* of 50%, 5% in case of an *average state of health services* of 75%, and 0% in case of an *average state of health services* of 100%. The *average state of health services* in Zimbabwe was extremely low at the time of the outbreak until international aid agencies were allowed access, and is expected to increase further. In the base model, the *average state of health services* –at least for cholera treatment– is assumed to be 15% from day 1 till day 130 of the epidemic, and to increase afterwards to 40% on day 183, to 70% on day 183, to 75% on day 250, and to 80% from day 300 on.

After an *average immunity period* of 6 years, Zimbabweans from the *recovered temporarily immune population* flow back to the *susceptible population*.

In the base model, the number of Zimbabwean citizens belonging, at the start of the epidemic, to the *susceptible population* is set at 3000000, the *recently infected population* is set at 1000, the *mildly infected population* is set at 950, the *heavily infected population* is set at 50, and the *recovered temporarily immune population* is set at 10226000 (this corresponds to the remaining population: 13228000 - 3002000). These numbers will also be varied in section 5.

2.2 Indirect Infection

In the model, the *indirect rate of infection* equals the product of following three factors: the *smoothed fraction of contaminated water*, the *effect of prevention and sanitation on the indirect degree of infection*, and the *connectedness of aquifers*. The *connectedness of aquifers* –a soft, uncertain factor which is further explored in section 5– is assumed to amount to 28% in the base model.

The input of the *effect of prevention and sanitation on the indirect degree of infection* is the maximum of two variables: the *level of prevention* and the *state of the sanitary infrastructure*. If the maximum of these two variables is 0% then the effect on the *indirect rate of infection* is assumed to amount to 100%, if it is 25% then the effect is assumed to amount to 90%, if it is 50% then the effect is assumed to amount to 50%, if it is 75% then the effect is assumed to amount to 10%, and if it is 100% then the effect is assumed to amount to 0%. The *level of prevention* and the *state of the sanitary infrastructure* lie between 0% and 100%. In Zimbabwe both are low: in the base model, the *level of prevention* is initially assumed to be 10% and the *state of the sanitary infrastructure* is initially assumed to be 30%. Both variables are soft and uncertain and their influence will be explored in section 5.

The *effect of the fraction of infected on the fraction of contaminated water* is a graph/lookup function: if the *fraction of infected* is 0% then the fraction of contaminated water is assumed to be 0%, if it is 12.5% then the fraction of contaminated water is assumed to be 5%, if it is 25% then the fraction of contaminated water is assumed to be 75%, if it is 50% then the fraction of contaminated water is assumed to be 90%, if it is 75% then the fraction of contaminated water is assumed to be 99%, and if it is 100% then the fraction of contaminated water is assumed to be 100%. This relationship is also a bold assumption: its influence will be explored in section 5.

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. Initially it equals 0.0004 (or 0.04%), initiating the epidemic.

And the *fraction of infected* equals of course the sum of the *recently infected population*, the *mildly infected population*, and the *heavily infected population*, divided by the entire population.

2.3 Implicit and Bold Assumptions of the Simulation Model

As already mentioned, the model contains many explicit and implicit assumptions, some of which correspond to boundary choices:

- Although cholera can be transmitted through direct faecal-oral contamination and indirectly through ingestion of contaminated water and food (World Health Organization 2008b), the System Dynamics model only incorporates indirect transmission through contaminated water: indirect contamination is assumed to occur much more often than direct contamination.

- Although the rainy season increases the likelihood of cholera outbreaks, it has not been included in the current model.
- The current population is focussed on, hence, population growth is not included.
- There are no further subdivision of subpopulations according to health, living conditions, environmental conditions, geographic concentration, et cetera (although such subdivisions may be introduced).

Several variables are truly uncertain or really soft. Bold assumptions have been included in the model to incorporate them. Following assumptions included in the model are bold:

- The *indirect degree of infection* and its influencing factors (the *connectedness of aquifers*, the *smoothed fraction of contaminated water* and the *effect of the fraction of infected on the fraction of contaminated water*, and the *level of prevention* and the *condition of the sanitary infrastructure* and their effect on the indirect degree of infection.
- The *effect of the average state of health services on the fraction of cholera deaths* and the values of the *average state of health services.*
- The sizes of the different subpopulations, especially the sizes of the *susceptible population* and the *recovered temporarily immune population.*

These assumptions will be explored in section 5.

