

# Evaluating epidemic intervention policies with systems thinking: A case study of dengue fever in Mexico

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## Abstract

In developing national epidemiological control strategies, understanding the environment in which an epidemic develops, the complex interrelationships of the relevant variables and their resulting behavior requires responsible health decision makers to develop comprehensive, effective policies. Systemic decision models can help managers understand the impact of alternative strategies for addressing disasters such as national epidemics. This paper discusses an interactive, systemic decision model developed in the Secretariat of Health of Mexico, at the advisory level, highlighting how the change in decision-making perspective provided valuable insight into strategically managing the control of dengue, a potentially catastrophic epidemic. Copyright ©1999 John Wiley & Sons, Ltd.

*Syst. Dyn. Rev.* **15**, 119–138, (1999)

By 1998 dengue has emerged as a major source of hospitalization and death (Gubler 1998: 446). Dengue, a mosquito-transmitted virus, causes a high fever accompanied by significant pain in the afflicted patient. The *aedes aegypti* mosquito is the primary disease carrier. Four closely related, but antigenically distinct, serotypes of dengue have been identified in the world (DEN-1, DEN-2, DEN-3, DEN-4). Dengue is of the genus *Flavivirus*. Though non-lethal in isolation, when combined the serotypes may cause dengue hemorrhagic fever/dengue shock syndrome (DHF/DSS), which is highly lethal (Gubler and Clark 1995). In Mexico, millions of people have been infected with DEN-1, to which they are now immune. If a mosquito carrying DEN-1 bites them in the future, nothing happens. If a mosquito carrying DEN-3 bites them, there is a high probability that they will develop DHF/DSS (Rawlings *et al.* 1995). The fatality rate for DSS can reach 44% (CDC 1998: 546). Over 16 million Mexicans have had and are immune to DEN-1 or DEN-2; thus they are at risk of getting DHF/DSS, if infected with another serotype. DEN-3 had been identified in Honduras. If this serotype were to enter Mexico, the impact could be catastrophic, under the existing epidemiological control system (Méndez Galván 1994).

To address the global problem of dengue, health organizations worldwide have invested heavily in researching the multiple causes and agents of transfer of this disease; yet to date there is no known vaccine or medicinal cure (Gubler and Clark 1995; Holmes, Bartley and Garnett 1998). Further

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System Dynamics Review Vol. 15, No. 2, (Summer 1999): 119–138

Received November 1997

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compounding the problem, the *aedes aegypti* mosquito is very difficult to eradicate. Four characteristics of this problem supported the Secretary of Health Advisory Board's use of a model-based approach:

- the great dynamic complexity of this highly dynamic disease;
- the multiple expert opinions on how to control the disease most effectively;
- its potential for devastation;
- the reactive political attitude toward its potential for spreading.

The project intent was four-fold:

- to integrate the multiple political, environmental, social and structural variables into a single strategic causal model;
- to establish and evaluate alternative intervention policies that integrate expert understanding;
- to test the different strategic, epidemic-control hypotheses;
- to communicate the findings in the most logical, concise and comprehensive manner.

### Problem description

As a result of the heavy workload carried by a relatively small staff of highly experienced health administrators, many decisions made in the health sector, affecting millions of citizens, are made under less than optimal decision-making conditions with less than perfect knowledge and decision models. The traditional decision-making approach at the Secretariat of Health (see Table 1) entails:

1. listing strategic variables and values (i.e., mosquito density, reported incidents over time, epidemic outbreak risk, control intervention costs);

Table 1. Traditional, intuition-based decision making

Rational task	Elements of task that challenge human cognitive abilities
List variables	What elements should be included and how they are related to each other?
General alternatives	What are the key assumptions underlying the interrelated elements in different scenarios?
Analyze alternatives	Are the alternative strategies internally consistent and consistent with each other? Are short-term and long-term strategies consistent with each other? Which policies provide the highest systemic leverage (Ritchie-Dunham 1998) over time?
Select alternative	Which criteria provide for the consistently 'best' alternatives?

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2. generating strategic decision alternatives (i.e., no financing during non-critical periods, pathology research, educational campaigns, control mechanism efficiency);
  3. analyzing political-budgetary decision alternatives (i.e., opportunity costs of spending versus political costs);
  4. selecting the most feasible strategy.

Some smart people meet, discuss the issues and decide. This traditional approach requires decision makers to integrate the interrelated effects of these decision factors and associated assumptions intuitively, in their heads; research has shown this to be cognitively difficult at best (Sterman 1989; Simon 1997). Though traditional decision-making methods, such as the classical rational analysis model (Barnard 1968) used at the Secretariat of Health, may be valid, research on organizational approaches to policy decision making shows that many organizations do not necessarily follow a simple causal sequence, often creating internally inconsistent strategies (Cyert and March 1963; Eisenhardt and Zbaracki 1992).

Since budgetary constraints significantly limit the ‘investment’ necessary for preventive measures, historically much of the epidemic control in Mexico has been reactive. During epidemics, this reactive nature has proven very expensive, inefficient, and ineffective in terms of lives and intervention resources (Gubler 1998). In short, the control mechanisms used to date have been less than totally effective as a result of limited budgetary resources and decision models caused by a short-term focus, high costs and an attitude of political appeasement—evidenced by recurring outbreaks of malaria and cholera.

This paper describes a model-based approach used to understand and improve national health intervention policy for effectively addressing epidemics. For health administrators to develop more rigorous policies to attack this complex problem, the problem situation needed to be modeled and presented as a clear paradigm. Clarity was required because long, jargon-filled medical presentations would be too difficult to communicate to the key decision makers, and therefore would be summarily dismissed. The case study shown in this paper was developed for Mérida, Yucatán in southern Mexico.

