Modeling Dengue Outbreak Dynamics in Karachi

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Abstract

Dengue fever poses a persistent threat to public health in urban centers like Karachi, where high population density, inadequate infrastructure, and environmental conditions contribute to recurring outbreaks. This study develops a system dynamics model to simulate the transmission of dengue in Karachi, capturing the interactions between mosquito population dynamics, environmental breeding conditions, and human infections over time. The model integrates key factors such as temperature, rainfall, drainage, waste disposal, water storage practices, and public health interventions.

Simulations were conducted under varying conditions to assess how changes in these factors influence outbreak severity. Results show that poor drainage and inadequate waste disposal significantly increase mosquito breeding sites, while higher water storage index values accelerate vector reproduction. Seasonal temperature shifts were found to affect mosquito survival and infection rates, with optimal transmission occurring around 30–34°C. Public health interventions, such as fogging and awareness campaigns, were shown to reduce infections, with stronger interventions cutting monthly cases by up to 50%. However, the model also revealed that interventions alone are insufficient without concurrent improvements in urban infrastructure.

Overall, the system dynamics model provides a valuable tool for analyzing the complex feedback mechanisms driving dengue outbreaks in Karachi. It highlights critical leverage points—such as drainage improvements and integrated vector control—that policymakers can target to disrupt the transmission cycle and reduce future disease burden.

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1 Introduction

Dengue fever, a mosquito-borne disease caused by the dengue virus (DENV), spreads primarily by *Aedes* mosquitoes, particularly through two species; *Aedes aegypti* and *Aedes albopictus* which thrive in urban environments. Pakistan's first encounter with dengue took place in 1994 and it has experienced annual dengue outbreaks ever since, with Karachi being one of the most affected cities. In October 2021, three dengue-related deaths were reported in Karachi, and 1,255 cases were detected within the city due to weather changes and heavy rainfall [9]. The city's vulnerability to this diseases has only continued to intensify with repeated dengue epidemics, leading to high morbidity and utilization of healthcare resources.

Karachi's semi-arid climate, with its urbanization and inadequate infrastructure, creates an environment conducive to mosquito breeding. Factors such as stagnant water, improper waste management, and limited public awareness worsen these conditions. In addition, rising temperatures and inconsistent, yet prolonged rainy seasons allow for ideal conditions for mosquito habitation throughout the year. In addition, Karachi is also famously known for poor water distribution, and intermittent water supply means

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more households rely on internal storage containers, which often serve as potential breeding sites. Seasonal flooding, such as the Karachi monsoon crisis in 2020, further adds to the problem by creating large pools of still water, a fertile ground for *Aedes* mosquitoes.

Traditional public health responses in Karachi have largely been reactive, typically initiated after the onset of an outbreak. While such efforts may help reduce case counts in the short term, they fail to address the structural and environmental factors that sustain dengue transmission. Studies like the one conducted in Saddar Town, Karachi, reveal that school children are among the principal targets of dengue infections. The study stresses the importance of household-level water storage and inadequate solid waste disposal as contributing factors to the spread of the disease. This research also highlights the critical role of education and awareness in dengue prevention strategies, especially when knowledge is transferred from schools to households. [7]

To design long-term and effective intervention strategies, it is essential to understand the mosquito population dynamics and factors that contribute to the increase in dengue spread. This study proposes a System Dynamics model to simulate and understand the spread of dengue in Karachi using VenSim, and capture the various processes surrounding a dengue outbreak. The central research question that guides this study is as follows:

Research Question

How can a system dynamics model of dengue transmission in Karachi help simulate and analyse the interaction between critical factors that influence the severity of outbreaks, and what policy interventions can most effectively disrupt this cycle?

While earlier studies have modeled dengue using compartmental SIR frameworks or statistical tools, few have integrated urban environmental drivers into a unified, dynamic system. By contextualizing the dengue epidemic in Karachi's urban ecosystem, this model contributes a novel, systems-level perspective to understanding this disease.

The remainder of this paper is structured as follows: Section 2 provides a detailed overview of Karachi's urban environment and dengue history. Section 3 outlines the methodology, including model structure and assumptions. Section 4 presents simulation results from various intervention scenarios. Section 5 concludes with key insights, limitations, and directions for future research.

2 Subject Demographics

Karachi, the largest city and economic hub of Pakistan, is also home to over 20 million citizens. The city lies on the Arabian Sea coast and throughout the year, enjoys an arid climate, with semi-extreme summers and mild winters. The monsoon season typically spans from July to September, during which the city receives an average annual rainfall of 150 to 180 mm, often in harsh rains that overwhelm its already inadequate drainage infrastructure (Pakistan Meteorological Department, 2021). [12]

Similarly, the temperature in Karachi remains high for most of the year, with summer temperatures often exceeding 30 C (Celcius), and winter temperatures rarely dropping below 15 C (Celsius). These conditions are conducive to the breeding and survival of the mosquitoes which thrives in warm and humid environments with abundant stagnant water sources; Pakistan is cited as at risk for mosquito-borne diseases [21].

A rapid and unregulated urban expansion has also resulted in the deterioration of the infrastructure and ecological conditions of the city. In 2020, Karachi was estimated to be host to around 16 million citizens as reported by the World Population Review [17], where this number is estimated to be approximately 18.1 million for 2025 and shows how the population of Karachi increases starkly over the years. As a result, many residents of the city suffer from the consequences of such overcrowding, where one consequence is limited access to clean water. Lack of a proper steady supply of clean water leads to residents storing water in open containers, where these containers frequently serve as breeding sites for mosquitoes. According to a study by Ghaffar et al.[6], 40% of surveyed households in low-income areas of Karachi stored water in open buckets or tanks, significantly increasing mosquito breeding risk.

The other consequences of improper waste management and inefficient sanitation infrastructure also contribute majorly to the development of breeding grounds for mosquitoes. Waste accumulation further exemplifies the issue as solid waste is often dumped in open plots or alongside roads due to insufficient municipal waste collection, that collect rainwater and create pools of stagnant water. Moreover, open manholes and clogged sewers are common across the city, many of which are not catered to by the Karachi Municipality Committee, with reports indicating that only 60% of Karachi's waste is formally collected and processed [2].

