Water Quality Modeling in Kranji Catchment

by

Erika C. Granger

B.S. Environmental Engineering
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SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING
AT THE
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Abstract

This thesis describes the process and results of applying the Soil and Water Assessment Tool (SWAT) to characterize bacterial fate and transport in the Kranji Catchment of Singapore. The goal of this process is to predict bacterial loading to Kranji Reservoir under the forcing of weather and other variables. Necessary data and input values were collected or estimated and input into the model. One of the most important of these values is the bacterial die-off rate. This rate must be accurate for the model to provide accurate predictions of bacterial loadings. In order to obtain a value for the bacterial die-off rate, an attenuation study was conducted. The results of this study were not typical. Bacterial growth was observed to occur during dark hours, and decay was observed to occur during sunlit hours. The resulting light and dark decay constants were combined for use in the model. The specific bacterial loading rates associated with the various agricultural activities occurring in the catchment are not available and thus were roughly estimated. Point source loadings were also estimated. Four years of model simulation daily output were analyzed, and results for specific subcatchments with differing character are discussed. This application of SWAT shows a good ability to make qualitative predictions of the presence or absence of bacteria; however, quantitative agreement between model predictions and field observations is poor. This run of the model is like a first draft—more refinement and more information are needed before it will make accurate predictions; however, the framework is in place.

Thesis Supervisor: Peter Shanahan
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To the MIT Women's Rugby Club, for rocking my socks.

To the sistas of Lambda Iota Zeta and Pi Omega Tau: may the pink and pink live on in infamy!
[redacted]

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1 Introduction

This chapter was written as part of a collaborative effort with Kevin Foley, Adriana Mendez, and Amruta Sudhalkar.

1.1 Singapore

The Republic of Singapore is an island city-state situated at the southern tip of the Malay Peninsula, 137 kilometers (85 mi) north of the equator. At 710.2 km^2 (274.2 square miles), Singapore is considered a microstate (a state with less than 1000 km^2 of non-sea area) and the smallest nation in Southeast Asia. Located at the southern tip of the Malay Peninsula and across from the large Indonesian island of Sumatra (Figure 1.1), Singapore controls the Strait of Malacca. Approximately one-fourth of today's global trade passes through this strait connecting the Indian and Pacific Oceans.

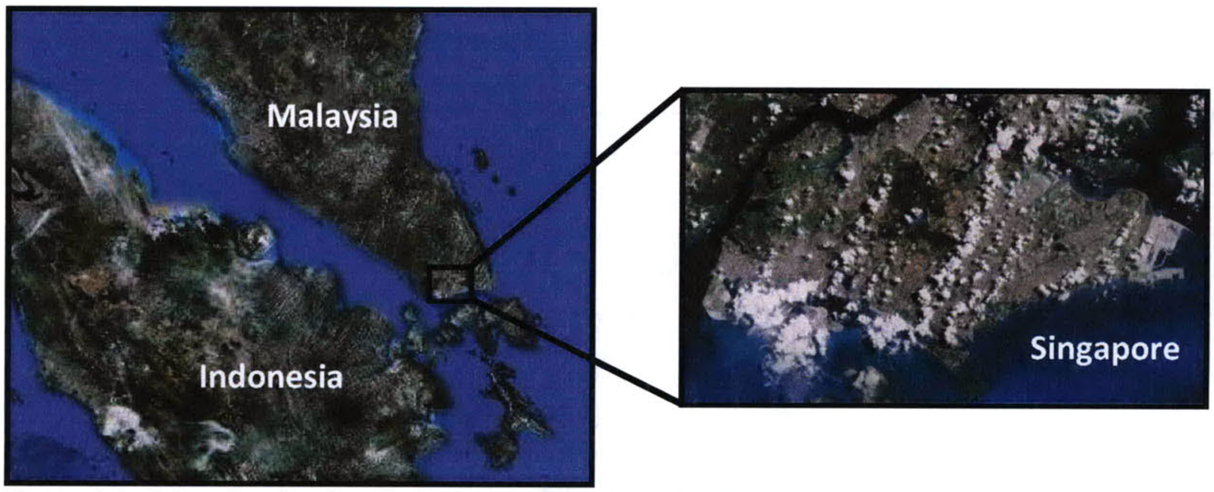

Figure 1.1: Map showing location of Singapore (GoogleMaps, 2010)

The British East India Company founded Singapore in 1819 as a trading colony. Singapore became one of the most important commercial and military centers of the British Empire, and the hub of British power in Southeast Asia. In 1963, Singapore achieved independence from Britain and merged with Malaya, Sabah, and Sarawak (Southeast Asian states) to form Malaysia. The union was short-lived, and two years later, Singapore became an independent republic, on August 9, 1965.

1.1.1 Economy

Singapore has had an open economy since it was established as a British trading post in 1819 (Abeysinghe, 2007). After Singapore gained independence in 1965, its economy grew 8.5% per year until 1990 (Krugman, 1994). This incredible growth rate was primarily due to the mobilization of the population; employment rose from 27% to 51% (Krugman, 1994). During this period, education of the workforce also drastically increased from more than half of all workers having no formal education to about two-thirds of all workers having completed secondary school (Krugman, 1994). In 2004, Singapore's gross national income (GNI) was US$113 billion, making it one of the 40 largest economies in the world (Abeysinghe, 2007), an impressive feat for such a small country (by area and population).

All of Singapore's gross domestic product (GDP) is generated via the industrial (27.8%) and service (72.2%) sectors (CIA). The service sector is dominated by financial services, business services, and services exported to visiting tourists (Abeysinghe, 2007). Due to the island's small population and lack of natural resources, the industrial portion of Singapore's economy relies almost exclusively on exporting products and importing intermediates (Abeysinghe, 2007). Like much of Asia, Singapore's primary exports are electronics (Table 1.1).