3 A Causal loop diagram of the Simulation Model

A possible aggregated feedback loop diagram of the simulation model is depicted in Figure 3. Both the short term and the long term behaviour may be deduced from it.

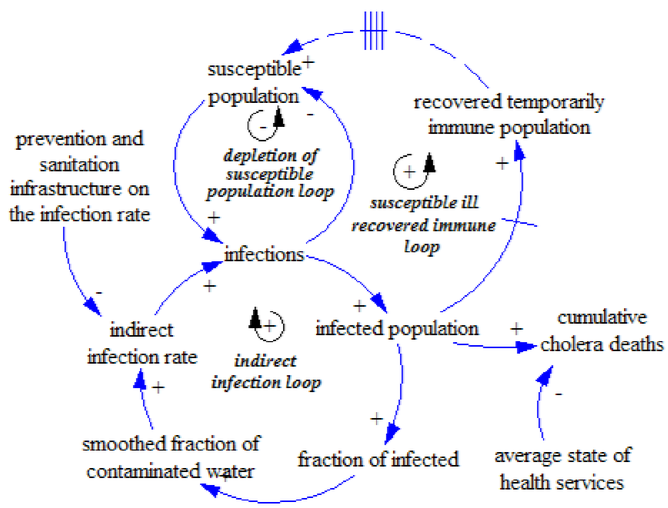


Figure 3: Aggregated causal loop diagram of the Cholera Model

The delay between the `recovered temporarily immune population` and the `susceptible population` –represented by the dashed link in the (+) `susceptible ill recovered immune` loop– is much longer (on average 6 to 10 years) than the second longest delay (on average 14 days). It is also much longer than the short term time horizon (see subsection 4.1). Hence, it does increase the size of the susceptible population (decrease the size of the recovered temporarily immune population) but it does not alter the short term dynamics. However, in the long run, this link becomes extremely important and really drives the long term behaviour.

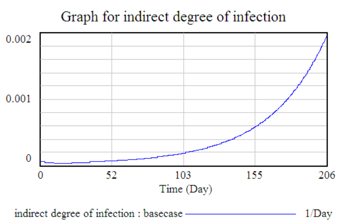
If the ⊕ `indirect infection loop` is strong enough, then it will lead, in the short term, to a boom of the number of infections. However, the number of infections also drives the ⊖ `depletion of the susceptible population` loop which will, in the medium term, lead to a collapse of the susceptible population, and hence, the number of infections. In the long term, however, the recovered temporarily immune population becomes susceptible again, through the ⊕ `susceptible ill recovered immune` loop, increasing the likelihood of a new outbreak.

4 Behaviour of the Simulation Model

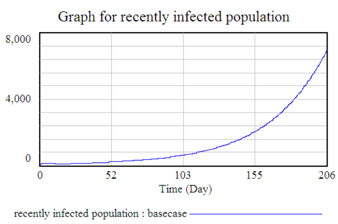
The short term, medium term, and long term dynamics of the base model are discussed here. The short term, medium term, and long term dynamics with additional intervention policies are discussed in subsection 6.1.

4.1 Short term behaviour

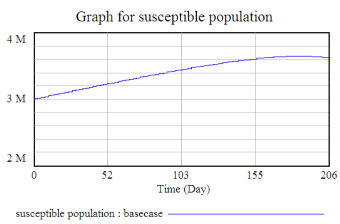
The first 130, 183, or 206 days may be chosen as short term time horizon since data about the cumulative number of cholera cases and deaths is available from mid August until 25 December 2008, until 20 February 2009, and until 14 March 2009. The period from mid August 2008 to 25 December 2008 corresponds to about 130 days, mid August 2008 to 20 February 2009 corresponds to 183 days, and mid August 2008 to 14 March 2009 corresponds to 206 days. The three periods are also characterised by different degrees of international medical aid, and hence the *average state of health services*. The period from mid August 2008 until 14 March 2009 is depicted in the graphs in Figure 4.