### **Application of system dynamics concepts**

System dynamics modeling allows the integration of multiple political, environmental, social, and structural variables into a single model. System dynamics models also calculate the behavior of all the variables in the system, allowing

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policies to be tested (Forrester 1961). The system dynamics modeling methodology has been applied many times to the health sector and proven itself in resolving complex, systemic issues (Levin, Roberts and Hirsch 1975; Homer and St. Clair 1991; DeMello 1993).

The modeling team included three members of the Secretary of Health Advisory Board: a dengue epidemiologist, a health care administrator, and a system dynamics modeler. The Advisory Board gave the team two weeks to deliver insightful ideas. The epidemiologist and the health care administrator worked half-time and the system dynamics expert full-time on the project for eight days, spending three days on the causal loop diagram, one day on causal loop diagram analysis, and four days on the stock-flow model.

The system dynamics methodology used in this case study begins with a causal loop diagram (CLD) exercise, continuing on to an analysis of the CLD, followed by a stock-flow simulation, results, and recommendations. These stages are explored in detail below.

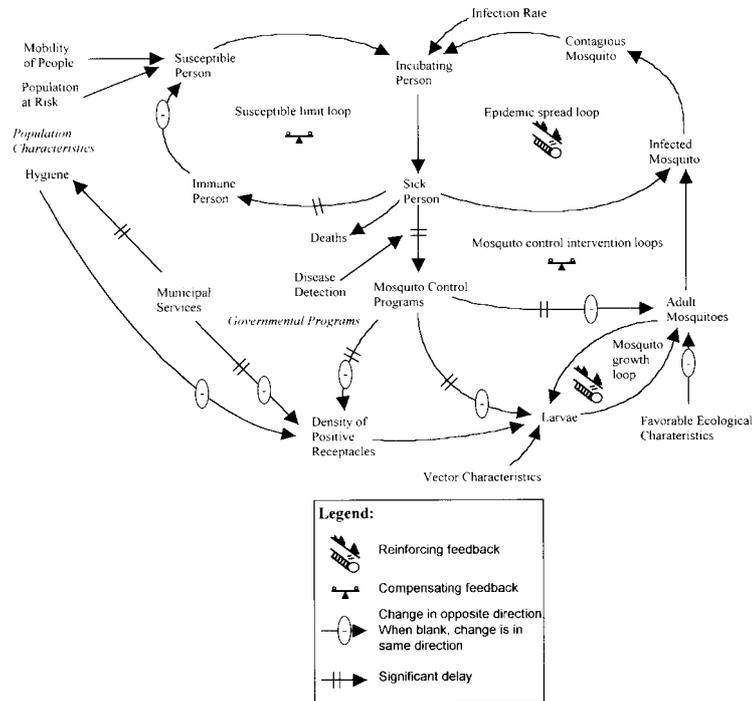
### *Causal loop diagram*

Model development began with the integration of key strategic decision variables from a Secretariat of Health report on dengue (Méndez Galván 1994) and interviews with epidemiological experts in the Secretariat of Health. The 125 variables captured during this process were divided into 19 categories. The modeling team mapped out the causal structure of these 19 high-level variables, as captured in the CLD in Figure 1. This CLD depicts the dynamics resulting from interrelating mosquitoes, humans, a virus, and government intervention policies. Specifically, these dynamics explain the entrance of a new serotype into a susceptible population. In this case study, the susceptible population is immune to DEN-1 and susceptible to DEN-3.

This CLD shows that some inherent reinforcing feedback loops accelerate the spread of the disease and some inherent compensating feedback loops slow the disease.<sup>1</sup> The high mosquito to person ratio facilitates rapid transmission, thus requiring the introduction of control interventions. The CLD shows these control interventions as programs that attack the adult mosquito and larvae populations, as well as the receptacles in which the mosquito lays its eggs (Ortiz Quesada *et al.* 1995).

Starting with the epidemic spread loop in the CLD in Figure 1, the undetected entrance of a dengue-carrying Sick Person into a region of high mosquito density provides fertile ground for an epidemic. Because of the high mosquito density, the Sick Person is bitten by an Adult Mosquito. This infected Adult Mosquito becomes Contagious after a few days and bites a person from

Fig. 1. The CLD shows reinforcing and compensating feedback loops inherent in the epidemic

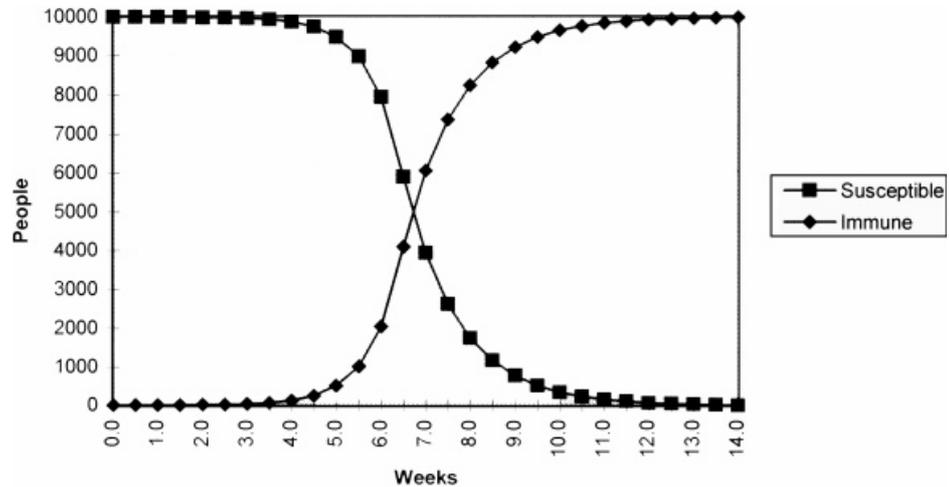


the Susceptible Human population. The infected person becomes an Incubating Person, and then a Sick Person after a brief period of time. When this Sick Person is bitten by a female Adult Mosquito, the cycle starts over again.

