# An Optimal Control Framework to Address the Relationship between Water Resource Management and Water-Borne Health Impacts: Focus on the Texas Lower Rio Grande Valley

## Authors

**Andrew J. Leidner**
**Graduate Research Assistant**
**Texas AgriLife Research, Texas A&M University**
**Department of Agricultural Economics**
**Texas A&M University**
**2124 TAMU**
**College Station, TX 77843-2124**
**979.845.4856**
**aleidner@tamu.edu**

**Ronald D. Lacewell**
**Texas AgriLife Research, Texas A&M University**
**2124 TAMU**
**College Station, TX 77843-2124**
**979.862.7138**
**r-lacewell@tamu.edu**

**M. Edward Rister**
**Texas AgriLife Research, Texas A&M University**
**2124 TAMU**
**College Station, TX 77843-2124**
**979.845.3801**
**e-rister@tamu.edu**

**Allen W. Sturdivant**
**Texas Agrilife Research and Extension**
**2401 East Highway 83**
**Weslaco, TX 78596-8344**
**awsturdivant@agprg.tamu.edu**

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**Andrew J. Leidner, Ronald D. Lacewell, M. Edward Rister, and Allen W. Sturdivant**

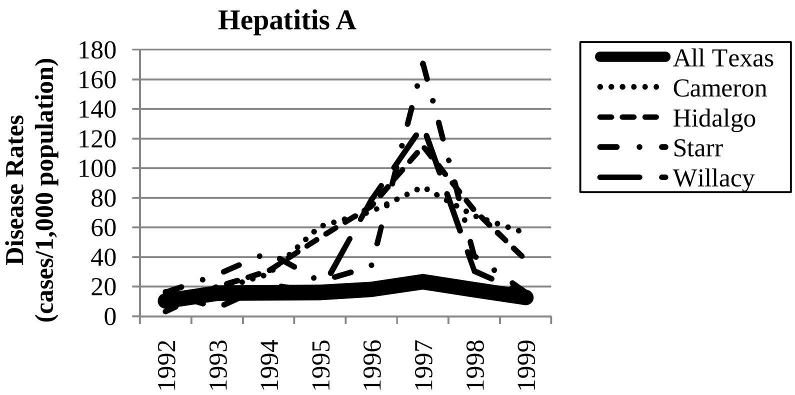

## Abstract

The objective of this study is develop a theoretical model that can evaluate two types of public health expenditures on water-borne health risks: water-related municipal services, an *ex ante* preventative measure against water-borne contamination, and medical treatment, an *ex post* treatment of the water-borne pollutant's harmful effects on human health. The modeled community can allocate resources in either centralized-municipal water-services, point-of-use water-services, or medical intervention, with expenditures subject to a budget constraint. The movement of a water-borne illness through the community is modeled with a susceptible-infected-susceptible (SIS) disease framework. An optimization framework is developed, including a statement of the problem's Hamiltonian and first-order-conditions. The first-order-conditions are discussed. Future work includes obtaining a numerical solution to the optimization problem.


## Introduction

Often rural-agricultural communities, in particular those communities along the US-Mexico border that are commonly called colonias, are developed hastily and some are not connected to water and/or wastewater services that may be considered standard in most parts of the United States Confounding the issue, local utility providers may be unwilling to extend expensive utility services to these communities because the perceived willingness to pay for service is low and the perceived tax revenues from municipal annexation of colonias is also low. Among those colonia residents without access to drinking water and sewer service in these communities, hygienic and sanitary conditions may become conducive to a variety of illnesses. Sanitary conditions in these communities may account for a portion of the increased levels in the water and sanitation-related illnesses Hepatitis A and Shigellosis in the counties of the Texas Lower Rio Grande Valley (Valley) (Figure 1).

a.




b.