Table 1.1: Exports of Singapore (MTI, 2007)

Top 10 Exports (2007)	% Share
Electronic Valves	23.5
Petroleum Products Refined	17.1
Parts For Office & Data Processing Machines	6.7
Telecommunications Equipment	5.5
Data Processing Machines	3.4
Electrical Circuit Apparatus	2.0
Electrical Machinery	1.7
Medicaments	1.6
Nitrogen-Function Compounds	1.6
Civil Engineering Equipment Parts	1.6

While Singapore exports most of the goods it produces, it also imports most of the goods it consumes. This economic system means that Singapore relies heavily on multinational corporations (Abeysinghe, 2007). In fact, foreign direct investment has been the main source of capital inflow since Singapore established independence (Abeysinghe, 2007).

The Monetary Authority of Singapore (MAS) is the central bank of Singapore (Abeysinghe, 2007). The MAS targets the nominal effective exchange rate to maintain price stability, a system that has worked very well for them thus far (Abeysinghe, 2007). The government of Singapore has a very conservative fiscal stance overall (they accumulate large budget surpluses in non-recessionary years), but they are willing to cut taxes and other charges to help businesses when needed (Abeysinghe, 2007). Overall, the economy of Singapore is very robust and is capable of withstanding fluctuations in the world market.

1.1.2 Water Issues in Singapore

Singapore is a water scarce country even though it receives over 2,400 mm of rainfall annually. This city-state has a surface area of approximately 700 square kilometers, and this imposes a limit on the extent to which water can be stored locally (Tortajada, 2006). Although Singapore has the highest GDP per capita in Southeast Asia, it has less than 1,000 m^3 of water available per person from within the country (categorizing it as a "water-stressed" country). Malaysia, which currently provides about 40% of Singapore's water needs, has one hundred and sixty eight times the annual per capita internal renewable water resources of Singapore (Lee, 2005). These statistics can be seen in Table 1.2.

Table 1.2: Water Resources of Asian Countries, GDP Per Capita, and Population: Year 2000 (UNDP, 2005)

Country	Annual Renewable Water Resources: Total (km^3)	Annual Renewable Water Resources: Per Capita (m^3)	Annual Water Withdrawals: Total (km^3)	Annual Water Withdrawals: Per Capita (m^3)	GDP Per Capita in 2000 (US$)	Population in 2000 (millions)
Cambodia	476	32,876	4.1	311	274	12.2
Indonesia	2,830	12,749	82.8	391	750	103.5
Laos PDR	334	57,638	3.0	567	328	5.2
Malaysia	580	23,316	9.0	392	3,870	23.2
Myanmar	1,046	20,870	33.2	699	142	49.0
Philippines	479	5,884	28.5	377	981	76.3
Singapore	1	139	---	---	23,071	4.0
Thailand	410	6,459	87.1	1,429	1,963	62.4
Vietnam	891	10,805	71.4	914	403	77.7

The Singapore Public Utilities Board (PUB) is responsible for management of the water systems of Singapore. This includes drinking water treatment and supply, wastewater treatment, and storm water management. In an effort to reduce Singapore's dependence on external sources of water, PUB has diversified its water sources extensively in the last decade.

PUB has adopted the *Four National Taps Strategy* for ensuring a sustainable supply of water to its population (Xie, 2006). The four taps strategy consists of the following elements:

→ Local Catchments:
Singapore currently has 15 reservoirs that collect rainwater, aided by a network of canals, drains and river channels. The larger reservoirs can be seen in Table 1.3.

Table 1.3: Singapore's Reservoirs and Storage Capacity (Wung and Pei, 2009)

Name of Reservoir	Year Completed	Storage Capacity (million m^3)
MacRitchie	1867 (enlarged in 1894)	4.2
Lower Pierce	1912	2.8
Seletar	1935 (enlarged in 1969)	24.1
Upper Pierce	1974	27.8
Kranji/Jandan	1975	22.5
Western Catchment	1981	31.4
Bedok/Sungei Seletar	1986	23.2
Total		136.0

→ NEWater (Reclaimed Wastewater):
Singapore currently has four wastewater reclamation plants with a fifth plant expected to be completed by 2010. Together, these plants will meet 30% of Singapore's current water needs by 2010 (Tortajada, 2006).

→ Desalination:
Singapore has been operating a desalination plant in Tuas since 2005. This plant can produce 30 million gallons of water per day (136,000 cubic meters) and is one of the region's largest seawater reverse-osmosis plants. This plant meets 8% of Singapore's current water needs (Tortajada, 2006). A summary of Singapore's domestic water statistics is provided in Table 1.4

Table 1.4: Domestic Water Statistics (NEA, 2005)

	2002	2003	2004
Number of raw water reservoirs in Singapore	14	14	14
Number of NEWater Plants (For Recycling Water)		2	3
Volume of Used Water Treated Per Day (1,000m^3/day)[16]	1,315	1,360	1,369
Water Tariffs			
Domestic (consumption ≤ 40 m^3 per month) (cents/m^3)	117	117	117
Domestic (consumption > 40m^3 per month) (cents/m^3)	140	140	140
Shipping (cents/m^3)	192	192	192
Sale of Water in Singapore	1,259	1,224	1,203
Domestic (1000 m^3/day)	687	690	686
Non-domestic (1000 m^3/day)	572	534	517
Domestic water consumption per person (litres/day)	165	165	162

→ Import of water from Malaysia:
An important source of water supply for Singapore comes from Malaysia. Singapore imports water from Malaysia under two existing "Water Agreements" signed by the two countries in 1961 (the Tebrau and Scudai Water Agreement) and 1962 (the Johor River Water Agreement). Under these agreements, Singapore is allowed to draw up to 336 MGD (1.53 million m^3 per day). In these Agreements, Singapore pays Malaysia 0.03 Singapore dollars for every 1,000 gallons drawn from the rivers (Lee, 2005).