This epidemic spread loop accelerates the rate of Susceptible Persons being infected, until it reaches ‘limits to growth’, when the Susceptible Population is emptied. This is captured in the compensating Susceptible Population loop. This dynamic causes S-shaped behavior in the Susceptible and Immune Populations (see Figure 2).

The population dynamics of the mosquito, a key element in the Epidemic spread loop, are reflected in the reinforcing Mosquito growth loop and the compensating Mosquito control intervention loops. In the Mosquito growth loop, as more (fewer) Adult Mosquitoes lay more (fewer) Larvae, the Larvae become more (fewer) Adult Mosquitoes after a brief maturation delay, thus the reinforcing nature of the loop. One female can, in one summer, leave behind a few billion descendants (Taubes 1998). The reinforcing growth implicit in the mosquito population is relatively offset by natural and human ‘controls’. Ecological conditions, such as high winds and temperature changes, control the growth of the mosquito population, by killing most of the population every day.

Fig. 2. The S-shaped behavior in the Susceptible and Immune Human populations, resulting from the initial exponential growth of the epidemic in the population, which is later limited by fewer and fewer susceptible people



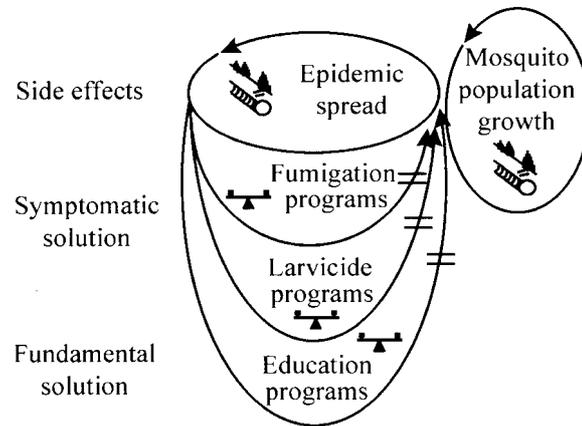
Human living conditions contribute to the mosquito growth dynamic. In the tropical regions where dengue is most prevalent, many people still have no access to running, sanitized water, and store water in stagnating receptacles. Inadequate refuse collection systems lead to piling up of refuse, such as tires and cans, typical of many homes in these regions (Gubler 1998). These receptacles provide ample refuge from the changing ecological conditions, idea for the mosquito to lay eggs. This lack of Hygiene and Municipal Services increases the Density of Positive Receptacles.

To control the epidemic, health officials can use Mosquito Control Programs, Positive Receptacle Removal, and Disease Detection. Mosquito Control Programs attack the Adult Mosquito population by fumigating and the Larvae population by dispersing larvicides in Positive Receptacles, killing the larvae in the receptacle. Positive Receptacle Removal programs educate people to remove from their houses the rubbish in which the mosquitoes lay their larvae. Disease Detection programs educate medical personnel to send in to reputable laboratories laboratory tests for patients with suspicious symptoms, and then to notify authorities of dengue cases in a timely fashion.

#### *Causal loop diagram analysis*

Historically the Secretariat fought the dengue outbreaks through fumigation and larvicide intervention programs, but this did not eliminate or control outbreaks, and often resulted in human deaths and high health costs. These fumigation and larvicide programs are 'symptomatic' solutions.

Fig. 3. Shifting the burden archetype



Experts have long proclaimed that the fundamental solution to controlling mosquito-transmitted epidemics requires a four-pronged approach:

1. Provide running water and efficient refuse pickup services (Brandling-Benett and Pinheiro 1996).
2. Educate medical staff to recognize and treat the disease.
3. Install a quick-response, national disease detection information system.
4. Deter sick people with dengue from entering the country.

These are 'fundamental' solutions. The efficiency of this fundamental approach was witnessed in the U.S.A. at the same time as DEN-3 was identified in Honduras. Dengue was detected in Texas with three cases, which were immediately quarantined, and the whole area was heavily fumigated, resulting in no outbreak (Rawlings *et al.* 1995). Unfortunately, many developing countries such as Mexico lack the infrastructure and budget to provide for such a 'quick response' fundamental solution (Gubler 1998). This fundamental versus symptomatic approach follows the 'shifting the burden' archetype (see Figure 3). By focusing on killing the mosquitoes (alleviating the symptoms) and not on education of the masses, the Secretariat was inadvertently making the fundamental education solution more difficult to achieve as people now associated disease control with heavy fumigation and larvicide interventions and would expect them again. This archetype teaches us to focus on the fundamental solution instead of solely on the symptomatic solution, and that a temporary symptomatic fix may be necessary to gain momentum in the desired, long-term direction.

Inspection of the CLD shows that epidemic control hinges on controlling the mosquito population and the sick human population. The strongest control of

the mosquito population comes from removing the receptacles where they lay their eggs: the rubbish in the yard and house. Control in the human population centers on isolating the sick person from the mosquitoes. In this light the advisory board determined that the best short-term solution, that would strengthen the long-term solution, would be to educate the masses to clean up their refuse, and to advise medical staff in high-risk regions.