Karachi also has an extensive history with dengue. The first significant outbreak occurred in 1994, and since then, the city has experienced recurring seasonal epidemics. The 2006 outbreak was one of the worst in the city's history, with over 1,900 laboratory-confirmed cases and 41 deaths [18]. A major outbreak again occurred in 2011, following intense rains and flooding, which overwhelmed the drainage system and resulted in the creation of thousands of new mosquito breeding sites. More recently, the 2020 monsoon season, coupled with urban flooding, led to a sharp increase in reported dengue cases in several districts of Karachi [8].

Overall, Karachi's environment demonstrates a complex system of variables that together shape the dynamics of dengue outbreaks. These interacting factors make the city an appropriate and urgent case for a system dynamics model aimed at understanding and mitigating the spread of dengue through informed and proactive intervention schemes.

3 Methodology

We implemented our System Dynamics learning and knowledge of popular models to try and construct the outbreak dynamics for dengue, using VenSim. Our goal was to identify the key factors that have been reported to influence the outbreaks and attempt to calibrate our model to learn from these findings and capture the trends and effects that the variables have on the overall outbreak.

3.1 Model Overview

Our model comprises of stock-and-flow structures that have been consolidated into 3 distinct interconnected layers:

- **Layer 1**: A human-level SIR (Susceptible–Infected–Recovered) model to represent the spread of the disease within the human population.
- **Layer 2**: A mosquito population dynamics model, which uses the mosquito birth rates and deaths to simulate the mosquito population growth.
- **Layer 3**: A mosquito breeding site dynamics model, similar to the population dynamics model, which is influenced by urban environmental variables such as stagnant water, improper waste management and intervention schemes.

All rates were calibrated to have time units of Months and the final results were simulated over a period of 24 months (2 years).

3.2 Layer 1

The foundation of our model begins with the human population stock in Karachi, as shown in **Figure 1**. For the human population, we took the estimate of 16 million as the total population [17]. We took the assumption that approximately 60% of this population would be susceptible to mosquitoes, as not everyone in Karachi is equally exposed to mosquitoes, an idea supported by local reports. People living in apartments or with access to better water storage facilities would encounter less mosquitoes than people living in informal housing and worse facilities. Thus, our initial susceptible human population was set to 9,600,000.

For the infected human population, there were **2,122** confirmed dengue cases in Karachi in 2020 (aggregated from all districts), as shown in **Figure 2**.

Dengue Outbreak 5

Sr. No.	Division/District	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Total
1	East Karachi	62	27	16	6	14	25	18	25	143	465	17	818
2	Central Karachi	57	29	21	6	16	16	12	17	62	183	9	428
3	South Karachi	34	13	13	5	3	11	6	10	42	237	11	385
4	West Karachi	30	19	7	5	8	2	3	6	15	25	1	121
5	Malir Karachi	8	4	4	1	0	5	0	4	16	47	1	90
6	Korangi Karachi	30	15	10	2	3	7	3	4	22	56	0	152
	Cases of Karachi-Unspecified Districts	12	7	4	1	0	0	0	1	0	99	4	128

Table-I. Month wise confirmed dengue cases in 2020 in Sindh Province of Pakistan

Figure 2: Confirmed Dengue Cases for Karachi in 2020

We estimate that these represent only 40% of actual symptomatic infections as 60% were asymptomatic [3]. Thus, the estimated total infected population would be **5,305**. For the recovered human population, 95% of infected individuals recover fully, based on global and local trends as mortality from dengue is rare when care is available. Thus, the estimated total recovered population would be **5,035**.

Now for the flows, the Infections flow represents the transition from the Susceptible Human Population Stock to the Infected Human Population Stock. We set a very minute base infection rate of 0.0005 which would be affected by the two variables 'Infectious Mosquitoes Fraction' and 'Infection Intervention Index'. The former represented the fraction of total mosquitoes that would be infectious (set to 0.15) and ready to infect while the latter represented interventions like mosquito repellants for e.g. that allowed us to experiment. The extent of the interventions was represented by an index ranging from 0 to 1, with 0 meaning no interventions and 1 meaning extensive interventions. The base human population was used to control the population factor (set to 9,600,000) and the mosquito population was fetched from Layer 2. The formula used for this is described below:

Infections Formula

IF THEN ELSE(Mosquito Population > 0, (Infection Rate * (Infectious Mosquitoes Fraction * (Mosquito Population)) * (Susceptible Human Population / Base Human Population))*(1 - (0.9*Infection Intervention Index)), 0)

Similarly, the Recoveries flow represents the transition from the Infected Human Population Stock to the Recovered Human Population Stock. We set a high base recovery rate of 0.95 as mortality from dengue is very unlikely and most patients do recover easily. A variable 'Healthcare Access' was included that represented the ease of access to healthcare facilities; the higher the index, the more facilities that are available to treat patients. These facilities can be in the form of hospitals, pop-up clinics or mobile camps and vans. Another variable 'Severity of Outbreak' was included to allow for experimentation where this variable was a rather simplified representation of how severe the outbreak was; the higher this index (0 to 1) was, the more difficult it would be to treat the patients and hence, the recovery rate would decrease. The formulas used for this component are described below:

Recoveries Formula

Recovery Rate = Base Recovery Rate * (Healthcare Access) * (1 - Severity of Outbreak)
Recoveries = Infected Human Population*Recovery Rate