In addition to Water Supply Management, PUB has adopted effective strategies for Water Demand Management, Community Involvement, Private Sector Participation, Governance, and Continuous Improvement to develop a holistic approach to water management that addresses the entire water cycle, not just supply.

Singapore's directives on water management at the national level have been effectively translated to the local level. This is evident from the efficient management of Singapore's reservoirs at the local level.

1.2 Kranji Reservoir and Catchment

The Kranji Reservoir in the Kranji Catchment (Figure 1.2) is located within the Western Catchment of Singapore. It is in the Northwestern corner of the island (1°25''N, 103°43''E) (NTU, 2008).

The Kranji Reservoir was created in 1975 by the damming of an estuary that drained into the Johor Straits that separate the Malaysian mainland from Singapore. The reservoir is approximately 647 hectares and the catchment is approximately 6,076 hectares in area. The catchment has four tributaries: Kangkar River, Tengah River, and Pengsiang River in the South, and Pangsua River in the North (NTU, 2008). The catchment has a variety of land-uses, including forests, reserved areas, agriculture, and residential areas.

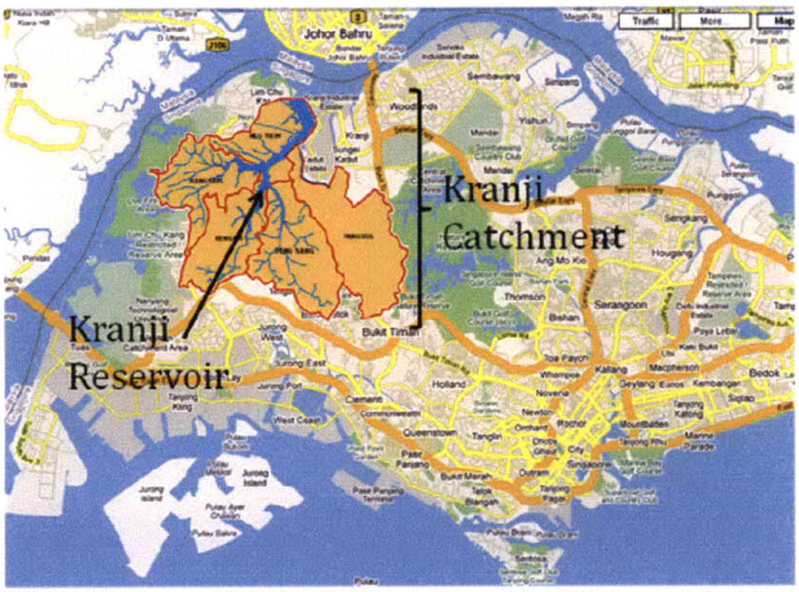

Figure 1.2: Map of Kranji Catchment and Kranji Reservoir (GoogleMaps, 2010)

1.2.1 Management of Kranji Reservoir

PUB wants to use its water resources not just for providing water, but also to provide a recreational venue for the people of Singapore. To achieve this goal, PUB launched the Active Beautiful Clean Waters Program in an effort to achieve national waters that are:
Active – open for different recreational activities such as boating or fishing.
Beautiful – aesthetically pleasing in a way that the nation's inhabitants can enjoy.
Clean – of sufficient quality for domestic, industrial, and recreational uses.

The program has a variety of elements, one of which is using drinking water reservoirs for recreation. By improving the quality, aesthetics, and access to Singapore's waterways, PUB hopes to foster a greater sense of ownership and respect for water in Singaporean communities.

The Kranji Reservoir is an important element in this plan, since it is located near some of the last remaining undeveloped land in Singapore. PUB intends to make the Kranji Reservoir serviceable for recreational use under the ABC Program. In preparation for these uses of the reservoir, the PUB commissioned a study by Nanyang Technological University (NTU) in 2008 that sought to characterize the Kranji Reservoir and Catchment and to model water quality within the reservoir (Dixon et al., 2009).

2 Water Quality Modeling in Kranji Catchment

As discussed above, water quality in Kranji Reservoir is very important to PUB. As part of the Active, Beautiful and Clean (ABC) initiative of Singapore's Public Utilities Board (PUB), an effort is being put forth to make the Kranji Reservoir safe for water-contact recreational activities. In order to do this, water quality in the reservoir must comply with World Health Organization (WHO) standards for recreational use (WHO, 2003). Part of the requirement for meeting these standards is maintaining acceptable levels of fecal indicator bacteria. This study is primarily interested in one fecal indicator bacterium, *Escherichia coli (E. coli)*. In order to accurately model water quality within the reservoir, it is important to understand the bacterial loading to the reservoir. To this end, my primary goal was to employ a watershed-scale model to characterize the fate and transport of indicator bacteria within Kranji Catchment.

2.1 Model Selection

In order to determine a viable and appropriate water quality model for use in Kranji Catchment, I identified key attributes and capabilities necessary for successful characterization of bacterial fate and transport within the catchment:

- Simulation of runoff quantity and composition
- Simulation of bacterial transport
- Simulation of bacterial fate
- Consideration of land use
- Continuous model—time step ≤ 1day
- Simulation of watershed containing urban and rural areas

Three potential models were identified which meet these criteria: the Storm Water Management Model (SWMM) (Huber and Dickinson, 1992), the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2005), and the Better Assessment Science Integrating point and Nonpoint Sources/Hydrologic Simulation Program-FORTRAN (BASINS/HSPF) (USEPA, 2001). All of these models are available freely from the U.S. EPA.