#### *Stock-flow model*

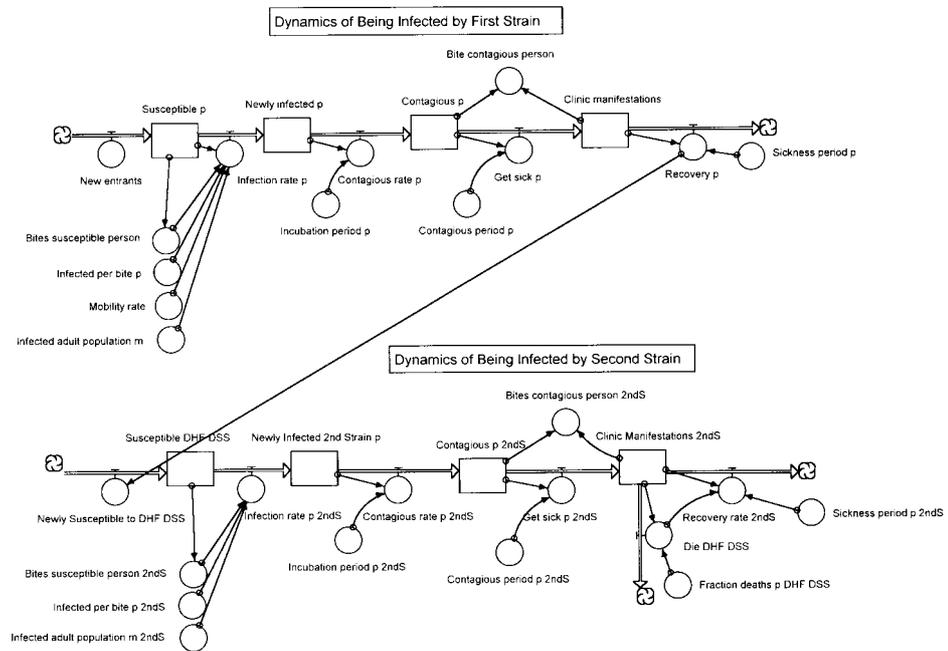
A mathematical simulator was then developed to test the effect of different Secretariat decision policies and hypotheses.<sup>2</sup> When the modeling team evaluated the trade-off between the time to develop the mathematical model, four days, and model predictive ability, they decided that, because of the decision urgency, this model should include sufficient detail to capture the epidemic's behavior within numerical ranges that seemed reasonably close to the epidemiologist. Forrester (1961) supports this approach to precise versus accurate models, especially for the model objectives set by the team, as presented earlier in this article.

This modeling exercise allowed the modeling team simultaneously to investigate in greater detail the relationships between multiple control policies and the short- and long-term effects of changes in certain control policies. Simulation also permitted the team to evaluate the performance that recommended policies would have on the system under various scenarios. The stock-flow model, based initially on Kalgraf's (1988) yellow fever model and Anderson and May's (1995) treatise on disease dynamics, includes four major subsections: humans, mosquitoes, intervention policies, and costs. Whereas the model could be aggregated to four stocks (sick people, adult mosquitoes, positive receptacles, and total costs), the modeling team included more detail to test different hypotheses about the core dynamics around each key component of the epidemic. Each subsection is discussed below.

The human submodel (see Figure 4) describes how an epidemic spreads through the human population, from its initial entrance to its development and demise, as well as the introduction of a second serotype. Given a high ratio of mosquitoes to humans from April to October, in the case study, one non-isolated sick person can kick off the whole epidemic; thus the Sick Person is the most influential variable in the model. During the winter months, when the mosquito population is lowest, due to the cold, the resulting low ratio of mosquitoes to humans lowers the potential for an epidemic.

With border control difficult at best, contagious individuals can easily enter the country undetected. Also, the virus does not manifest itself as dengue until

Fig. 4. The human submodel simulator shows the status of the evolution of the disease in the human population



the third or fourth day, making it possible for an unsuspecting, ill-feeling person to cross into Mexico without even knowing they are jump starting an epidemic.

The Susceptible Population is affected by the inflow of new entrants, human migration from one area to another, births, and the outflow of people being infected. People are infected at a rate determined by the ratio of Contagious Mosquitoes to Susceptible Humans, the ratio of female to male mosquitoes (only female mosquitoes bite humans), the frequency with which female mosquitoes bite, and the percentage of bites that spread the virus. Dengue evolves in the human, with the Newly Infected Human becoming Contagious after an incubation period. The person then becomes sick, expressing Clinic Manifestations after a contagious period.

After recovering from the first serotype, people become immune to it, but susceptible to DHF/DSS when exposed to a second serotype. The dynamics are the same for the second serotype until there are Clinic Manifestations; while the probability of death from the first serotype is negligible, with the second serotype the probability of death from DHF/DSS increases to 15%.

The human submodel interacts directly with the mosquito submodel through two points:

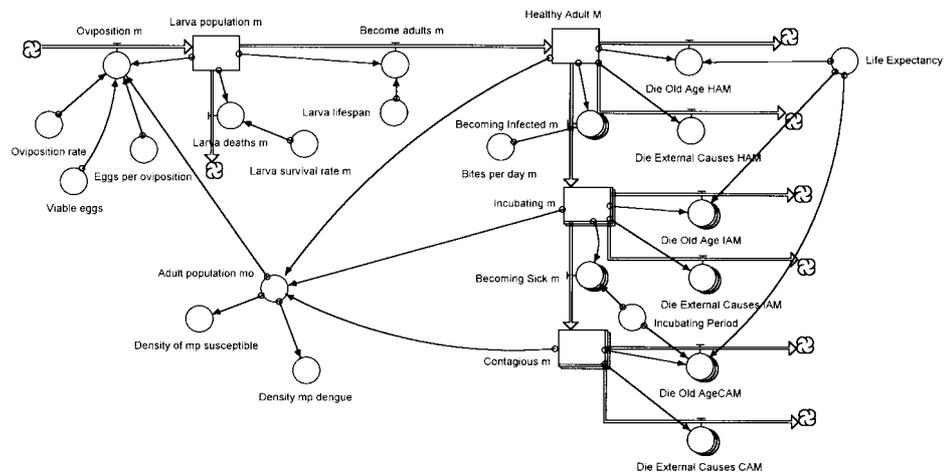
- the contact of mosquitoes with contagious humans;
- the contact of contagious mosquitoes with susceptible humans.