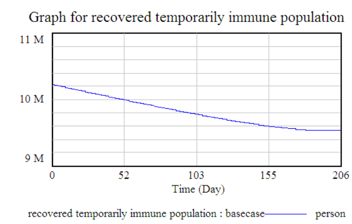
(a) ind. degree of infection (ST)



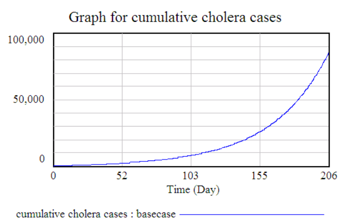
(b) recently infected population (ST)



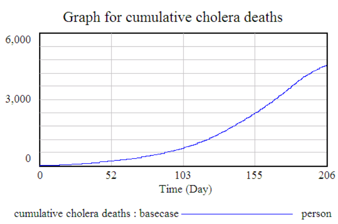
(c) susceptible population (ST)



(d) recovered t. immune pop. (ST)



(e) cumulative cholera cases (ST)



(f) cumulative cholera deaths (ST)

Figure 4: Short term behaviour of the Cholera Model (ST)

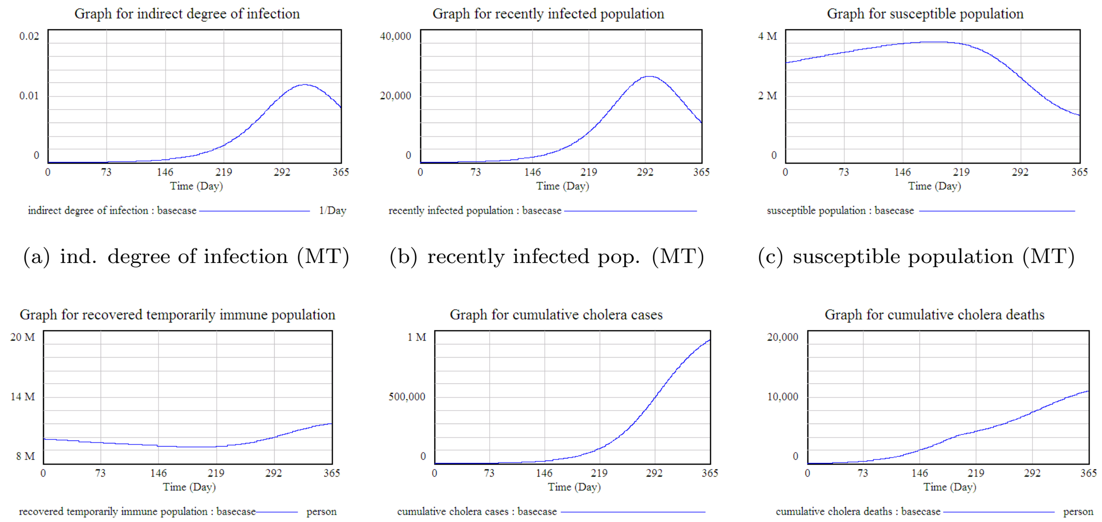
These graphs show that the *indirect degree of infection* (4a) increases exponentially, driving the exponential increase of the *recently infected population*[3] (4b), slowing –and near the end of the short term time horizon, stopping– the net increase of the *susceptible population* (4c) and the net decrease of the *recovered temporarily immune population* (4d). The number of *cumulative cholera*

[3] Note that the *recently infected population* consists of infected individuals who will develop (mild or severe) symptoms *as well as* infected individuals who will not develop any symptoms: '[a]bout 75% of people infected with cholera do not develop any symptoms, although the pathogens stay in their faeces for 7 to 14 days and are shed back into the environment, potentially infecting other individuals' (World Health Organization 2008b)

cases (4e) consequently increases exponentially, and the number of *cumulative cholera deaths* (4f) increases exponentially at first and converges later on –influenced by the assumed increase of the *average state of health services*, brought about by the medical emergency aid of international aid agencies.

4.2 Medium term behaviour

A Medium Term (MT) time horizon of 1 year is opted for. The behaviour of the model in the short and medium term is displayed in Figure 5.



(a) ind. degree of infection (MT) (b) recently infected pop. (MT) (c) susceptible population (MT)

(d) recovered t. immune pop. (MT) (e) cumulative cholera cases (MT) (f) cumulative cholera deaths (MT)

Figure 5: Medium term behaviour of key variables of the Cholera Model (MT)

Looking only at these graphs, one may be tempted to conclude that the *indirect degree of infection* (5a) and *recently infected population* (5b) have peaked and are on their way down, that the *susceptible population* (5c) is reduced to less then half its initial value, that the *recovered temporarily immune population* (5d) has been lifted to a higher level, that the number of *cumulative cholera cases* (5e) enters the last phase of an S-shaped growth, and that the number of *cumulative cholera deaths* (5f) seems to be leveling off[4]. Towards the very end of the medium term time horizon, all variables seem to improve. One may even be tempted to conclude that the medical short term intervention –the international medical intervention leading to an improvement of the *average state of health services*– may solve the problem in the long term...