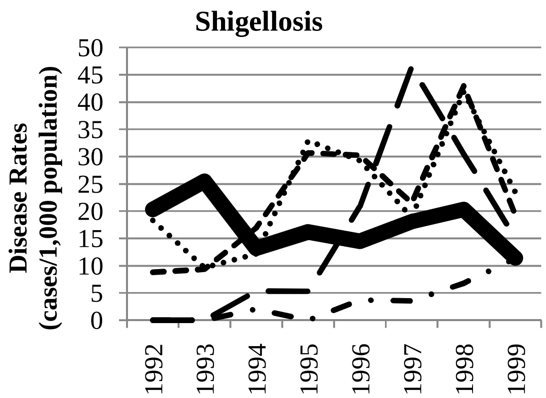



**Figure 1. Disease prevalence rates for Hepatitis A (a) and Shigellosis (b) from 1992 to 1999 in the four counties of the Texas Lower Rio Grande Valley and the average prevalence for all of the State of Texas. Source(s): USGS 2010a and TXDHS 2007.**

High levels of disease impose costs on the colonia residents in terms of reduced quality of life and reduced labor value, which include reduced energy levels, lower productivity, and in severe cases, absences from work. The struggles of the colonias in the Valley to attain standard levels of water, wastewater, and other civil infrastructure are well documented (Olmstead 2003; Perkins et al. 2001; Reed, Stowe and Yanke, LLC 2001; U.S. Federal Reserve Bank of Dallas 1996; Williams 2006). A survey completed by the United States Geological Survey (USGS) reported in 2007 as many as 34,924 colonia residents (18% of colonia residents) in Cameron, Hidalgo, and Willacy counties did not have access to standard levels of either potable water or wastewater services (Table 1) (USGS 2010b).

With rapidly constructed residential communities like the colonias of the Valley in mind, this paper constructs and investigates a theoretical model of a community concerned with public health. In the model, the public health of a community can be enhanced in two ways. First, the community may engage in water-service infrastructure to enhance drinking water access and sanitation in an *ex ante* attempt to reduce new infections from any contaminated water and thereby reduce public health damages from water-borne contamination. Secondly, the community may

**Table 1. County-level colonias' populations and percentages of populations in the Texas Rio Grande Valley at various states of infrastructure as categorized by USGS (2010b), 2007.**

| | Cameron | | Hidalgo | | Starr | | Total | |
|---|---|---|---|---|---|---|---|---|
| | Pop. | *%* | Pop. | *%* | Pop. | *%* | Pop. | *%* |
| Red[a] | 4,786 | *10* | 17,253 | *15* | 12,885 | *37* | 34,924 | *18* |
| Yellow[b] | 17,067 | *36* | 54,283 | *48* | 6,108 | *18* | 77,458 | *39* |
| Green[c] | 25,753 | *54* | 42,748 | *37* | 15,631 | *45* | 84,132 | *43* |
| Total | 47,606 | *100* | 114,284 | *100* | 34,624 | *100* | 196,514 | *100* |

Source(s): USGS, 2010b.

[a] Community infrastructure has inadequate potable water supply or inadequate wastewater disposal.

[b] Community infrastructure has adequate potable water and wastewater service, but inadequate solid waste services, roads, or drainage.

[c] Community infrastructure has adequate services and infrastructure for potable water, wastewater, solid waste, roads, and drainage.

engage in *ex post* medical treatment of infected individuals to reduce the disease's morbidity and mortality. Water-service improvements can take two distinct forms: centralized-municipal (CM) services, and point-of-use (POU) services.

## Model Description

### *Model City*

One way to conceptualize the model is to consider a linear city with increasing distances away from the community center associated with increasingly lower levels of water-service infrastructure. This linear city is 1 unit long. The areas of this city nearest to the city center, $A_t^w$, represent those residents that are connected to CM water-services. The neighborhood of $a_t^p$ represent those residents that use point-of-use (POU) water services, such as in-home drinking water filters and home or local septic systems. The residents which are not in either the CM neighborhood or the POU neighborhood are without water service of any kind, i.e., $(1 - A_t^w - a_t^p)$. The division of a continuous surface into a few discrete levels is a common method to approximate the true continuous spatial surface (Smith, Sanchricho, and Wilen 2009). In the case of the CM neighborhood, the approximation is particularly reasonable because in many communities water-service utilities have clearly defined service-areas beyond which the acquisition of water-services is left to individual residents. The optimal control problem considered in this paper will evaluate how large, if at all, the optimal portions of the population with each type of water-service infrastructure given a fixed budget for all community services.