For the area being modeled, a section of Mérida, Yucatán, this model assumes a relatively high human population density, facilitating the epidemic spread. Based on this assumption, the model excludes mosquito migration and human interaction dynamics.

As stated above, early detection and isolation of sick people represent key determinants in controlling the epidemic. In Mexico, with slow medical reporting mechanisms in the poor rural areas, the epidemic can be well on its way before it is detected. Detection is further frustrated by inadequate training of medical staff in rural areas as to disease detection, and the lack of laboratory testing facilities, as well as the need for the patient to be seen twice to determine positively that the disease is dengue. Earlier detection, such as the four-hour immediate dangerous disease alert system in the U.S.A., would allow quick responses to outbreaks, but these systems are very expensive and require extensive training.

The mosquito submodel (see Figure 5) describes the mosquito life cycle and epidemic development in the Adult Mosquito population. The mosquito's age, incubation period, and contagious period must all be measured, since the mosquito may come into contact with the virus at any age and this affects the amount of time during which the mosquito can infect humans. In Mérida, studies show that the mosquito lives up to 30 days, depending on climatic changes and food availability (Méndez Galván 1994). If a 25-day-old mosquito bites an infected human, the mosquito would acquire the virus and incubate it for the next seven days before it can pass the virus to a human. This mosquito would most probably die of 'old age' before infecting a human. The Adult

Fig. 5. The mosquito submodel simulator shows the status of the mosquito population in the Larvae and Adult Mosquito stages, as well as the development of the epidemic in the Adult Mosquito population



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Mosquito population matrix (see Figure 5) calculates these characteristics for the entire mosquito population.

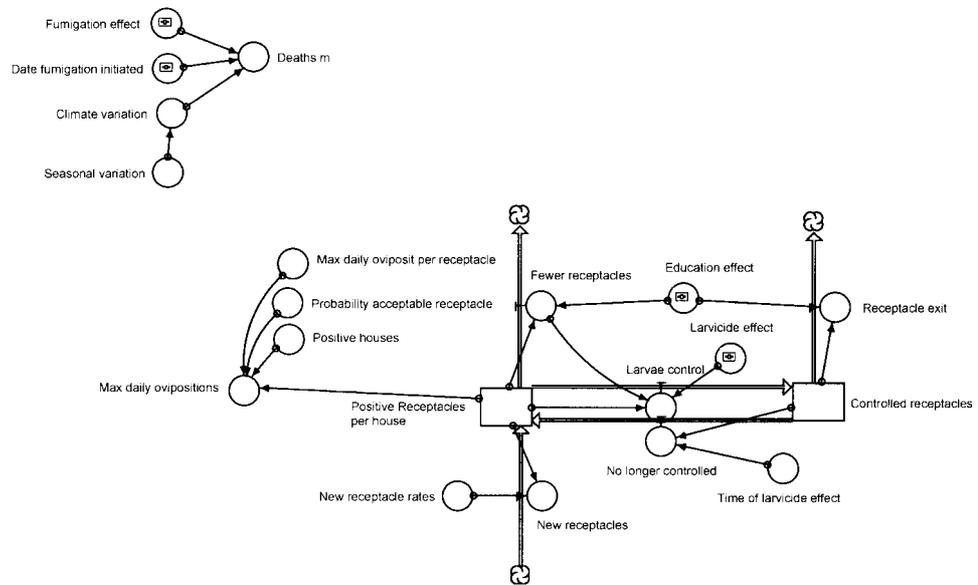
Following the stock-flow model logic, the Larvae population is affected by the inflow of new eggs and the outflow of dying Larvae and maturing Larvae. The inflow of new eggs is a function of the number of female Adult Mosquitoes, how often the female oviposits, the number of eggs per oviposition, and the percentage of viable eggs per oviposition. This level of detail allowed the modelling team to test different hypotheses about mosquito characteristics, which differ significantly from one type of mosquito to another (e.g., *aedes albopictus* versus the *aedes aegypti*). The outflow of dying Larvae is determined by Larva survival rate. The outflow of Larvae maturing into adulthood follows a brief maturation period.

The Adult Mosquito population contains three stages of development of the epidemic: Healthy, Incubating and Contagious. The Healthy Adult Mosquito population is affected by the inflow of maturing Larvae and the outflows of Adults Becoming Infected, Adults Dying of Old Age and Adults Dying from External Causes. Healthy Adult Mosquitoes Become Infected when they bite a Contagious or Sick Person. Healthy Adult Mosquitoes Die of Old Age, if they live that long. Healthy Adult Mosquitoes Die from External Causes, which can be induced either by changing ecological characteristics or by mosquito control programs. The Incubating Adult Mosquito is affected by the inflow of mosquitoes Becoming Infected and by the outflows of Becoming Sick, Dying of Old Age and Dying from External Causes. They Become Sick after an Incubating Period. They die from the same mechanisms as the Healthy Adult Mosquitoes. They do not die from dengue, probably because they do not live long enough. Likewise, the Contagious Adult Mosquito is affected by the inflow of mosquitoes Becoming Sick and the outflows of Dying of Old Age and Dying from External Causes. They die from the same mechanisms as the Healthy and Incubating Adult Mosquitoes.