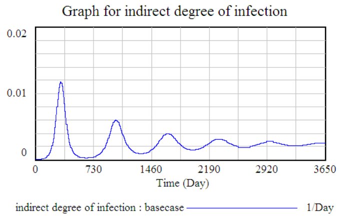
4.3 Long term behaviour

However, simulating the model over the long term –say 10 years– may lead to very different conclusions. The long term behaviour of the simulation model is displayed in Figure 6.

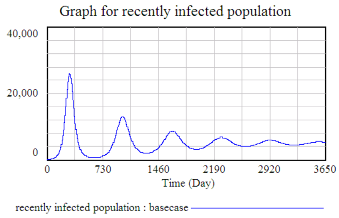
Note that these simulation results only correspond to the real-world epidemic if the model is a good representation of the real-world problem – in other words, if the ensemble of (bold) assumptions holds. It should also be kept in mind that (rainy) seasons, social-geographic conditions, et cetera, are not taken into account here.

The graphs of the long term simulations show that –even with the international medical intervention– the *indirect degree of infection* (6a), the *recently infected population* (6b), the *susceptible population* (6c) and the *recovered temporarily immune population* (6d) oscillate, be it in

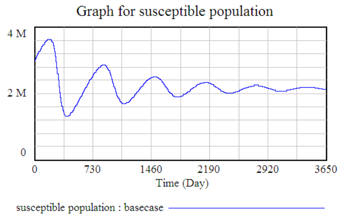
[4] The leveling off is clear if a lightly larger time horizon is used.



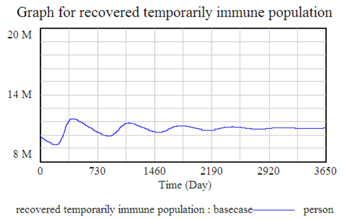
(a) ind. degree of infection (LT)



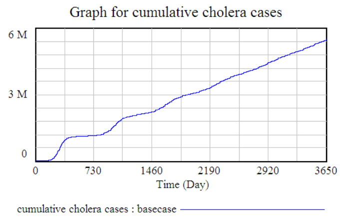
(b) recently infected pop. (LT)



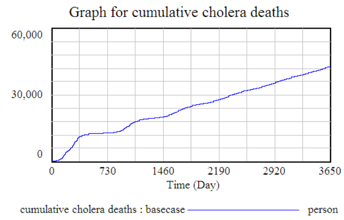
(c) susceptible population (LT)



(d) recovered t. immune pop. (LT)



(e) cumulative cholera cases (LT)



(f) cumulative cholera deaths (LT)

Figure 6: Long term behaviour of the Cholera Model (LT)

a damped way, and that the *cumulative cholera cases* (6e) and *cumulative cholera deaths* (6f) keep on rising... These cyclic epidemic periods –becoming endemic after a while– are of course extremely undesirable.

First it is tested in section 5 whether this problematic behaviour is caused by some bold assumptions or whether it structurally resides within the problem itself. Then additionally needed policies –to solve the cholera problem in Zimbabwe– are tested in subsection 6.1.

5 Exploration of Validity, Sensitivity, and Uncertainty

The model has not been validated by Cholera experts yet. Currently it contains some bold assumptions: Cholera experts may be able to refine/improve some parts of the model and/or fill in certain (data) gaps.

However, there will always be deep uncertainties that cannot be reduced by further research or more expertise. Some of these uncertainties may be dealt with by means of exploration as suggested by Lempert, Popper, and Bankes (2003) and Pruyt (2007) (see subsection **??**).

Although it should be clear that perfectly mimicking the real-world behaviour is *not* aimed at, a (rough) comparison of the reported cholera cases and cholera deaths with the cholera cases and cholera deaths generated with the simulation model (see Figures 4e and 4f) may provide some confidence: After about 206 days, 4037 cumulative cholera deaths and 91164 cumulative cholera cases were reported by the MoHCW (World Health Organization 2009b), compared to about 4540 simulated cholera deaths and 85000 simulated cholera cases (with mild and severe symptoms – the total number of infected –including all those infected without any symptoms– amounts to almost 303000).