### *Disease Dynamics*

A primary issue is the tradeoff between water-service infrastructure and medical care in the presence of water-borne contamination or disease (hereafter, referred to as disease). Water-borne disease is captured by considering a susceptible-infected-susceptible (SIS) disease model. Similar models have been used by economists in a cost-minimization setting (Goldman and Lightwood, 2002; Zaric and Brandeau, 2001; and Brandeau, Zaric and Richter, 2003).

The disease model used in this paper is an adaptation from the SIS model presented in Goldman and Lightwood (2002). As they did, a population size normalized to one is assumed:

[1] $S_t + I_t = N_t = 1$,

where $S_t$ is the population portion of susceptible individuals $I_t$ is the portion of population that is infected, and $N_t$ is the total population level all at time $t$. The dynamics of the disease through the population is represented by the derivatives of $S$ and $I$ through time:

[2] $\frac{dS}{dt} = \dot{S}_t = \frac{a(S_t+I_t)-bS_t-\beta(A_t^w,a_t^p)S_t+\delta(a_t^m)I_t}{1+a-b-vI_t}$,

where $a$ is a population birth rate that is not affected by the proportion of people who are infected. This is a reasonable assumption for many water-borne diseases, i.e., most are non-sterilizing and symptomatic for only a few weeks. Take, for example, *E. coli* outbreaks; they do not likely affect birth rate of an entire population. The transmission function is: $\beta(A_t^w, a_t^p)$, where $A_t^w$ represents the level of CM water-services, and $a_t^p$ represents the portion of population that has access to POU water-services. Depending on particular diseases, increasing levels of $A_t^w$ and $a_t^p$ will reduce the population's average transmission rate. Therefore, the transmission function should have negative derivatives with respect to $A_t^w$ and $a_t^p$:

[3] $\frac{d\beta(A_t^w,a_t^p)}{dA_t^w} < 0$, and

[4] $\frac{d\beta(A_t^w,a_t^p)}{da_t^p} < 0$.

Just as the portion of individuals in the susceptible class is reduced by transmissions, those who are infected, and survive, rejoin the susceptible class at a recovery rate equal to the function $\delta(a_t^m)$, where $a_t^m$ is the level of medical treatment deployed to the total population, with $a_t^m$ constrained to be less than or equal to the infected class. Therefore, the recovery function should have a positive derivative with respect to $a_t^m$:

[5] $\frac{d\delta(M_t)}{dM_t} > 0$.

The denominator of $\dot{S}_t$ consists of changes made to the size of total population, which is normalized to one. As before, $a$ is the birth rate, $b$ is the natural death rate, and $v$ is the disease-induced death rate, which only affects the infected class. Invoking equation [1] (i.e., $S_t = 1 - I_t$), equation [2] can be rewritten in terms of only the infected class:

[6] $\dot{S}_t = \frac{a((1-I_t)+I_t)-b(1-I_t)-\beta(A_t^w,a_t^p)(1-I_t)+\delta(a_t^m)I_t}{1+a-b-vI_t}$.

Invoking the assumption that population birth rate is equal to the natural death rate (i.e., $a = b$) leads to further simplification of the susceptible population's state equation:

[7] $\dot{S}_t = \frac{bI_t-\beta(A_t^w,a_t^p)(1-I_t)+\delta(a_t^m)I_t}{1-vI_t}$.

Once again, invoking equation [1], equation [7] can yield the state equation for the infected class:

[8] $\dot{I}_t = -\dot{S}_t = (-1)\frac{bI_t-\beta(A_t^w,a_t^p)(1-I_t)+\delta(a_t^m)I_t}{1-vI_t} = \frac{-bI_t+\beta(A_t^w,a_t^p)(1-I_t)-\delta(a_t^m)I_t}{1-vI_t}$.