2.1.1 Potential Model: SWMM

As mentioned above, PUB commissioned a study by NTU to characterize Kranji Catchment and Reservoir. As part of this process, NTU applied XPSWMM, a commercial version of the EPA's SWMM model (Huber and Dickinson, 1992), to characterize nutrient source loads and flow rates entering the reservoir from the contributing catchment area as a function of storm events (NTU, 2008). SWMM was developed to model runoff in primarily urban areas (Huber and Dickinson, 1992); however, the majority of Kranji Catchment is undeveloped. Nevertheless, SWMM can be applied to watersheds containing both developed and undeveloped areas (NTU, 2008). SWMM does not have an integrated component for modeling bacterial fate and transport, which is a major drawback, considering my goals. In terms of output time step, the SWMM output time step is dependent upon the input time step, which means that as long as input data of sufficient resolution is used, a daily or sub-daily output time step is possible. Aside from the fact that it would be redundant to reapply a model that has already been applied to the catchment, my time constraints for this project are not conducive to attempting to create bacterial fate and transport components for SWMM.

2.1.2 Potential Model: SWAT

SWAT is a continuous model that was developed by the USDA to simulate large complex watersheds with diverse land use and management practices (Neitsch et al., 2005). SWAT simulates hydrologic response, including runoff quantity and quality. Additionally, SWAT does have an integrated component for bacterial fate and transport (up to two different bacteria may be modeled). Similar to SWMM, the output time step of SWAT depends on the resolution of the input data.

2.1.3 Potential Model: BASINS

BASINS is very similar to SWAT; in fact, SWAT is one of the underlying models run as part of BASINS (USEPA, 2001). This means that BASINS has all of the functionality of SWAT. However, BASINS also incorporates the HSPF and QUAL2E models, making it a more complex model. For the purposes of this study, the primary difference between BASINS and SWAT is that the instream modeling component of BASINS is far more complex; reaches are discretized more finely than they are in SWAT, and the flow of water and the fate and transport of chemicals within the reaches are modeled with greater complexity (USEPA, 2001).

2.1.4 Final Selection

After consideration of the advantages and disadvantages of each of the potential models, I decided to utilize SWAT to model the fate and transport of indicator bacteria within Kranji Catchment. SWMM does not have an integrated component for modeling bacterial fate and transport, so using it would have been much more difficult. Additionally, XPSWMM has previously been applied by NTU, and one of my objectives in completing this thesis was to apply a model from start to finish. Applying SWMM would not have met this learning objective. BASINS seems overly complex for the objectives of this study. The eventual loading to the reservoir is the primary output of interest, and this can effectively be modeled using SWAT. BASINS also possesses the functionality to do this; however, SWAT is simpler and will accomplish the same goals.

2.2 SWAT Overview

2.2.1 Development

The Soil and Water Assessment Tool (SWAT) was created for the USDA Agricultural Research Service by Dr. Jeff Arnold (Neitsch et al., 2005). SWAT incorporates the following models into one comprehensive, continuous time, physically based, whole watershed model (Neitsch et al., 2005):

- Simulator for Water Resources in Rural Basins (SWRRB)

- Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS)
- Groundwater Loading Effects on Agricultural Management Systems (GLEAMS)
- Erosion-Productivity Impact Calculator (EPIC)
- Routing Outputs to Outlet (ROTO)

The primary purpose of SWAT is to model large watersheds with varying soil types, land uses, and management practices over long periods of time and to predict the impact of the watershed's composition on water, sediment, and agricultural chemical yields (Neitsch et al., 2005). SWAT was developed to model large, primarily rural watersheds.

2.2.2 Overview of Components

SWAT can be used to model a multitude of physical processes; however, this study utilizes a limited number of these components. This study is primarily interested in the fate and transport of indicator bacteria within the catchment, which means none of SWAT's chemical fate and transport components were taken advantage of.

Using data input by the user, SWAT delineates the watershed into constituent subbasins. A particularly useful and convenient capability of SWAT is that it incorporates the ROTO model, which was developed specifically to model flow from subbasin to subbasin in the SWRRB model (from which SWAT was primarily developed) (Neitsch et al., 2005). Each subbasin is composed of one or more Hydrologic Response Units (HRUs) with unique land use, management, soil, and slope characteristics. The HRUs are not hydraulically connected and multiple unconnected areas in the same subbasin can be part of the same HRU. The runoff and loading coming from each HRU is summed, along with any flow and loading into the subbasin, to calculate flow rate and loading coming out of the subbasin.

Water balance is the motivation behind all hydrologic activity within the watershed. SWAT simulates rainfall, canopy storage, infiltration, redistribution, evapotranspiration, lateral subsurface flow, surface runoff, tributary channels, and return flow. Weather is simulated by SWAT using its "Weather Generator" which generates daily weather using monthly average values for temperature, precipitation, solar radiation, wind speed, and relative humidity input by the user (Neitsch et al., 2005).

Within the hydrologic simulation conducted by SWAT, bacterial fate and transport is also modeled. Bacterial growth and decay is modeled as a first-order process. SWAT has the capability of modeling up to two kinds of bacteria. These two species are modeled on foliage, in solution in the top 10 mm of soil, and as sorbed to soil particles in the top 10 mm of soil. Bacteria that percolate deeper into the soil profile are assumed to die. Bacteria on foliage and in the top 10 mm of the soil profile are free to interact with runoff. Bacteria may be introduced to the catchment by both point (e.g. outfall from a sewage treatment plant) and non-point (e.g. manure application to agricultural land) sources. My primary interest in modeling bacterial fate within the transport was in how the bacteria behave while being transported in reaches.

3 Fieldwork

3.1 Methods

3.1.1 Background

Fecal contamination is commonly associated with the presence of coliform bacteria. Two measures often used to quantify contamination are the concentrations of *Escherichia coli* (*E. coli*) and total coliforms. These fecal indicator bacteria have been found in the runoff from Kranji Catchment, as well as in Kranji Reservoir itself (Dixon et al., 2009). As mentioned above, PUB would like to make Kranji Reservoir available for recreational use. In order to do this, the reservoir must maintain bacterial levels within the standards for recreational use. SWAT is equipped to model bacterial fate and transport, given parameters about the bacteria. In order to model coliform fate and transport accurately, I need to understand how coliform bacteria behaves in the environment in Singapore. For this reason, I chose to conduct a field attenuation study in Kranji Catchment.