This fast-growth, fast-death cycle results in a relatively stable mosquito population during the warm months in Mérida from April to October. However, in the colder months the mosquito population shrinks significantly, as a result of the higher death rate from ecological conditions. The population remains relatively low until the start of the warmer months (Méndez Gálvan 1994).

The mosquito control alternatives submodel (see Figure 6) describes the effect of different intervention strategies. The model divides the control alternatives into two subsections: fumigation and climate, and receptacle control. In the upper left-hand corner, the model calculates the deaths resulting from fumigation and climate variation. The number of Adult Mosquitoes killed by fumigation programs is determined by the Fumigation Effect, how well the

Fig. 6. The mosquito control alternatives submodel simulator shows how different intervention policies affect the mosquito population



fumigation program works, and when the program is initiated. The Adult Mosquito population killed by Climate Variation depends on seasonal variation in temperature and wind speeds.

The Receptacle Control subsection models the effects of education and larvicide intervention programs. Following the stock-flow model logic, the number of Positive Receptacles per House is affected by the inflows of new receptacles and receptacles no longer controlled by larvicides, and by the outflows of removing receptacles and protecting receptacles. New Receptacles represent the increasing amount of garbage that collects in the house and near it. Receptacles are no longer controlled by larvicides after the larvicide effect diminishes. Receptacles are removed by the impact of the Educational programs teaching people to keep their homes clean. Receptacles are also protected by larvicide. The number of Controlled Receptacles is affected by the inflow of receptacles being controlled by larvicide, the outflows of receptacles no longer being controlled by larvicides, and those that are removed as a result of education programs. This model shows that larvicide programs may be helpful for large water systems such as septic tanks, but the strongest effects come from picking up the garbage and from creating less garbage. Though seemingly obvious, consumer products are increasingly more 'disposable' and refuse-collection infrastructures weaker (Gubler 1998). Initial attempts at educating the people to remove these positive receptacles have met with some success and are relatively inexpensive (Folkers *et al.* 1998).

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The low efficiency of these expensive equipment and labor-intensive larvae and mosquito control programs, as low as 15–20% eradication, indicates that controlling the mosquito population is non-trivial, as evidenced historically. The problem is worsened with the realization that the mosquito lives in homes, where it is protected from the environment. Most of the mosquitoes outside are killed by changing temperature, winds, or predators. Protecting houses from the environment provides a safe refuge for the mosquito, almost nullifying the effect of airplane and truck-sprayed fumigation techniques.

Larvicides are also largely unsuccessful as they require the brigades to find all possible places for the mosquito to lay eggs. A few studies have indicated that brigades identify approximately 20% of the positive receptacles in a home (Méndez Galván 1994). Whereas Larvicide strategies render Positive Receptacles ‘controlled’ for an assumed six months, Educational strategies remove Positive Receptacles from the system. The Larvicide and Educational strategies combine to affect the number of Positive Receptacles where female Adult Mosquitoes lay eggs, affecting the Maximum Daily Ovipositions, which affects the Oviposition\_M inflow to the Larvae stock.

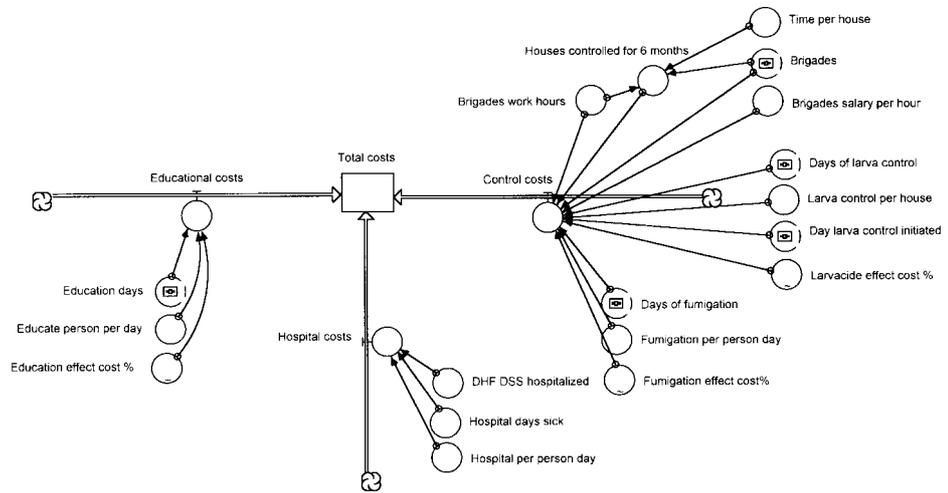
The cost submodel (see Figure 7) describes the overall and partial cost implications of different epidemiological control intervention strategies, including:

- larvae control through larvicide distribution;
- adult mosquito control through fumigation;
- available egg-laying receptacle control through education programs;
- the medical cost of treating infected humans as a result of lack of epidemic control.

Costs are measured in pesos, and are accumulated over the whole period of the model to test the overall long-term costs of each alternative. Each intervention policy is linked to the mosquito control alternatives submodel.

Each submodel was tested separately by the epidemiologist, verifying the logic and the results the submodels gave under varying conditions. This resulted in the fine tuning of some parameters and minor alterations of the structural logic of the submodels. When the epidemiologist was satisfied with the results obtained in each submodel, the whole model was tested for the speed of spread and the level of severity of the epidemic, under varying conditions. The results fell within what the epidemiologist considered realistic ranges, based on knowledge of other outbreaks. This approach of validating the model based on expert logic checks is founded on the earlier discussion of precisely mapping expert knowledge versus accurately matching history, and on the limited time available.