Susceptible Population Formula

Susceptible Population = -Infections

Infected Population Formula

Infected Population = Infections - Recoveries

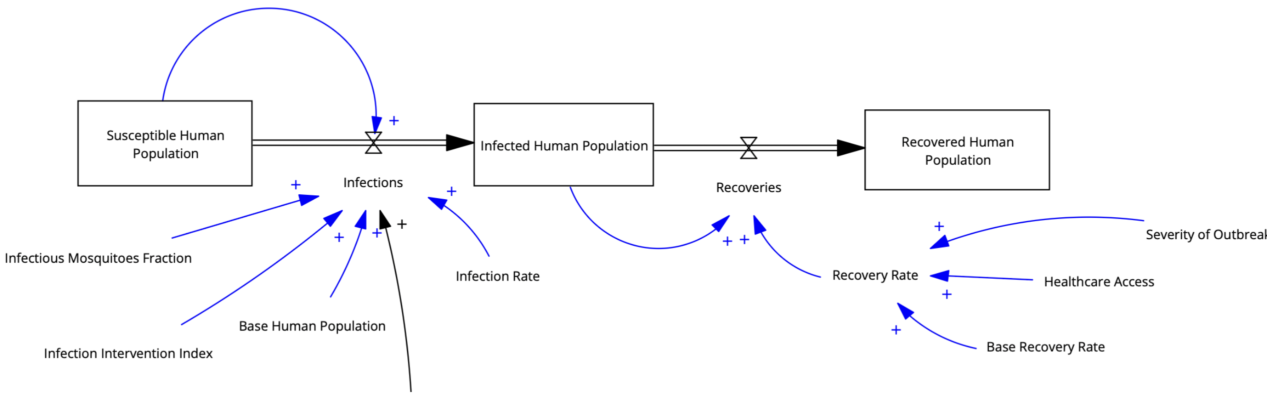

Figure 1: Layer 1: Human Population SIR Model

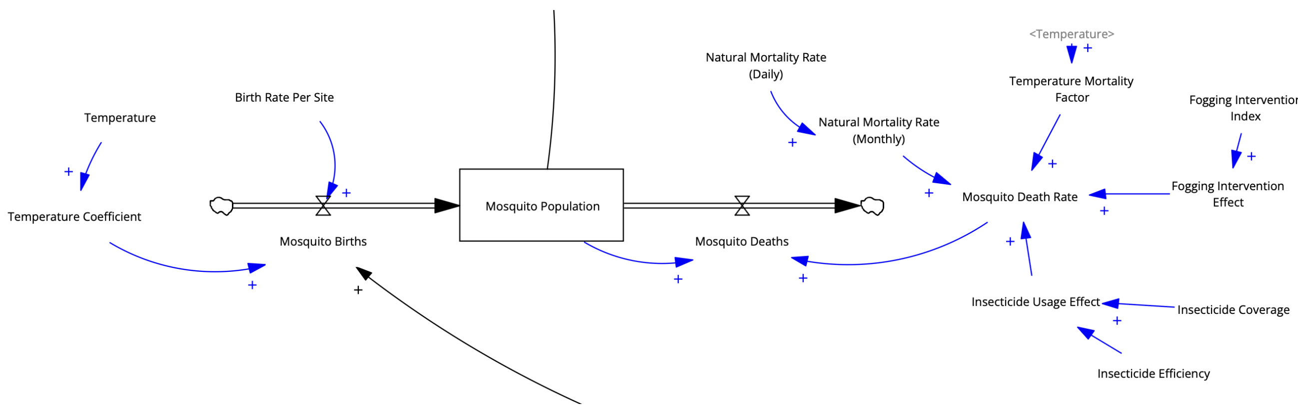

Figure 3: Layer 2: Mosquito Population Model

3.3 Layer 2

Figure 3 shows the layer of the model that simulates the life cycle of the *Aedes* mosquito population, focusing on how environmental and intervention variables influence births and deaths within the population. The mosquito population is modeled as a stock that is increased by Mosquito Births and decreased by Mosquito Deaths. The Mosquito Population stock also connects with Layer 1, thus solidifying the flow and effects of increasing or decreasing the mosquito population on the human population groups.

We started with an estimate of **5,000,000** for the initial mosquito population but any plausible value could have been chosen for this. Here, **Layer 2** differs from **Layer 1** in the sense that we only require the one stock that tracks the mosquito population and are not concerned with the other two end-stocks.

For the first flow 'Mosquito Births', we included the variables 'Temperature' and 'Birth Rate Per Site'; the latter being the base rate of mosquito births per breeding site, and the former being the city temperature. For the birth rate per site, *Aedes* mosquitoes lay 100–200 eggs per cycle, out of which only a fraction reach adulthood. Studies have suggested that around 20-50 adults survive per breeding site depending on the relevant conditions [16]. Moreover, each cycle lasts approximately 10 days, as shown in **Figure 4** [5].

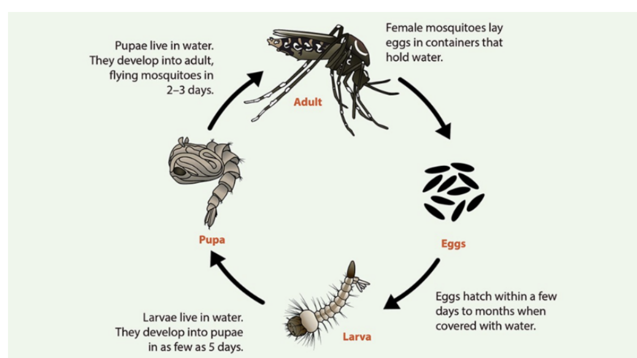

Figure 4: Aedes Mosquito Lifecycle

Thus in a month, there would be 150 mosquitoes birthed per breeding site. As for the breeding sites, Karachi has approximately 2.5 million households [13]. Assuming 20% have potential breeding spots (tanks, buckets, open containers), this gives us 500,000 and adding public stagnant water and drainage areas (approx. 100,000), we have a total **600,000** breeding sites (assumed).

We also included the effect of temperature on the mosquito birth rate. *Aedes* mosquitoes breeding is found to be optimal when the temperature is in the 25 - 32 C (Celsius) range. If the temperature drops below 16C, then breeding halts wherease if the temperature exceeds 32C, the rate decreases as breeding slows down. We implemented this phenomena using if-else statements to define a 'Temperature Coefficient' that dynamically contributes to the birth rate depending on the temperature. The formulas are as follows:

Temperature Coefficient Formula

IF THEN ELSE(Temperature < 16, 0 , IF THEN ELSE(Temperature < 25, ((Temperature - 16) / 9), IF THEN ELSE(Temperature <= 32, 1 , IF THEN ELSE(Temperature < 35, 1 - ((Temperature - 32) * 0.067), 0.5))))

Mosquito Births Formula

Births = Birth Rate Per Site * Temperature Coefficient * Mosquito Breeding Sites

For the first flow 'Mosquito Deaths', we included several variables as we wanted to experiment here and analyze how we could intervene to control the mosquito population and consequently, the dengue outbreak. The daily mortality rate for these mosquitoes is generally 10% however in our model, we convert daily mortality rates into monthly equivalents for compatibility with simulation timesteps.:

Monthly Mortality Rate Formula

Rate = 1 - (1 - Natural Mortality Rate (Daily))^{30}

As mentioned before, the temperature also plays a part in the death rate as certain temperatures do not allow for mosquito habitation. The formula below describes the viable range for mosquitoes to survive.

Monthly Temperature Mortality Factor Formula

Factor = IF THEN ELSE(Temperature < 16, 1 + (16 - Temperature) * 0.03, IF THEN ELSE(Temperature > 32, 1 + (Temperature - 32) * 0.05, 1))

Interventions-wise, we included two particular interventions; Fogging and Insecticide Usage. For fogging, the WHO Pesticide Evaluation Scheme (WHOPES) field trials [14] suggest that one session kills 30% - 50% of adults, and two sessions can have a compounded effect of 40%, which we set as our 'Fogging Intervention Index'.