3.1.1.1 Factors Affecting Coliform Survival

Bowie et al. (1985) divide the primary contributing factors that contribute to coliform disappearance into three categories: physical, physicochemical, and biochemical-biological.

Light has been implicated as the one of the most important physical factors in coliform disappearance by many studies (Bowie et al., 1985). The primary mechanism by which light causes coliform death has been debated in several studies, but no definitive conclusion has been reached. Sedimentation is another mechanism believed to contribute to coliform disappearance; adsorption of coliforms to suspended particles, flocculation of coliforms, and coagulation of coliforms enhance sedimentation. Because temperature influences many other processes, it is one of the most important physical factors affecting coliform disappearance rates.

One physicochemical factor that affects coliform disappearance is salinity, due both to osmotic effects and enhancement of light effects (Bowie et al., 1985). High pH has also been shown to affect coliform disappearance rates. Heavy metal toxicity and redox potential also affect coliform disappearance.

The influence on disappearance rate by biochemical-biological factors is primarily due to nutrient levels and predator concentrations (Bowie et al., 1985). Nutrient levels have been found to be important on their own, but also because the addition of some nutrients reduces the toxicity of some heavy metals. Nutrients may also influence the concentration of predator, which in turn influences disappearance rate.

3.1.1.2 Coliform Persistence in Tropical Climates

There is evidence that fecal indicator bacteria can occur naturally (without fecal contamination) or persist for extended periods of time in tropical environments. A study conducted by Rivera et al. (1988) showed the presence of fecal indicator bacteria in water collected from bromeliads in the rain forest of Puerto Rico. This bacteria was either not of fecal origin or had persisted long after fecal contamination. The study by Rivera et al. raises some questions on the validity of using *E. coli* and total coliforms as indicators of recent fecal contamination in a tropical environment, such as that of Singapore.

The runoff entering the drainage system in Kranji Catchment is not nearly as clean as the water sampled in the study by Rivera et al. (1988); there is definitely potential for fecal contamination of the runoff by humans or animals. Because I believe that there are sources of *E. coli* and other coliforms present in the catchment, I am primarily concerned with modeling the fate and transport of these bacteria, rather than determining if they also occur naturally. Nonetheless, the possibility of coliform growth in Singapore's tropical waters is a potential factor in modeling the catchment.

3.1.1.3 Modeling Coliform Survival

The effects of the physical, physicochemical, and biochemical-biological factors on coliform concentration can be modeled independently or collectively using first-order kinetics, as seen in Equation 3.1 (Bowie et al., 1985).

$$C(t)=C_0e^{-kt} \qquad (3.1)$$

t = time
C(t) = coliform concentration at time t
C_0 = initial coliform concentration
k = first-order decay constant

A first-order decay constant can be assigned to each factor affecting coliform survival and summed to achieve a total decay constant that can be used to model overall coliform survival. I am interested in the total decay constant for modeling coliforms within the catchment. While runoff composition may vary greatly throughout the catchment, it has been shown that the largest contributing factors to coliform die-off are solar radiation, salinity, sedimentation, and predation (Bowie et al., 1985). Kranji Catchment is 6,076 hectares in area and it is safe to assume that temperature and light intensity do not vary greatly over this area. Predation is mainly a product of the concentration of predator organisms, which I also assume does not vary greatly throughout the catchment. Salinity greatly increases the effect of solar radiation; however, Kranji Catchment is a freshwater catchment and salinity effects are negligible.

Because coliform concentration can be modeled using first-order kinetics, it is relatively simple to compute a comprehensive decay constant when the upstream coliform concentration, downstream coliform concentration, and travel time are known. In order to obtain a comprehensive decay constant for Kranji Catchment, I designed and ran an attenuation study in a reach of drainage channel in KC2.

3.1.2 Setup

The attenuation study consisted of simultaneously taking a sample and releasing a tracer from the upstream end of the study area, taking a sample at the downstream end of the study area when the tracer passed, recording the travel time of the tracer, and analyzing the samples for total coliform and *E. coli* concentrations. I selected an appropriate reach in which to conduct the attenuation study. The reach is in KC2; it is a long, straight segment that is exposed to direct sunlight during the day. See Figure 3.1 for location of the study reach.