Fig. 7. The cost submodel simulator showing the partial costs in Mexican pesos of epidemic control as they contribute over time to the total cost



The learning laboratory (see Figure 8) provides a user-friendly interface to the stock-flow model. To enhance understanding of the behavior seen, the learning laboratory provides access to the underlying stock-flow model, when the downward-pointing triangles on the right-hand side of each control lever are clicked. This learning laboratory allowed the modeling team to test multiple working hypotheses in an easy-to-interpret format. The modeling team used the

Fig. 8. The learning laboratory provides a user-friendly interface to the stock-flow model, with which health administrators test different intervention strategies

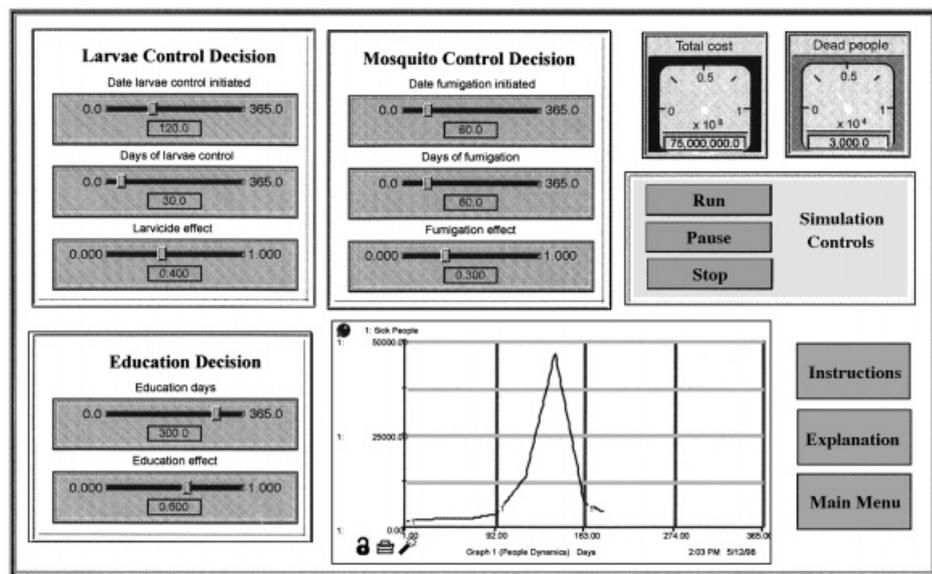


Fig. 9. The scenario initialization screen in the learning laboratory allows the user to set up the model to run under different scenarios

Cost Information (US Dollars)	
Larvicide per home	0.4
Educate person day	0.0
Fumigation per person	0.1
Hospital per person day	437.5
Education effect cost	10.0
Fumigation effect cost	0.0
Larvicide effect cost	4.9

Simulation Information	
Day	271.0
Month	9.0
Simulation year	0.0
Simulation period = 1 Day Beginning date = January 1st	

Serotype 1 Information	
Incubation period p	4.5
Contagious period p	4.5
Sickness period p	2.5

Serotype 2 Information	
Incubation period 1	4.5
Contagious period p 1	4.5
Sickness period p 1	2.5

Population Information	
Population	1,000,071
Persons per house	5.0

Control Programs Information	
Receptacles per house	16.4
Brigades salary per ho	1.3
Brigades work hours	5.0
Time per house	15.0

Dashboard

learning laboratory along with the CLD to communicate the group's findings and proposed intervention policies to the other members of the advisory board and the Secretary of Health. The ability to test a variety of intervention strategies before implementing these strategies in the real world of very expensive fumigation techniques and widespread deadly diseases proved very exciting to the policymakers involved. This is supported by Saeed (1993), who shows that simulation strengthens theoretical understanding of complex social systems through experimental learning.

As an additional feature, the learning laboratory allows the user to set, on another screen (see Figure 9), scenario-dependent policies and model constants on each run.

## Results

The advisory board tested eight intervention strategies in the simulator (see Table 2), varying the degree of Fumigation, Larvicide, and Education campaigns. Fumigation and larvicide campaigns either were started proactively (Early), before the Larvae and Adult Mosquito populations reached critical levels, or were started reactively, Just-in-Time (JIT), when the population had already reached critical levels. Additionally, Fumigation and Larvicide campaigns were either Partial, to control the mosquito population growth, or Full, to eradicate the mosquito population. Education campaigns were either not run (None) or they were run (Full).

Table 2. Simulated intervention strategies

	Intervention strategy			Results	
	Fumigation	Larvicide	Education	Financial efficiency	Elimination effectiveness
1	JIT, Partial	JIT, Partial	None	Low	Very low
2	JIT, Full	JIT, Full	None	Very low	Low
3	Early, Partial	Early, Partial	None	Low	Low
4	Early, Full	None	None	Very low	Low
5	Early, Full	Early, Full	None	Very low	Low
6	None	None	Full	High	Medium
7	JIT, Partial	JIT, Partial	Full	Low	Medium
8	Early, Partial	Early, Partial	Full	Medium	High