Performing traditional sensitivity analyses, it can be concluded that the model is:

- numerically sensitive to changes of the value of the *connectedness of the aquifers*.
- numerically sensitive to changes in the *effect of the fraction infected on the fraction contaminated water* and behaviourally sensitive if the lookup function is shifted downward.

- strongly (numerically and behaviourally) sensitive to changes in the *level of prevention* and the *condition of the sanitary infrastructure.*
- strongly (numerically and behaviourally) sensitive to changes in the *average state of the health services*, although only in terms of the (cumulative) number of cholera deaths.

The main (policy) conclusions following from these sensitivity analyses performed on the base model are that:

- Drastic and sustained improvements of the *level of prevention* and/or the *condition of the sanitary infrastructure* are absolutely required to prevent cholera epidemics from reoccurring in Zimbabwe (see subsection 6.1).
- A drastic and sustained improvement of the *average state of health services* is necessary to reduce the number of cholera deaths in the current (and future) epidemic.

Since these improvements are feasible (but require political will, investments, and time), cholera outbreaks in Zimbabwe ought to belong to the past.

Following uncertain variables/functions may have to be explored, both univariate and multivariate, too: the function of the *indirect degree of infection*, *effect of the fraction of infected on the fraction of contaminated water* and the delay of *smoothed fraction of contaminated water*[5], the *effect of prevention and sanitation on the indirect degree of infection*, the *level of prevention* and the *condition of the sanitary infrastructure*, the *effect of the average state of health services on the fraction of cholera deaths* and the *average state of health services*, the *connectedness of aquifers*, the *effect of the average health condition on the fraction of mildly infected of all infected*, the *average immunity period*, the initial sizes of the subpopulations, and the influence of seasonality.

6 Model Use

The System Dynamics model could be used for several purposes. It may be used to increase the understanding of the link between structure and dynamics of cholera epidemics. It may be used for testing policies (see subsection 6.1). It may also be used as a 'hot' testing/teaching case (see subsection 6.2).

6.1 Testing Policies

Four policies are simulated by means of the System Dynamics model and their corresponding long term simulation results are compared:

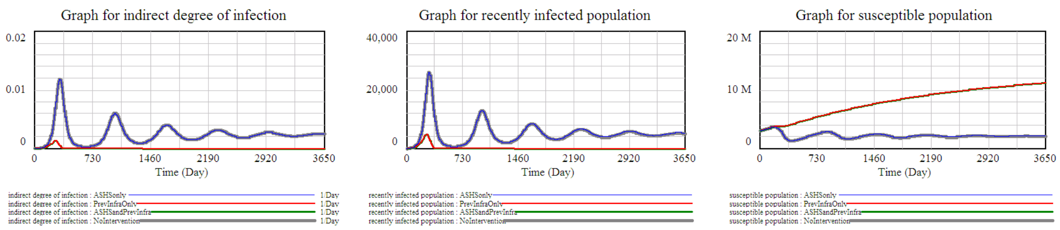
1. The first intervention policy [ASHSonly] is a gradual medical intervention of the base case: there the *average state of health services* increases from a disastrous 15% from day 1 till day 130, to 40% on day 183, 70% on day 183, 75% on day 250, and 80% from day 300 on.
2. The second intervention policy [PrevInfraOnly] is a policy focussed on gradually improving the *level of prevention* and the *condition of the sanitary infrastructure* without the gradual medical intervention as in the base case. The *level of prevention* is assumed to increase from 10% from day 1 till day 130, to 30% on day 183, to 50% on day 206, to 80% from day 365 on[6]. The *condition of the sanitary infrastructure* is assumed to improve more slowly, from 50% on day 1, to 55% on day 183,to 60% on day 365, to 85% on day 1825, and to 90% on day 3650. These improvements may be too optimistic given the current political situation.

[5]The importance of the role of aquatic reservoirs of V. cholerae and their interaction with other factors for driving cholera epidemic is largely unknown (Codeco 2001): the uncertainties are explored here, instead of omitted.