Monthly Fogging Intervention Formula

Fogging Intervention Effect = 1 - (1 - Fogging Intervention Index)^2

As for insecticide usage, the WHO Indoor Residual Spray Guidelines [15] suggested that insecticides are able to cover 20% to 80% of the mosquito population exposed to the treated areas and are effective in eliminating 40% to 80% of the population. We used the average of these two ranges to define the 'Insecticide Coverage' (set to 0.5) and 'Insecticide Efficiency' (set to 0.6) and used the two to define the 'Insecticide Usage Effect' as follows:

Monthly Insecticide Intervention Formula

Insecticide Usage Effect = Insecticide Coverage * Insecticide Efficiency

Finally, we defined the Mosquito Death Rate and Mosquito Deaths:

Mosquito Death Formulas

Natural Mortality Rate (Monthly) * Fogging Intervention Effect * Insecticide Usage Effect * Temperature Mortality Factor
Mosquito Deaths = Mosquito Death Rate * Mosquito Population

3.4 Layer 3

Figure 5 models Layer 3 which encompasses the creation and elimination of mosquito breeding sites, arguably the most critical component of our model. This layer represents how environmental conditions and municipal interventions affect the number of available breeding sites, which in turn directly influence mosquito population growth from Layer 2.

The initial value for the breeding sites was set to **600,000** as calculated before. As for the inward flow 'Creation of Breeding Sites', this represented the increase in breeding sites and consequently, more mosquitoes being born. For this, we set the base creation rate to be **100,000** as each mosquito contributes to roughly 0.01 – **0.02** new breeding sites per month, indirectly, through the reproductive cycle and oviposition behavior, and our base mosquito population was set to **5,000,000**.

For the factors that would contribute to the creation of said sites, we selected two major factors, 'Stagnant Water' and 'Waste Management', both represented by indexes ranging from 0 to 1, respectively. The latter was much simpler to define; a higher value means better waste management facilities/services. According to a study, the SSWMB (Sindh Solid Waste Management Board) claims it was able to "collect 70% of the waste and take it to the two landfills" [4]. Another article cited that "Karachi generates 20,000 tonnes of solid waste per day but only 3,000 tonnes to 4,000 tonnes of waste is picked up." [10]. We went over a few more articles and decided

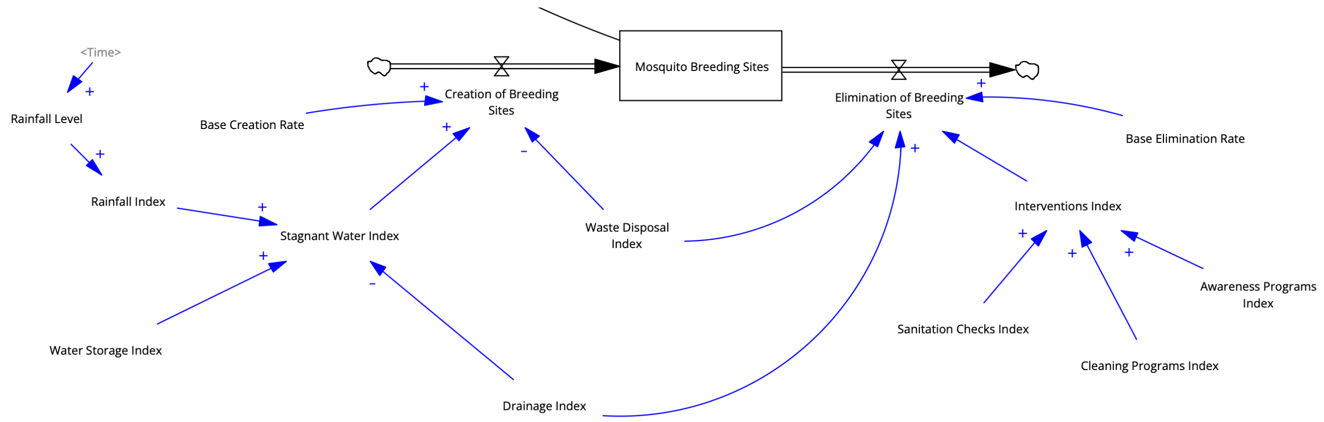

Figure 5: Layer 3: Mosquito Breeding Sites Model

to set this index to a **0.7**.

As for the more complex **Stagnant Water Index**, this comprised of three separate factors, each of which contributes to the increase in still or standing water bodies, ideal breeding grounds for mosquitoes. The first one is the poor drainage system and infrastructure. The Karachi Solid Waste Emergency and Efficiency Project report by the World Bank stated that "uncollected waste contributes to clogged drains and stagnant water, creating mosquito breeding grounds." [2]. Other studies have identified poor drainage networks as a primary cause of urban flooding in Karachi, particularly in areas like DHA Phase 6 [1], which inherently contributes to water accumulation. We decided on setting this index to a **0.7** as well, reasons for which will be discussed shortly.

A minor contributor to stagnant water, yet the most obvious one was water storages. Practices like in-house water tanks or open-air containers are common in Karachi due to the inconsistent and inefficient water supply system. In areas like Manzoor Colony, nearly every household has overhead water storage tanks [11]. These water storage facilities granted small, do contribute largely when compounded and hence, we set this index to a **0.65**.

The last factor that arguably contributes the most to stagnant water is rainfall. Karachi, due to its geolocation and proximity to the Equator, enjoys monsoon rainfall each year. The city experiences an average annual rainfall of approximately 167 mm, with significant variability across months; the monsoon season (June to September) accounts for the majority of rainfall, with August being the wettest month, averaging around 57 mm [20]. We took the monthly data for rainfall collected for one calendar year and implemented the 'Rainfall Index' to translate the data into a value between 0 and 1. The formulas for the index calculation and data integration were as follows:

Rainfall Level Data Integration

= WITH LOOKUP(MODULO(Time, 12), ([(0, 1.8)-(11, 57.4)], (0, 4.6), (1, 5.1), (2, 2.9), (3, 1.1), (4, 1.8), (5, 12), (6, 55.3), (7, 57.4), (8, 18.4), (9, 3.2), (10, 2.2), (11, 2.7))

Rainfall Index Formula

Rainfall Index = Rainfall Level / 57.4 (57.4 being highest rainfall in August)

Once the factors were calculated, we calculated the Stagnant Water Index and then the 'Creation of Breeding Sites' flow. A higher value of the 'Drainage Index' would mean that the drainage system is good and that less water is remaining stagnant, thus we catered for this in the formula.