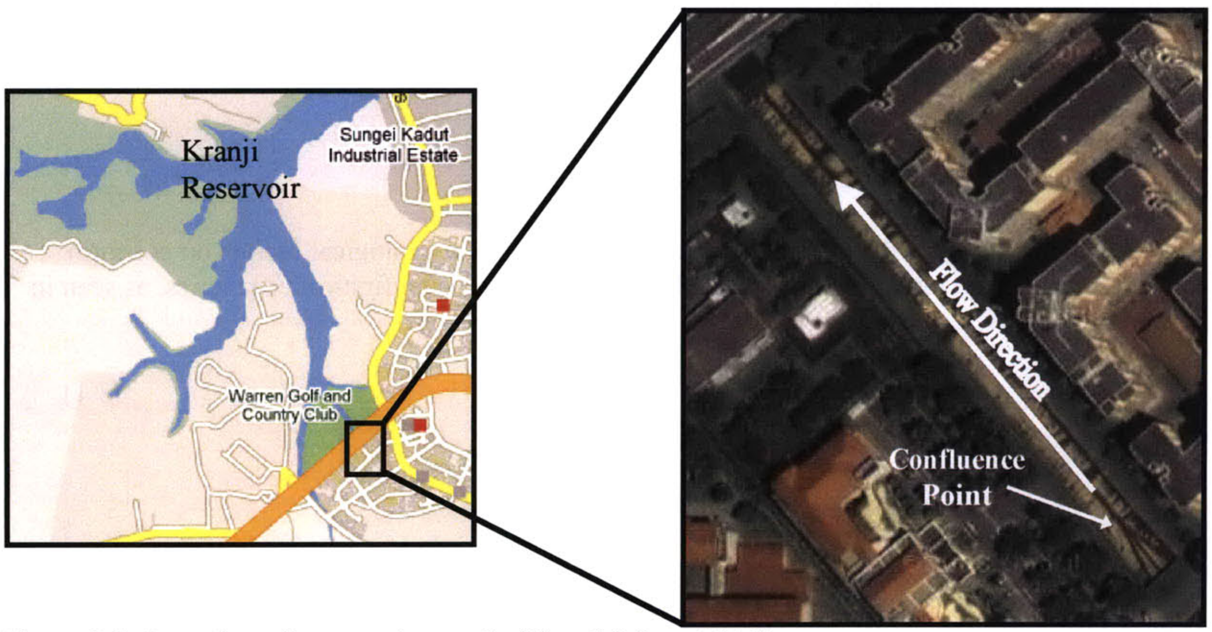

Figure 3.1: Location of attenuation study (GoogleMaps, 2010).

Figure 3.1 shows that the upstream end of the reach is the confluence point of three smaller drains. This presented a bit of a challenge in that the flows from the three smaller drains do not mix for a good portion of the drain length. It was important that the channel be well-mixed so that I could be sure I was sampling the same parcel of water at both the upstream and downstream ends of the study area. After several unsuccessful attempts at designing, building, and using a toothed weir to mix the channel, we decided to use concrete blocks to find a configuration that would work to mix the channel. After several attempts, we arrived at the configuration shown in Figure 3.2. The blocks induced a hydraulic jump that caused rapid mixing. We used visual inspection of rhodamine and fluorescein dye released upstream of the blocks to determine at what point the channel became well-mixed after the hydraulic jump. A schematic of the final setup is shown in Figure 3.3.

After experimentation with a few different tracers, I decided to use leaves floating in the channel. Their low profile kept them out of the wind, moving at the same velocity as the water in the channel, and they were very easy to track. Leaves were also much simpler to use than salt or dye, which would have required sensing equipment to measure concentration. For each repetition of the test, one leaf was used as a tracer.

Figure 3.2: Induced hydraulic jump to promote mixing of three confluent channels at upstream end of attenuation study.

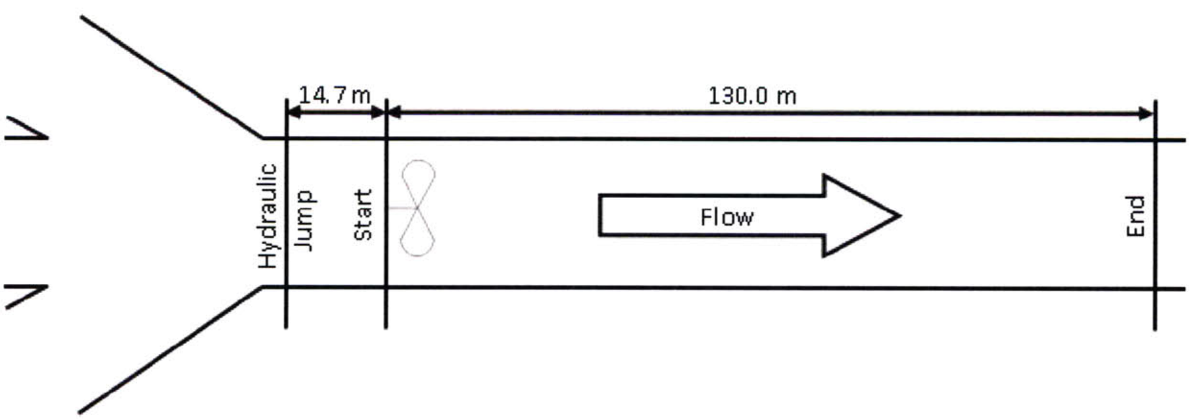

Figure 3.3: Schematic of attenuation study. Starting point of study also marks point at which channel became well-mixed. String was placed across the channel at Start and End points.

The procedure for the attenuation study was fairly straightforward. For quality-control purposes, a blank sample consisting of bottled water stored in a sterile 100-mL Whirl-Pak® bag was stored on ice in a cooler from the beginning of the attenuation study. A tracer leaf was selected and released in the center channel upstream of the hydraulic jump. As the leaf passed under the string at the upstream end of the study area, a 100-mL sample was collected there in a sterile 100-mL Whirl-Pak® bag. Simultaneously, the travel time stopwatch was started. The sample was then labeled and placed in the cooler of ice containing the blank. As the tracer leaf passed under the string at the downstream end of the study area, another sample was collected from the downstream point and the travel time was recorded. This sample was also labeled and stored in the cooler of ice. This procedure was repeated five and four times for the light and dark studies, respectively. The light study was conducted starting at 11:00 on January 14, 2010. The dark study was conducted starting at 19:30 on January 19, 2010. After completion of each study, the samples were transported back to the laboratory and analyzed for E.Coli and total coliforms.