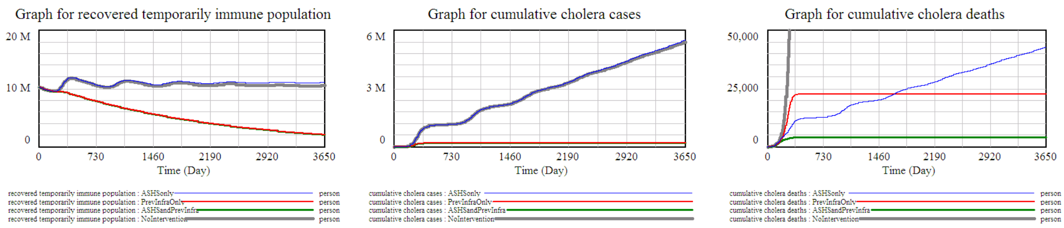
[6]It is assumed that the level of prevention will never be water tight.

3. The third intervention policy [ASHSandPrevInfra] combines a medium term improvement of the *average state of health services* as in the base case, with gradual improvements of the *level of prevention* and the *condition of the sanitary infrastructure* as in the second policy [PrevInfraOnly].

4. The fourth intervention policy [NoInterv] consists of 'no intervention at all' (corresponding to Mugabe's initial line of policy).



(a) ind. degree of infection (LT) (b) recently infected population (LT) (c) susceptible population (LT)



(d) recovered t. immune pop. (LT) (e) cumulative cholera cases (LT) (f) cumulative cholera deaths (LT)

Figure 7: Policies: ASHSonly (blue), PrevInfraOnly (red), ASHSandPrevInfra (green), NoIntervention (grey)

The graphs of the long term consequences of the different policies (see Figure 7) show that:

- A sufficient *level of prevention* and a decent *sanitary infrastructure* are necessary to decrease the *indirect degree of infection*, *recently infected population* and the cumulative cholera cases in the short and medium term, and to prevent future cholera outbreaks in the longer term (see Figures 7a, 7b, and 7e).
- The *susceptible population* will consequently increase and the *recovered temporarily immune population* will decrease (see Figures 7c and 7d).
- The number of *cumulative cholera deaths* cannot be controlled with medical interventions alone.
- Prevention and infrastructure are beneficial in the longer term in terms of the *cumulative number of cholera deaths.*
- Medical intervention+prevention+infrastructure is an even better option in the short and long term in terms of *cholera deaths.*
- Lack of intervention has disastrous consequences in terms of cholera deaths (see Figure 7f) and future cholera outbreaks.

The policies discussed above are not abrupt, nor are they innovative. They correspond more or less to WHO policies and take difficulties of field interventions in third world countries into account:

- 'Once an outbreak is detected, the usual intervention strategy aims to reduce mortality – ideally below 1%– by ensuring access to treatment and controlling the spread of disease' (World Health Organization 2009c).
- 'Measures for the prevention of cholera mostly consist of providing clean water and proper sanitation [...,] health education and good food hygiene' (World Health Organization 2009c).
- 'Given the outbreak's dynamic, in the context of a dilapidated water and sanitation infrastructure and a weak health system, the practical implementation of control measures remains a challenge' (World Health Organization 2009a).

6.2 'Hot' Teaching/Testing Case

This model was developed in the first week of January, was converted into a 'Hot' System Dynamics Testing/Teaching Case (see (Pruyt 2009b) and (Pruyt, Slinger, van Daalen, Thissen, and Yucel 2009)), and was used as an exam case on 14 January 2009 (SEPAM BSc exam at the Faculty of Technology, Policy and Management of Delft University of Technology). Other recent examples of 'Hot Testing/Teaching Cases' developed and used at Delft University of Technology include (Pruyt 2009c) and (Pruyt 2009a).

The case description of the 'Cholera in Zimbabwe' case is included in the appendix A. This case is a classic System Dynamics case in the sense that students are asked to make a System Dynamics simulation model corresponding to the case description (see Figure 2), to make an aggregated feedback loop diagram of the simulation model (see Figure 3), to simulate the short term behaviour (first 150 days) and make specific graphs (see Figure 4), to validate the model briefly[7] to simulate the long term behaviour (10 years) and make graphs (see Figure 6), to perform sensitivity/uncertainty analyses, to propose and test policies, and to formulate a policy recommendation.