Stagnant Water Index Formula

Stagnant Water Index = ((1 - Drainage Index) + Rainfall Index + Water Storage Index)

Similar to the 'Drainage Index', a higher value of the 'Waste Management Index' would also mean that waste is being managed properly and water would not be accumulated in these waste areas. Dividing the result by 4 allows for the index to remain in the range of 0 to 1.

Creation of Breeding Sites Formula

= Base Creation Rate * (1 + ((Stagnant Water Index + (1 - Waste Disposal Index)) / 4))

The final component of our model, the 'Elimination of Breeding Sites' flow, we wanted to experiment with this to the fullest as this is one of the areas where interventions can be simulated and tested to see if they are effective. For the base elimination rate, we set this to half the base creation rate, i.e. **50,000** per month.

Earlier, we set the 'Drainage Index' and 'Waste Management Index' to moderately higher values. We did this as these two particular indexes contribute to both the creation and elimination of breeding sites, and we wanted to see what would be the result.

For the Interventions Index, we again expanded this index into three separate factors; sanitation checks, cleaning programs and awareness programs. In Karachi, delayed fumigation and poor sanitation have been linked to increased cases of vector-borne diseases, highlighting the importance of timely and effective cleaning programs. An article cites that, "It is widely known that 70-80% of infectious diseases can be reduced simply through proper sanitation and access to clean drinking water" but also mentions for Karachi; "poor waste management and sanitation, including malfunctioning disposal system, and an overall unhygienic environment in the city, which have created ideal breeding grounds for mosquitoes and other disease vectors." [19]. Given the challenges in Karachi, we felt a 'Cleaning Programs Index' of 0.3 (ranging from 0 to 1) and a 0.2 for 'Sanitation Checks Index' were reasonable.

Awareness about dengue is also a big issue. Even though Karachi is a metropolitan city and the economic hub of Pakistan, a large part of the population is uneducated. Although here the concern is not on the lack of education, it is more focused on the lack of basic health education that does not require much time and training to learn. A survey in Karachi revealed that while 72% of students knew mosquitoes cause dengue, only 13% were aware of the mosquito's biting times, indicating a gap in comprehensive awareness [7]. Again, given the partial awareness, an Awareness Programs Index of 0.15 seemed reasonable.

It is easy to observe that the interventions are being kept low to allow for experimentation and checking whether the increase in such intervention schemes produces fruitful results in terms of reducing dengue transmission.

The 'Interventions Index' and 'Elimination of Breeding Sites' flow was then calculated as follows:

Interventions Index Formula

Interventions Index = (Awareness Programs Index + Cleaning Programs Index + Sanitation Checks Index) / 3

Elimination of Breeding Sites Formula

= Base Elimination Rate * (1 + ((Drainage Index * Waste Disposal Index * Interventions Index)))

4 Results

To analyse dengue transmission in Karachi, a system dynamics model was developed and simulations were run under various environmental and intervention conditions as shown in **Figure 6**. The initial set of values was used to establish a **reference scenario**, which helped provide a baseline for comparison with later experimental runs. As the model is complex and encompasses a large set of features and control variables, our results show only a subset of the possibilities. We encourage readers to test out the model by implementing it using the instructions in Section 3.

4.1 Reference Scenario

The first simulation used default values for all sliders. This served as a reference case, simulating an average year in Karachi with no extreme conditions or interventions. Over time, mosquito populations and breeding sites increased steadily. Infections rose month by month, and the susceptible population declined gradually. This confirmed the basic structure of the model: that even under standard conditions, Karachi's dense population, warm climate, and stagnant water sources allow dengue transmission to grow over time if left unchecked.

4.2 Temperature Effects

Simulations with varying temperature levels showed the importance of climate in the dengue cycle. At 34°C, mosquito births and infections increased consistently, supporting the notion that this is within the optimal range for *Aedes aegypti*. When the temperature rose to 40°C, the mosquito death rate increased, as shown in **Figure 7**, and total mosquito deaths per month also grew, slowing population growth. At 20°C, both mosquito births and infections reduced, suggesting that cooler months in Karachi naturally suppress dengue activity. These results align with Karachi's seasonal trend of rising dengue cases in the summer and sharp declines in the winter.

4.3 Water Storage and Breeding Sites

The Water Storage Index was tested at values of 1.0 and 1.5 to reflect different levels of open water storage. As shown in **Figure 9** With an index of 1.5, there was a clear acceleration in the growth of mosquito breeding sites, which led to higher mosquito births and more infections. This supports concerns in Karachi where frequent water supply issues lead households to store water in open containers—creating ideal mosquito habitats.

4.4 Waste Disposal and Drainage Infrastructure

Both the Waste Disposal Index and Drainage Index were varied to examine their impact. Lower waste disposal effectiveness (index 0.2) resulted in more breeding sites and increased infections as shown in **Figure 10**, while a value of 0.6 kept the mosquito growth more contained. Similarly, a Drainage Index of 0.9, as shown in **Figure 12** showed moderate growth in breeding sites and infections, whereas a further reduction to 0.7 led to a noticeable increase in both as shown in **Figure 11**. This demonstrates how even small decreases in drainage performance can have a substantial impact on dengue transmission in Karachi, where blocked drains and stagnant water are common in many neighbourhoods.