Equation [8] defines the class dynamics that will be used later in the optimal control problem. Next, the transmission and recovery functions are defined further to give an explicit relationship between water-service infrastructure, medical treatment, and the dynamics of the water-borne disease through the population. The transmission function is defined as follows:

[9] $\beta\left(A_t^w, a_t^p\right) = \beta^w A_t^w + \beta^p a_t^p + \beta^0\left(1 - A_t^w - a_t^p\right)$,

where the natural, or spontaneous, transmission rate $\beta^0$ of the disease only affects the portion of the population that receives neither CM or POU water-services. Similarly, $\beta^p$ and $\beta^w$ are the transmission rates associated with residents on CM and POU water-services, respectively. Depending on the disease under consideration, the values of the three transmission rates may be different or the same. A typical case, for a disease such as cholera, the following conditions may hold:

[10] $\beta^w = \beta^p = \beta^1$, and $\beta^1 < \beta^0$.

The right-hand side of [10] is the reason for the negative signs in the partial derivatives in equations [3] and [4]. In this case, CM and POU water-services provide the same level of protection against cholera and, assuming $\beta^1$ is quite small, the only portion of the population with significant exposure to cholera are those individuals without any form of water-services. Additionally note if water-service is sufficiently high (i.e., $\left(1 - A_t^w - a_t^p\right)$ is small), then the effect of the higher, natural transmission rate will be negligible.

The recovery function is defined in a similar way:

[11] $\delta(a_t^m) = \delta^0(I_t - a_t^m) + \delta^m a_t^m$,

where $a_t^m$ is the portion of the total population that receives medical treatment. Since giving medical treatment to individuals who are not infected makes no sense, a reasonable constraint is: $a_t^m \leq I_t$; and at full treatment of all infected individuals: $a_t^m = I_t$. The two recovery coefficients are defined as follows: $\delta^0$ is the natural, or spontaneous, rate of recovery; and $\delta^m$ is the medically-enhanced recovery rate. The derivative of the recovery function, equation [5], is positive precisely because the medically-enhanced recovery rate is greater than the spontaneous recovery-rate (i.e.,$\delta^m > \delta^0$).

*Abatement Strategies*

This section introduces more specifics about the three possible disease abatement strategies, starting with CM water-services ($A_t^w$). Since CM water-services have, relative to POU water-services, dynamic properties (i.e. must be constructed, maintained through multiple time periods, and can depreciate), CM water-services is represented in the model by a second state variable with the following derivative with respect to time:

[12] $\dot{A}_t^w = \frac{(1-A_t^w)}{C^w} x_t^w - \gamma A_t^w$,

where $A_t^w$is the level of build out, with full-infrastructure at $A_t^w = 1$; $C^w$is a constant component of CM water-service cost; $x_t^w$ is a control variable, representing an administrator's expenditures towards water infrastructure; and $\gamma$ is a depreciation term used to represent maintenance on existing infrastructure. The most important implication for the first term in the CM water-services state equation (i.e., $((1 - A_t^w)/C^w)x_t^w$) is that expenditures on water supply improvements exhibit decreasing marginal returns. By inverting [12], an expenditure, or cost, function can be generated:

[13] $x_t^w = \left(\dot{A}_t^w + \gamma A_t^w\right) \frac{C^w}{(1-A_t^w)}$

$$= \dot{A}_t^w \left(\frac{C^w}{1-A_t^w}\right) + \gamma A_t^w \left(\frac{C^w}{1-A_t^w}\right).$$