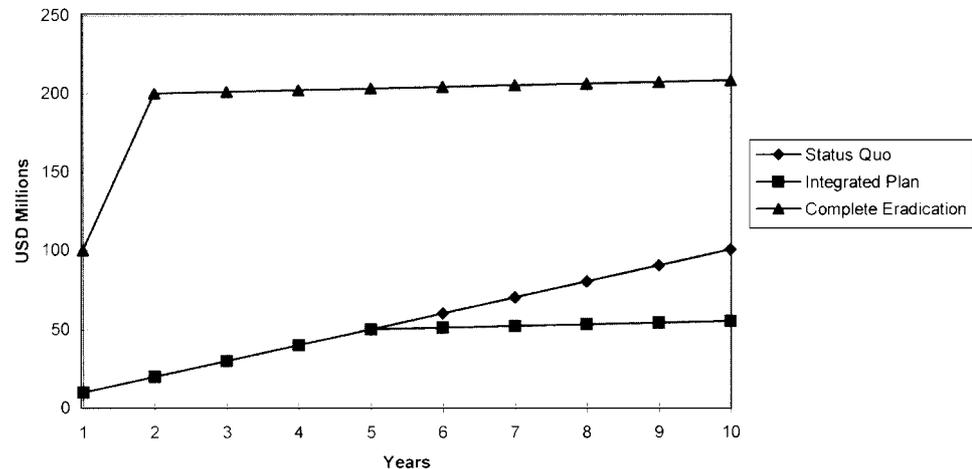
The results were evaluated against two critical performance criteria: disease and mosquito elimination *Effectiveness* and financial *Efficiency*. The extremely limited financial resources available made fulfilment of these two criteria critical. Strategy #8—early and partial Larvicide and Fumigation campaigns with full Educational campaigns—though still resulting in hundreds of deaths, was determined to be the most effective, and financially feasible option, given the very limited financial resources and time remaining for the Secretariat. The Secretary of Health recommended this strategy to the Mexican National Academy of Medicine (de la Fuente Ramírez 1995) and later implemented it.

Subsequently, the project findings were confirmed by similar, independent results presented later by the Pan American Health Organization (PAHO) (1995), showing the estimated costs of three alternatives (see Table 3). The cumulative costs for each alternative over a ten-year period are shown in Figure 10. These numbers correspond closely to those in the simulator. In the Central American Regional Meeting on the Prevention and Fighting of Dengue in Guatemala City, the assembly of seven countries adopted Alternative #2, which provided the highest probability of long-range control of this disease and

Table 3. Three PAHO viable intervention strategies

	Alternative	Estimated costs
1	<b>Status quo.</b> Continue to attack the larvae and mosquito with insecticides heavily.	US \$10 million per year
2	<b>Integrated plan</b> to concentrate on educating the communities to take responsibility for removing positive receptacles from homes, as well as larvae and mosquito preventive insecticide measures	US \$10 million per year for first 5 years; US \$1 million per year for subsequent years
3	<b>Complete eradication</b> of the <i>aedes aegypti</i> mosquito from the region. Remove mosquito and then use preventive measures to prohibit return.	US \$100 million per year for first 2 years; US \$1 million per year for subsequent years

Fig. 10. The cumulative costs associated with the PAHO intervention strategies over a ten-year period



its transmitter. Alternative #2 closely resembles Strategy #8 from the Advisory Board project.

## Conclusions

Most policy-level decisions are made in the absence of a complete understanding of crucial variables and their interrelationships, independent of the decision's importance or the decision maker's abilities. The system dynamics modeling exercise enabled the advisory board to the Mexican Secretary of Health to integrate multiple expert viewpoints on a very divisive issue into a concise model that enabled the board to communicate to the Secretary of Health a comprehensive understanding of the prioritized critical issues and feasible solutions, in a very short time period. The Secretary of Health of Mexico chose the CLD (Figure 1) to present his epidemic intervention control strategy to the National Academy of Medicine and International Conference on Dengue (de la Fuente Ramírez 1995), because, as he shared with one of the authors, he felt that the CLD was the tool that provided the most concise, integrated view of multiple issues, with an easy-to-tell story line, for communicating his three-pronged strategy to a large group of experts.

This project provides another data point among the published system dynamics projects that substantiate that modelling complex policy decisions using a systematic, systemic approach adds great clarity to the decision process (Richmond 1993). Additionally, system dynamics modeling techniques allow

non-technical decision makers to use sophisticated simulations in learning laboratories. Since the system dynamics approach focuses on the behavior of key decision policies in a complex system of multiple interrelationships and utilizes a learning laboratory interface, it provides a user-friendly, expert knowledge view of the system, allowing policy makers to understand better the ramifications of their decisions, and it fortifies their decisions by comprehension of the entire system.

Before this project, health administrators developed solutions with a reductionist approach that analyzed many factors simultaneously, greatly straining their highly trained cognitive abilities (see Table 1). The traditional process resulted in reactive, expensive, and extensive fumigation programs too late to be effective. The systemic approach used in this project greatly enhanced the health administrators' ability to take a more proactive view of epidemic intervention strategies, promoting a proactive, economical, three-pronged approach to controlling an epidemic (de la Fuente Ramírez 1995). Whether or not this project and the policies implemented as a result were fully responsible, there was no catastrophic outbreak!

### **Further work**

In addition to the strategic-level, administrative decisions made at the Secretariat of Health of Mexico, regional administrators and operational personnel also needed to be convinced of the integrated intervention strategies being proposed. Owing to the initial success in explaining complex intervention strategies to the Secretary of Health and epidemiology administrators, the Advisory Board determined that the learning laboratory should be used to train regional epidemic control personnel in the purpose and results of the proposed intervention techniques. The model and learning laboratory have also been shared with the vector-borne disease control departments within the Texas Department of Health and the U.S. Centers for Disease Control and Prevention.

### **Acknowledgements**

The authors thank two anonymous reviewers and Andrew Ford for comments on the first version, Secretary of Health advisory board coordinator Federico Ortíz and advisor Javier Rosado for comments on the medical decision process and disease pathology, and Jim Dyer, Richard Reid, Guillermo Abdel Musik, Leslie Ritchie-Dunham, and Iran Echávarry for useful comments on writing

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style. A special thanks to Conrado Garcia Madrid for his assistance with the learning laboratory.

## Notes

1. Richardson (1997) discusses the effectiveness of using icons or +/- for indicating feedback loop polarity. We used icons in this project.
2. Full details of the model can be obtained from James L. Ritchie-Dunham.

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