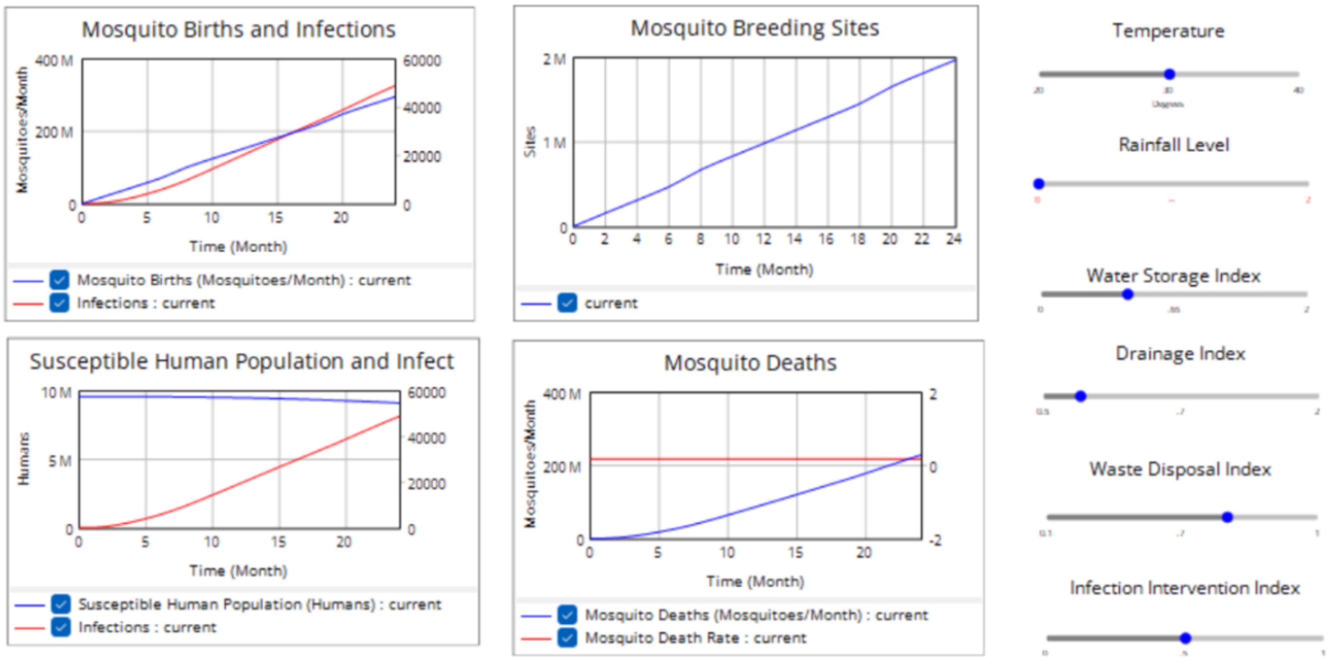

Figure 6: Reference scenario with all default values.

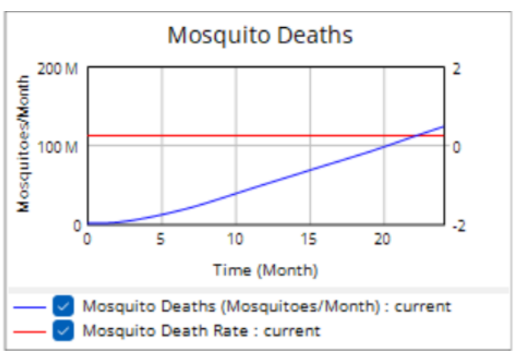

Figure 7: Mosquito deaths increase significantly at 40°C.

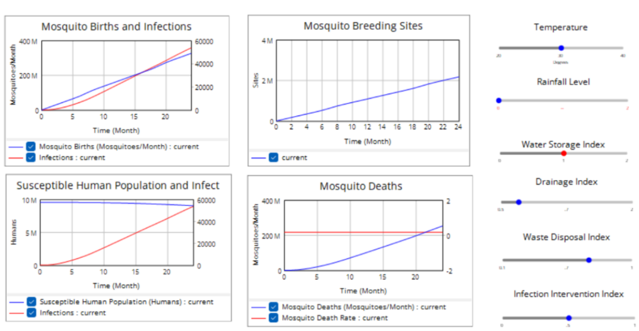

Figure 8: Water Storage Index = 1.0

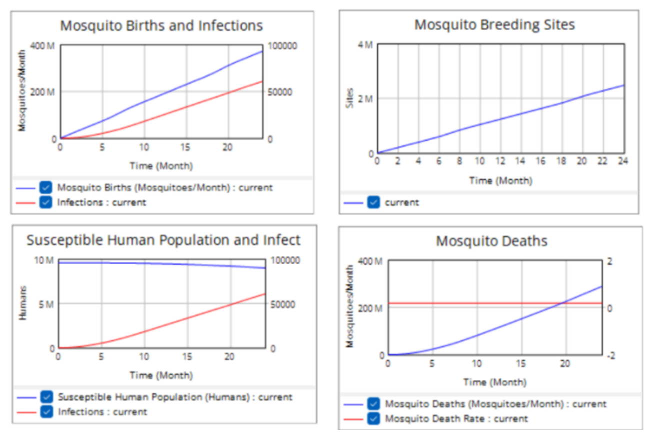

Figure 9: Water Storage Index = 1.5 increases breeding and infection rates.

4.5 Infection Intervention Index

This index was tested to simulate the impact of fogging, awareness campaigns, and other intervention efforts. At a low value of 0.2, infections continued rising sharply over time, as shown in **Figure 13**. As the index increased, infections decreased steadily. Between an index of 0.5 and 0.8, infections dropped from around 5,000 to approximately 2,500 per month, as shown in **Figure 14**, showing that stronger interventions significantly reduce new infections—but do not completely flatten the curve. Instead, they reduce the slope of growth. This highlights that interventions are effective, but only part of a broader solution.

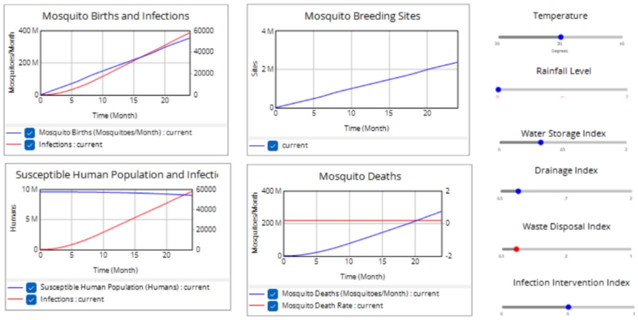

Figure 10: Waste Disposal Index = 0.2 increases breeding and infections.

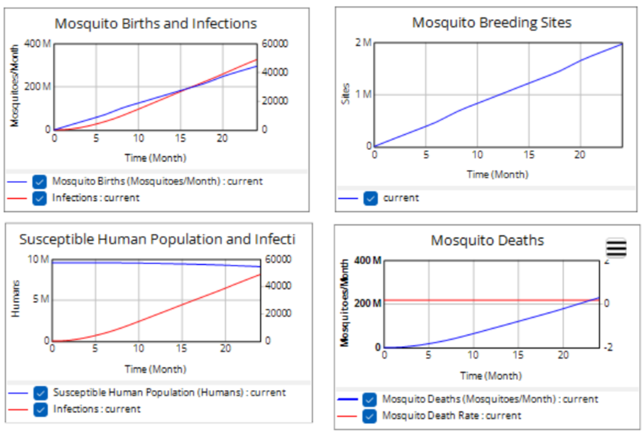

Figure 11: Drainage Index = 0.7 (poor drainage).