7 Conclusions and Further Research

7.1 Conclusions

Although further research and validation is required to reduce/explore uncertain relationships and gain more confidence in the System Dynamics model of the cholera epidemic in Zimbabwe, it promises to be useful. Using the model, it can be shown that:

- Drastic and sustained improvements of the *level of prevention* and/or the *condition of the sanitary infrastructure* are absolutely necessary to prevent the current Zimbabwean cholera epidemic from recurring and becoming endemic.
- A drastic and sustained improvement of the *average state of health services* is necessary to reduce the number of cholera deaths in the current –and future– epidemics.
- A short term medical emergency response should go hand in hand with long term educational action related to cholera prevention and improvement of the sanitary infrastructure.
- Since these improvements are feasible, Zimbabwean cholera outbreaks ought to belong to the past soon.
- Further research may be focussed on the bold assumptions, as well as on the inclusion of the impact of rainy season, the possibility of direct contamination, social, geographic, environmental details.

[7]Here students are among other things required to apply several validation tests and to (roughly) compare the reported cholera cases and cholera deaths with the model outputs. In order to to this, students need to add the `cumulative cholera cases` stock variable.

Hence, future cholera outbreaks can and ought to be prevented in Zimbabwe. Drastic and sustained improvements of the *level of prevention* and/or the *condition of the sanitary infrastructure* are needed to prevent the 2008-2009 cholera epidemic from recurring and becoming endemic.

Concerning the hot teaching/testing case, it can be concluded that the case is a relatively simple, but good, hot teaching & testing case for introductory System Dynamics courses.

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Appendices

A Open System Dynamics Modelling Question: The Cholera Epidemic in Zimbabwe (/25)

A.1 Introduction (background information)

The deterioration of the Zimbabwean sanitary and health infrastructures over the past years has lead to a lack of safe drinking water and health services, especially in and around the cities, which lead to a cholera outbreak in August 2008.

Cholera is an infectious disease caused by the ingestion of bacterium Vibrio cholerae present in faecally contaminated water. Symptoms are severe diarrhoea and dehydration. The extremely short incubation period is about 1 day.

The Zimbabwean Ministry of Health and Child Welfare (MoHCW) and the WHO reported a total of almost 30000 cholera cases and almost 1600 cholera deaths between August 2008 and January 2009

However, cholera can be prevented (rather easily) by taking the necessary precautionary hygienic measures and/or a good sanitary infrastructure. In case of a fast and appropriate treatment, the mortality is low, about 1%. That percentage was much higher in Zimbabwe.

Several international aid organisations offered to provide the necessary medical and sanitary facilities, safe water, and programmes to train aid workers to deal with and prevent cholera. At first, Mugabe refused international aid, but by mid December 2008, he allowed international aid organisations to provide clean drinking water. By that time, half of the population was undernourished ...

A.2 Susceptible, Infected, Recovered and Immune Populations

When individuals from the *susceptible population* become infected (*cholera infections*), they shift to the *recently infected population*. The number of *cholera infections* is the product of the *susceptible population* and the *indirect infection rate*. Those shifted to the *recently infected population* leave that stock after an *average incubation time* of only 1 day and flow:

- as *mildly infected* to the *mildly infected population* if they show mild or moderate symptoms, or if they are infected but do not show any symptoms at all (all asymptomatic cases);
- as *heavily infected* to the *heavily infected population* in case of severe symptoms.

The fraction of the *recently infected population* getting only *mildly infected* depends on the *average health condition* of the average Zimbabwean. The fraction used in the base model equals 95%. In other words, only 5% of the *recently infected population* in the base model becomes very ill after an *average incubation time* of 1 day.

All sick persons belonging to the *mildly infected population* shift –after an *average duration of the illness* of 10 days– as *recovered from mild infection* towards the *recovered temporarily immune population*. The sick persons belonging to the *heavily infected population* either die (*cholera deaths*) or recover and become immune (*recovered from heavy infection*) after the same *average duration of the illness* of 10 days. The fraction of the *heavily infected population* dying or recovering depends on the *effect of the average state of health services on the fraction of cholera deaths*, and hence, on the *average state of health services*.

The values of the *effect of the average state of health services on the fraction of cholera deaths* and the *average state of health services* can be estimated based on WHO information: suppose that the *effect of the average state of health services on the fraction of cholera deaths* is 100% in case of an *average state of health services* of 0%, 50% in case of an *average state of health services* of 25%, 20% in case of an *average state of health services* of 50%, 5% in case of an *average state of health services* of 75%, and 0% in case of an *average state of health services* of 100%. The *average state of health services* in Zimbabwe was extremely low at the time of the outbreak (until international aid agencies were allowed access): assume that the *average state of health services* amounts to 15%.