Expenditures ($x_t^w$) to CM water-services are applied to either new additions (i.e., $\dot{A}_t^w(C^w/(1-A_t^w))$) or maintenance on existing infrastructure (i.e., $\gamma A_t^w(C^w/(1-A_t^w))$). Both the new addition and the infrastructure repairs are weighted by a factor (i.e., $C^w/(1-A_t^w)$) that results in increasing marginal costs. With this specification, marginal costs increase to infinity as the level of CM water-service approaches 1. This assumption is reasonable for cities with dense central populations and more sparse populations on the outskirts and rural areas, where costs to bring water services to the more rural residents would be increasing with their distance from the city centers; and ultimately, someone in the population will be so far from the city center such that to make a CM service connection would be prohibitively expensive . An alternative specification for this problem may include a CM water-service with high fixed costs and decreasing marginal costs. Such a specification would be consistent with the literature on natural monopolies that gives credence to the public-ownership of many municipal water-service providers.

The other two controls in this model, POU water-services and medical treatment, are not represented as state variables. This assumes that POU water-services and medical treatment cannot be stored across time periods. Alternatively, this means POU water-service equipment and medical treatment are completely non-durable, or their depreciation rate is set at 100%. The expenditure specifications for POU water-services and medical treatment are defined as follows:

[14] $x_t^p = C^p a_t^p$, and

[15] $x_t^m = C^m a_t^m$,

where $x_t^p$ and $x_t^m$ are, respectively, the expenditures applied to medical treatment of the infected individuals and the expenditures applied to POU water-services; $C^p$ and $C^m$ are constant unit-costs; and $a_t^m$, which was introduced earlier, is the portion of the total population receiving medical treatment and has constrained to be less than the proportion of infected individuals. For this to be a reasonable method to depict cost of a medical treatment, the total population must remain constant. That is a tenuous requirement because equal rates for the population's natural births and deaths were defined previously. Therefore, if both virulence and the infected class are greater than zero, then, with no other influences to the population size, the population is in decline. As total population declines, the cost of giving medical treatment to a fixed portion of the total population should decrease, i.e., giving ORT to 10% of 100 should be cheaper than giving ORT to 10% of 1,000,000. Imposing a constant total population, while including the possibility of virulence deaths, implies that those that die from the disease are immediately replaced by immigrating susceptible individuals. This is argued as a reasonable assumption in locations where the total population level is by-and-large unaffected by this disease. In these locations, other factors such as immigration, war, deadly car accidents, or even other diseases are dictating the total population level, not water-borne illness. Another way to think about this could be that population birth rate is essentially equal to the sum of population natural deaths and virulence deaths (i.e., $a = b - vI_t$). In this way, the maximum population level is maintained over time, where the population level is some carrying capacity that is constrained by some other resource(s) or factors.

The costs of providing POU water-services (equation [14]) and medical treatment (equation [15]) are constant across the spatial dimension, unlike the costs of CM water-services. This assumption seems reasonable, but may be revisited at a later time. Many arguments that favor applying increasing or decreasing costs through space onto the POU water-service cost structure may also be applied to the costs structure of medical treatment. The nature of acquiring or distributing POU water-services and medical treatment are very similar, i.e., a resident can either travel into a city to purchase one or the other, or the social-planner can pay for the delivery of one or the other.

*The Social Planner's Problem*

In this model, the social planner's objective is to minimize the damages from a particular water-borne disease with a fixed annual expenditure. The damages from a given disease are defined as follows:

[16] $D(I_t) = k_I I_t + k_v I_t v,$

where the damage from the disease are separated into two components, called the morbidity damage ($k_I I_t$) and the mortality damage ($k_v I_t v$); $k_I$ and $k_v$ are, respectively, the per-unit costs of contracting a disease and dying from the disease. The final equation included in the model is a budget constraint on expenditures, ensuring that the social-planner spends exactly the full budget:

[17] $x_t^m + x_t^p + x_t^w = E_t,$

where $E_t$ is some exogenous level of expenditure. The administrator is given the task of optimally dividing up funds equal to $E_t$ towards the goal of minimizing the damages caused by water-borne disease. The value of $E_t$, essentially the size of an administrator's budget determined by either a higher-ranking administrator or some legislative action, could vary across time periods. Certainly this is most likely in many nations and regions. In this model,the issue of fluctuating levels of $E_t$ is not addressed; hence,$E_t$ is considered as a constant through time. Mathematically, the problem of the administrator is:

[18] $\min_x \int_0^T (k_I I_t + k_v I_t v)\, dt$

Subject to:

[18.1] $\dot{I}_t = \frac{-bI_t + \left(\beta^w A_t^w + \beta^p a_t^p + \beta^s\left(1 - A_t^w - a_t^p\right)\right)(1 - I_t) - (\delta^s(I_t - a_t^m) + \delta^m a_t^m)}{1 - vI_t}$

[18.2] $\dot{A}_t^w = \frac{(1 - A_t^w)}{C^w} x_t^w - \gamma A_t^w$

[18.3] $x_t^m = C^m a_t^m$

[18.4] $x_t^p = C^p a_t^p$

[18.5] $x_t^m + x_t^p + x_t^w = E_t$

[18.6] $a_t^M \leq I_t$

[18.7] $a_t^P \leq 1 - A_t^w$

[18.8] $A_t^w, a_t^P, a_t^M \geq 0.$

The objective function and many of the constraints have been discussed previously. Two additional constraints that require further explanation are equations [18.6] and [18.7]. Equation [18.6], if binding, suggests universally-distributed medical services to the infected proportion of the population. Equation [18.7], if binding, suggests universally distributed water services to the entire population, both susceptible and infected. Water services may be either CM or POU. Each of these constraints imposes two important conditions on the social planner's problem for the context of many water-borne illnesses. Equation [18.6] ensures the portion of the population receiving medical services does not exceed the portion that is infected. In other words, healthy individuals are not given medical treatment. Equation [18.7] ensures that the portion of population receiving POU does not exceed the portion of the population that does not have CM water services. In other words, individuals can have either CM water services or POU water services, but not both.

### Hamiltonian and First Order Conditions

This section develops a Hamiltonian for the social planner's problem (equation [18]). From the Hamiltonian, a set of first order conditions are generated and the economic implications of several of the first order conditions are discussed. By first substituting constraints [18.3] and [18.4] directly into the budget constraint (equation [18.5]), the problem is shortened, but qualitatively unchanged, and yields the following Hamlitonian:

$$[19]\ H \equiv k_I I_t + k_v I_t v$$

$$+\lambda_t^I\left(\frac{-bI_t+\left(\beta^w A_t^w+\beta^p a_t^p+\beta^s\left(1-A_t^w-a_t^p\right)\right)(1-I_t)-(\delta^s(I_t-a_t^m)+\delta^m a_t^m)}{1-vI_t}\right)$$

$$+\lambda_t^A\left(\frac{(1-A_t^w)}{C^w}x_t^w-\gamma A_t^w\right)$$

$$+\phi_t^E\left(E_t-C^m a_t^m-C^p a_t^p-x_t^w\right)$$

$$+\phi_t^M\left(I_t-a_t^M\right)$$

$$+\phi_t^p\left(1-A_t^w-a_t^P\right).$$

The following first-order conditions are generated from this Hamiltonian:

$$[20.1]\ \frac{dH}{dx_t^w} \equiv \quad \lambda_t^A\frac{(1-A_t^w)}{C^w}-\phi_t^E=0$$

$$[20.2]\ \frac{dH}{da_t^p} \equiv \quad \lambda_t^I\left(\frac{(\beta^p-\beta^s)(1-I_t)}{1-vI_t}\right)-\phi_t^E C^p-\phi_t^p=0$$

$$[20.3]\ \frac{dH}{da_t^m} \equiv \quad \lambda_t^I\left(\frac{\delta^s-\delta^m}{1-vI_t}\right)-C^m\phi_t^E-\phi_t^M=0$$

$$[20.4]\ \frac{dH}{dA_t^w} \equiv \quad \lambda_t^I\left(\frac{(\beta^1-\beta^3)(1-I_t)}{1-vI_t}\right)+\lambda_t^A\left(\frac{x_t^w}{C^w}-\gamma\right)-\phi_t^p=-\dot{\lambda}_t^A$$