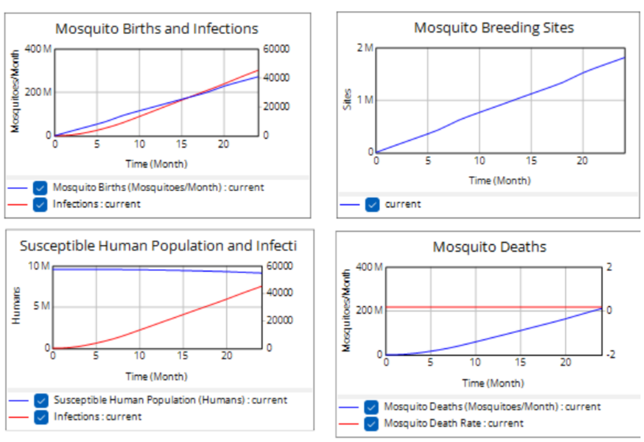

Figure 12: Drainage Index = 0.9 (improved drainage reduces breeding).

4.6 Interpretation

These experiments show that dengue outbreaks in Karachi are driven by interconnected environmental and social factors. The system dynamics model offers a way to simulate these factors over time and explore their cumulative effects. Key insights include:

- Temperature and rainfall set the conditions for seasonal outbreak risk
- Water storage and poor waste disposal directly increase breeding site formation
- Drainage infrastructure improvements and fogging interventions can meaningfully reduce infections
- Stronger interventions reduce infections, but their impact is amplified when combined with improved urban conditions

Rather than relying on one-time responses, the model shows that continuous and multi-layered interventions are needed. By testing different combinations of policies and environmental states, the model gives city planners a clearer picture of how to allocate limited resources to achieve maximum impact against dengue.

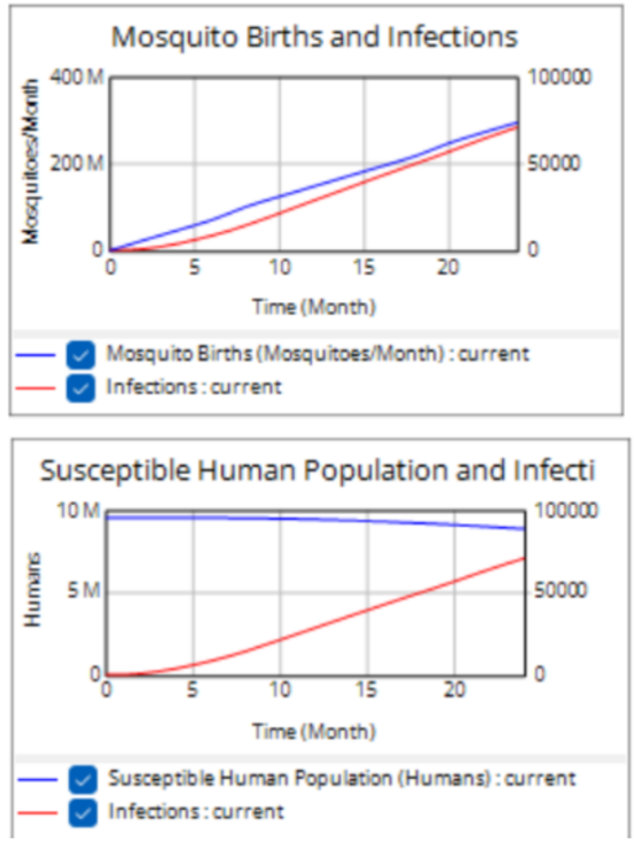

Figure 13: Infection Intervention Index = 0.2 (minimal intervention).

5 Limitations and Future Work

While the model provides valuable insights into the transmission dynamics of dengue in Karachi, several limitations should be acknowledged. First, the availability of detailed, centralised and reliable data remains a significant constraint. Many of the variables used in the model were represented using indexes derived from general assumptions, public reports, or scaled approximations. More

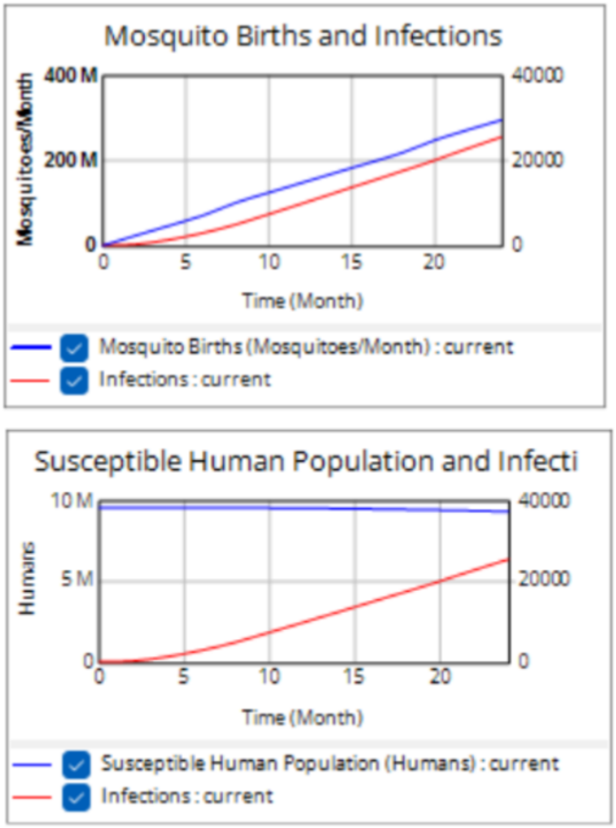

Figure 14: Infection Intervention Index = 0.8 (moderate reduction in infections).

granular, quantitative data would allow for finer calibration of these parameters and improve the model's predictive accuracy.

Second, the model assumes dengue as a uniform disease entity, without accounting for its clinical variability or the presence of multiple serotypes. In reality, dengue is often curable with timely intervention and supportive care, and many cases may remain asymptomatic or self-resolving. As a result, the modeled infection burden may reflect theoretical spread rather than actual real-world impact. We would like to add more factors in the model and if possible, explore the inter-relations or 'intra-effects' between the current variables, see if there are any confounding variables, to allow for a more holistic understanding of dengue outbreaks.