After a first-order *average immunity period* of 6 years, Zimbabweans from the *recovered temporarily immune population* flow back to the *susceptible population*.

The number of Zimbabwean citizens belonging, at the start of the epidemic, to the *susceptible population* can be assumed to amount to 3000000, the *recently infected population* to 1000, the *mildly infected population* to 950, the *heavily infected population* to 50, and the *recovered temporarily immune population* to 10226000 (this corresponds to the remaining population: 13228000 - 3002000).

A.3 Indirect Infection

The *indirect rate of infection* equals the product of following three factors: the *smoothed fraction of contaminated water*, the *effect of prevention and sanitation on the indirect degree of infection*, and the *connectedness of aquifers*. The *connectedness of aquifers* is assumed to amount to 28% in the base model.

The input of the *effect of prevention and sanitation on the indirect degree of infection* is the maximum of two variables: the *level of prevention* and the *state of the sanitary infrastructure*. If the maximum of these two variables is 0% then the effect on the *indirect rate of infection* is assumed to amount to 100%, if it is 25% then the effect is assumed to amount to 90%, if it is 50% then the effect is assumed to amount to 50%, if it is 75% then the effect is assumed to amount to 10%, and if it is 100% then the effect is assumed to amount to 0%. The *level of prevention* and the *state of the sanitary infrastructure* lie between 0% and 100%. In Zimbabwe both are low: in the base model, the *level of prevention* is initially assumed to be 10% and the *state of the sanitary infrastructure* is initially assumed to be 30%.

The *effect of the fraction of infected on the fraction of contaminated water* is a graph/lookup function: if the *fraction of infected* is 0% then the fraction of contaminated water is assumed to be 0%, if it is 12.5% then the fraction of contaminated water is assumed to be 5%, if it is 25% then the fraction of contaminated water is assumed to be 75%, if it is 50% then the fraction of contaminated water is assumed to be 90%, if it is 75% then the fraction of contaminated water is assumed to be 99%, and if it is 100% then the fraction of contaminated water is assumed to be 100%.

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. Initially it equals 0.0004 (or 0.04%), initiating the epidemic.

And the *fraction of infected* equals of course the sum of the *recently infected population*, the *mildly infected population*, and the *heavily infected population*, divided by the entire population.

A.4 Questions:

1. (/7.5) Make a System Dynamics simulation model of the Zimbabwean cholera epidemic as described above in subsections A.2 en A.3. Save the model on the exam drive. Verify your model.
2. (/4) Make an (extremely) aggregated/simplified '*causal loop diagram*' of this model.
3. (/3) Simulate the model over the first 150 days of the cholera epidemic. Make graphs of the evolution of the *heavily infected population*, the number of *cumulative cholera deaths* and the *smoothed fraction of contaminated water*.
4. (/3) Validate the model. Propose 3 appropriate validation tests (except traditional sensitivity analysis), apply these validation tests and describe your results/conclusions. Use for example the WHO information that about 30000 cholera infections and about 1600 cholera deaths were reported after about 100 days. [Hint: Create a new structure to keep track of the number of *cholera infections* since the outbreak of the epidemic.]
5. (/2) It should be clear that this cholera epidemic will carry on unless drastic action is taken. The risk that drastic action is not taken is real as long as Mugabe is in power. Simulate the model over a period of 10 years. Make graphs of the evolution of all subpopulations and the cumulative cholera infections and cholera deaths (on the computer and your paper copy). What could be concluded from this long-term simulation?
6. (/2.5) Investigate (not too detailed!) the sensitivity of the model given small changes of following variables: the *connectedness of the aquifers*, the *effect of the fraction of infected on the fraction of contaminated water*, the *level of prevention*, and the *average state of health services*. Describe your conclusions as concisely as possible.
7. (/3) Suppose that following measures are implemented abruptly 150 days after the outbreak of the cholera epidemic:

   - The *level of prevention* is changed abruptly from 10% to 70% (by means of water filters, decontamination pills,...).
   - The *average state of health services* is increased suddenly from 35% to 70% (by means of field/emergency hospitals and the arrival of international aid organisations and large numbers of qualified medical personnel).

   What are the consequences in terms of the number of *cumulative cholera deaths* and the *cholera infections*? Draw the graphs on your exam copy. Are these measures sufficient?

B Equations of the System Dynamics Model

The model/equations can be derived from the case description. It will be provided upon request.