3.1.3 Sample Analysis

Samples were analyzed using IDEXX Quanti-Tray®/2000 trays and Colilert® reagent (IDEXX, 2007; IDEXX, 2002). Three dilutions of each sample were prepared: 1:10, 1:100, 1:10,000. This was to ensure that at least one valid reading was obtained for each sample (counts not too high or too low). A 100-mL sample of each dilution was prepared in a washed and autoclaved glass container. For the 1:10 dilution, 90 mL of deionized (DI) water and 10 mL of sample were combined. The DI water was measured using a sterile graduated cylinder. The sample was measured using an Eppendorf Research Pippette® set to 1 mL. A new sterile Eppendorf Tip® was used for each sample. For the 1:100 dilution, 99 mL of DI water and 1mL of sample were used. The same measurement tools were used. For the 1:10,000 dilution, 99 mL of DI water and 1 mL of 1:100 dilution were used. For each 100-mL dilution sample, 1 aliquot of Colilert® reagent was added. This was mixed until the Colilert® dissolved. The mixture was then poured into a labeled Quanti-Tray®/2000 tray and sealed in the Quanti-Tray® Sealer. The trays were then incubated at 34°C for 24-28 hours. After the incubation period, the trays were read. Wells yellow in color tested positive for total coliform and wells yellow in color that also fluoresced under 365-nm UV light tested positive for *E. coli*. The number of positive large and small wells was recorded for total coliforms and *E. coli* for each tray. These procedures were followed in accordance with published IDEXX procedures for IDEXX Quanti-Tray®/2000 and Colilert® (IDEXX, 2007; IDEXX, 2002). Bacteria were quantified by reference to the most probable number (MPN) table distributed with IDEXX Quanti-Tray®/2000 trays.

3.2 Results

3.2.1 Calculated Decay Rates

Following analysis of the samples from the light and dark attenuation studies, I used Equation 3.1 to calculate decay rates for each dilution of each study repetition with valid upstream and downstream readings. I then calculated an average decay rate for both light and dark conditions for *E. coli* and total coliforms. See Table 3.1 below. Table 3.1 includes decay constants calculated with and without outliers omitted. Outliers were defined as decay constant values not of the same order of magnitude as the majority of values for that particular bacteria and study. For all values, please see Appendix A.

Table 3.1: Average first-order decay constants (k) in units of hr^{-1}. Values rounded to one significant figure. Decay constants reported as averages ± one standard deviation.

	Data Included in Average	Total Coliforms		*E. coli*	
		k (1/hr)	# Points Included	k (1/hr)	# Points Included
Light	All	0.2 ± 3	5	3 ± 2	11
	No Outliers	2 ± 1	3	3 ± 1	9
Dark	All	-2 ± 4	5	-1 ± 1	8
	No Outliers	-1 ± 1	3	-1 ± 1	7

These values are significantly different than those found in literature. See Table 3.2 for sample literature values. The average values of the decay constants from the light attenuation study are generally much higher than those found in literature; however, the literature values do vary a lot, covering four orders of magnitude. The average values calculated for decay constants for the dark attenuation study are all negative, which indicates growth. While all of the literature values indicate decay, growth has been observed in tropical climates, as noted above in discussion of Rivera et al. (1988).

Table 3.2: First-order decay constants from literature. These data are from Table 8-2 in Bowie et al. (1985).

Location	k (1/hr)	Source
Glatt River (Switzerland)	1.1	Wasser et al. (1934)
Ford Lake (Michigan, August)	0.4	Gannon et al. (1983)
Tennessee River (Chattanooga, Summer)	0.005	Kittrell and Furfari (1963)
Tennessee River (Knoxville, Summer)	0.043	Kittrell and Furfari (1963)
Cumberland River (Summer)	0.23	Kittrell and Furfari (1963)

3.2.2 Uncertainty and Error

Table 3.1 shows that there is high uncertainty associated with these results. Even when outliers are excluded, one standard deviation is around 50% of the average. There are many possible explanations for the variability seen in Table 3.1. Potential sources of error include laboratory and field errors, such as cross-contamination (before and after sample transport). There were also two very small inflows into the study reach originating from seepage from the sides of the channel; I assumed that their effect was negligible. Besides error, there are many other sources of variability. There is inherent variability associated with field and lab work. For example, there is imprecision associated with the measurement of travel time and measurements in the laboratory. Additionally, there is higher variability associated with higher dilutions due to the decreased sample size. There is also natural variability; the literature values shown in Table 3.2 show almost one order of magnitude of variability for decay rates calculated in the same river.

3.2.3 Implications

Even though uncertainty in my results is high, I can still draw some conclusions. All of the average decay rates I obtained for the light attenuation study are positive, indicating decay. All of the average decay rates I obtained for the dark attenuation study are negative, indicating growth. Growth of *E. coli* and other coliforms has been shown to occur in tropical climates in a study by Rivera et al. (1988) in the rainforest of Puerto Rico. Another study, by Muñiz et al. (1989), also demonstrated growth of *E. coli* in the Mameyes River of Puerto Rico. Like Puerto Rico, Singapore has a tropical climate, so it is plausible that *E. coli* and coliform growth is occurring under dark conditions. Because there is a high degree of variation in my results, more work needs to be done to better characterize the behavior of these bacteria. While some natural variation is to be expected, measuring die-off over a short reach would tend to increase the sensitivity of the results to the measured time of travel. Future studies should be conducted in a variety of channels with higher travel times, at different times of day, and on different dates. This would provide a broader, more comprehensive set of results over which to average.

4 Model Application

To simplify the application of SWAT, I used the ArcSWAT Version 2.3.4 (Winchell et al., 2009) extension for ArcGIS Version 9.3 (ESRI, 2008). ArcSWAT provides a graphical user interface for adding SWAT model inputs and for running SWAT.

4.1 Watershed Delineation

Watershed delineation is the determination of the area drained through a point of interest. This is the first step in applying ArcSWAT. The watershed boundary determines what precipitation, point sources, and land area contribute to discharge through the point of interest (Kranji Reservoir, in this study). The watershed is then divided into smaller contributing watersheds, or subbasins. Flow is modeled from subbasin to subbasin until it reaches an outlet point. The flow out of a subbasin is determined by a mass (water) balance: Flow out = Flow from contributing subbasins + precipitation – evapotranspiration – infiltration + groundwater discharge to drainage network. The composition of the flow leaving a particular subbasin is also determined by a mass balance: Load out = Loading from contributing subbasins + runoff loading from within subbasin – decay + growth. In this case, "load" is the number of bacteria.