$$[20.5]\ \frac{dH}{dI_t} \equiv \quad k_I+k_v v$$

$$+\lambda_t^I\frac{-b-\left(\beta^w A_t^w+\beta^p a_t^p+\beta^s\left(1-A_t^w-a_t^p\right)\right)-\delta^s}{1-vI_t}$$

$$-\lambda_t^I\frac{v\left(bI_t+\left(\beta^w A_t^w+\beta^p a_t^p+\beta^s\left(1-A_t^w-a_t^p\right)\right)(1-I_t)-(\delta^s(I_t-a_t^m)+\delta^m a_t^m)\right)}{(1-vI_t)^2}$$

$$+\phi_t^M$$

$$=-\dot{\lambda}_t^I$$

[20.6] $\frac{dH}{d\phi_t^E} \equiv \quad E_t - C^m a_t^m - C^p a_t^p - x_t^w = 0$

[20.7] $\frac{dH}{d\phi_t^M} \equiv \quad I_t - a_t^M = 0$

[20.8] $\frac{dH}{d\phi_t^p} \equiv \quad \phi_t^p(1 - A_t^w - a_t^P).$

Some basic insights can be gained from interpretation of this set of first order conditions. Rearranging [20.1] generates:

[21] $\lambda_t^A = \phi_t^E \frac{C^w}{(1-A_t^w)}$,

where, in optimality, the marginal value to the objective function of another unit of water supply infrastructure ($\lambda_t^A$), or the shadow price of water infrastructure, is exactly equal to the shadow price of the budget constraint ($\phi_t^E$) weighted by the marginal cost of an addition to water infrastructure ($C^w/(1 - A_t^w)$). Similar results are found for POU services:

[22] $\lambda_t^I \left(\frac{(\beta^p - \beta^s)(1-I_t)}{1-vI_t}\right) = \phi_t^E C^p + \phi_t^p,$

where the shadow cost of an additional infected individual (i.e, $\lambda_t^I$) multiplied by the difference in a susceptible individual's infection rate with POU services (i.e., $(\beta^p - \beta^s)(1 - I_t)/(1 - vI_t)$) is exactly equal to the shadow price of the budget share multiplied by the unit cost of another unit of POU (i.e., $\phi_t^E C^p$) plus the shadow price of switching an individual from POU to CM services (i.e., $\phi_t^p$). Similarly, for medical intervention:

[23] $\lambda_t^I \left(\frac{\delta^s - \delta^m}{1-vI_t}\right) = C^m \phi_t^E + \phi_t^M,$

where the shadow cost of an additional infected individual (i.e, $\lambda_t^I$) multiplied by the difference in that infected individual's recovery rate with medical intervention (i.e., $(\delta^s - \delta^m)I_t/(1 - vI_t)$) is exactly equal to the shadow price of the budget share multiplied by the unit cost of another individual's medical intervention (i.e., $C^m \phi_t^E$) plus the shadow price of providing medical intervention to only infected individuals (i.e., $\phi_t^M$). Here, as with CM and POU water services, the rule of setting marginal costs equal to marginal benefits holds.

## Summary and Future Directions

The next steps for this research are to calculate a numeric solution using suggested values for the model's parameters (i.e., rates of transmission, recovery, virulence, etc.) based on several water-borne diseases, potentially including: cholera, arsenic poisoning, and *E. coli*. Overall, the goal of this paper is to develop a theoretical model related to water-borne illness that included the abatement strategies of increasing one of two kinds of water services or medical services for a modeled community. Equating the marginal costs and marginal benefits of each abatement strategy is shown to hold in optimality. There are examples in South Texas where not all of the residents have potable water delivered to their households. This situation may result in water-contamination problems that may eventually end up causing water-related illnesses. With the onset of illness, there are costs related to medical treatment for some cases as well as loss of time on the job plus potential cross contamination to the food industry. Assisting communities manage and view these issues in a comprehensive manner is one goal of this effort.

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