Third, although the interventions tested, such as fogging, public awareness campaigns, and drainage improvements, performed as expected in reducing infections, the model assumes a relatively moderate base infection rate in the absence of interventions. This limits the observable impact of any one intervention. In real-world scenarios where outbreaks are more severe, the urgency and effectiveness of interventions could vary considerably. Therefore, for meaningful long-term impact, more permanent solutions such as infrastructure upgrades and improved urban planning should be prioritized over temporary or short-term solutions like the ones proposed in the model.

Finally, while the model structure was capable of capturing core dynamics, it did not explore latent feedback mechanisms or inter-variable dependencies in depth. For example, the model currently assumed that once a human has recovered, they are immune to any future dengue infections, something that is not necessary and should be looked into further.

Future models could explore partial immunity, delayed reinfection, and confounding effects to further improve realism and policy relevance. Future work could also focus on exploring the interdependencies between variables, identifying possible intra-variable effects, and testing for confounding factors that may be influencing the system.

6 Conclusion

This study demonstrates the value of system dynamics modeling in understanding and simulating dengue transmission in a complex urban environment like Karachi. By simulating key interactions between mosquito population dynamics, environmental conditions, infrastructure quality, and public health interventions, the model provides a comprehensive view of how outbreaks emerge and evolve over time.

The results show that no single factor drives transmission in isolation. Instead, dengue outbreaks are the outcome of multiple reinforcing feedback loops involving breeding site creation, temperature-dependent mosquito activity, and public responses. Scenarios with poor drainage, inadequate waste disposal, and open water storage showed a sharp rise in mosquito populations and infections. Conversely, improvements in these areas significantly reduced the number of breeding sites and delayed the increase in infections. Simulations also indicated that while intervention campaigns, such as fogging and awareness drives, can reduce infections, their impact is maximized when combined with strong improvements in the foundations of the drainage and waste management systems and facilities (increasing the base rates).

Overall, the model highlights the importance of sustained, multi-pronged strategies in urban mosquito control for Karachi. Reactive interventions during outbreak seasons are not enough; proactive infrastructure planning, consistent community engagement, and integrated public health efforts are necessary to break the transmission cycle. This modeling approach offers a useful support tool for decision makers seeking to allocate resources effectively and reduce the long-term burden of dengue in Karachi and other high-risk urban centers, an example being Lahore which also has a history with dengue.

Ultimately, we believe the model offers a foundation for further refinement and application in public health planning.

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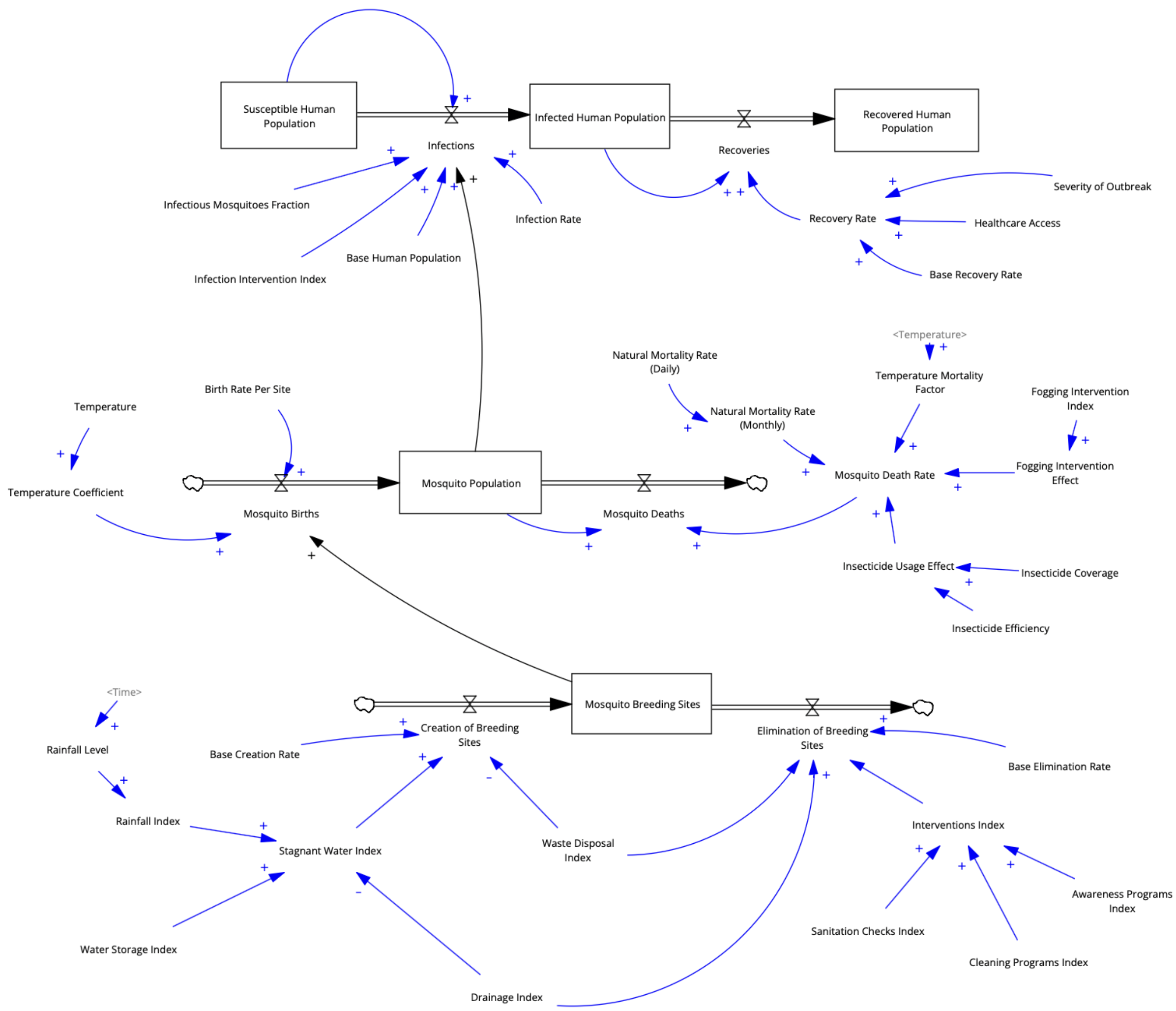

Figure 15: Model for Dengue Outbreak Dynamics