ArcSWAT has a built-in "Automatic Watershed Delineation" tool that allows the user to graphically delineate the watershed and corresponding subbasins. The user first inputs a Digital Elevation Map (DEM) file in ESRI GRID format. I generated this elevation file using an elevation contour file, a shapefile containing the man-made drains in the catchment, a shapefile of Kranji reservoir, and the "Topo to Raster" tool in ArcMap. GIS coverages were provided by PUB. With the Topo to Raster tool, I was able to interpolate the contour file to obtain a DEM GRID file. I was also able to input the drain file and the reservoir file to artificially lower the elevation for these known features. Doing this helps to ensure that the watershed delineator places streams as accurately as possible.

The "Automatic Watershed Delineation" generates predictions of stream locations within the model by using multiple pre-defined GIS files: the DEM (elevation data), a mask (another GRID file indicating the extent of the watershed), and a stream shapefile containing locations of known streams (drains, in this case). ArcSWAT also takes into account a threshold drainage area (I chose the minimum for this value: 7 hectares), which essentially defines the resolution of the watershed delineation and stream generation. After generating streams, I input the locations of point sources within the catchment. The next step is to identify "Whole Watershed Outlets." Whole watershed outlets are points through which all water leaving the basin drains. I selected these points as the endpoints of streams discharging directly into the reservoir. ArcSWAT then generated the watershed and subbasin boundaries. Each stream segment has its own subbasin and all subbasins are contained within the watershed boundary. See Figure 4.1 for the completed watershed delineation.

4.2 Definition of Hydrologic Response Units

Each subbasin is composed of one or more hydrologic response units (HRUs), each consisting of land having uniform land use, soil, and slope characteristics. SWAT does not model flow between HRUs; they are hydraulically connected to each other within the model. Runoff is predicted separately for each HRU and summed to obtain the total runoff for each subbasin (Neitsch, 2005).

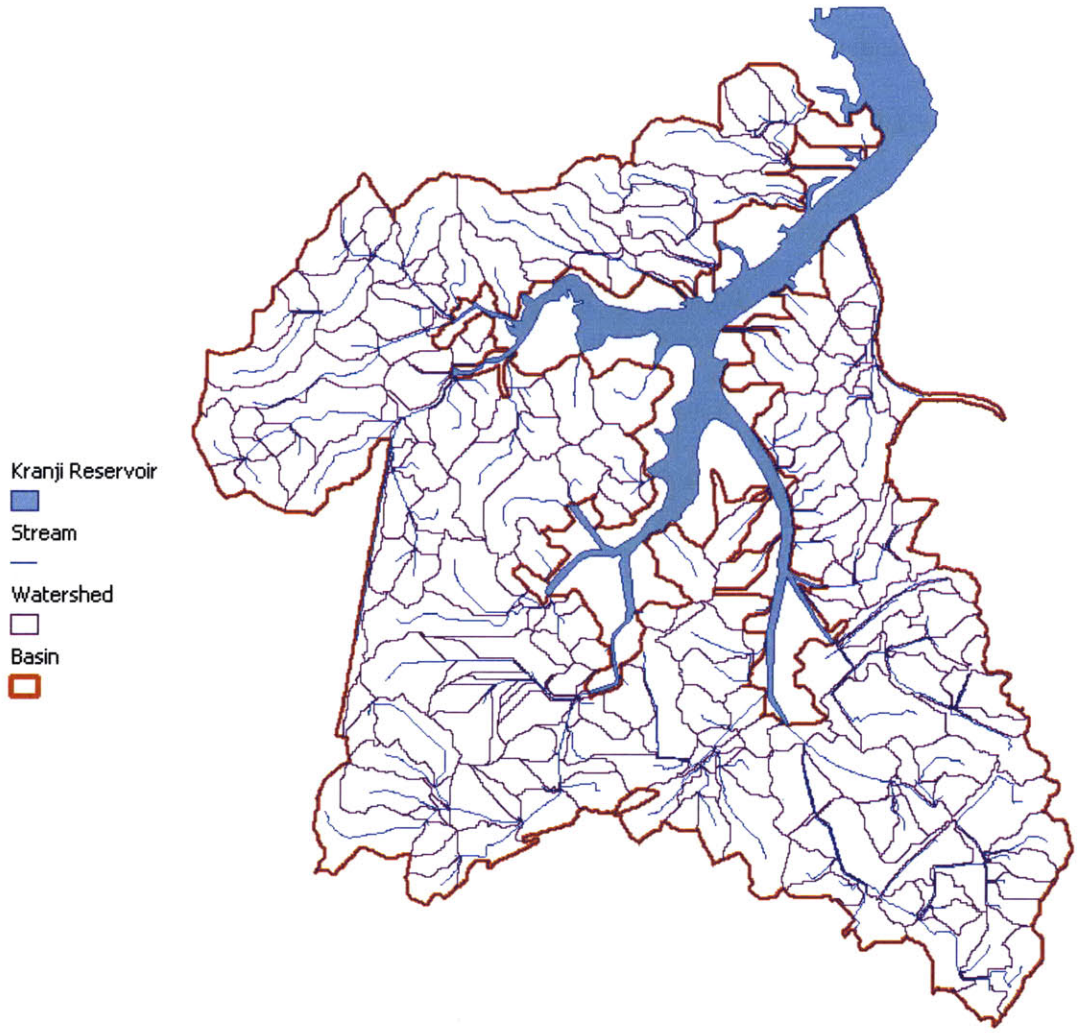

Figure 4.1: Subbasin boundaries determined by ArcSWAT watershed delineation.

4.2.1 Land Use

SWAT takes a multitude of parameters from land use type. I do not have SWAT-required values for each specific land use within Kranji Catchment, so I used a Singapore land use map provided by PUB (in the form of a GIS shapefile) and the predefined land uses in the SWAT2005 database to condense the 23 land uses presented in the Singapore land use shapefile down to nine predefined land uses from the SWAT2005 database. See Table 4.1 for land use redefinition. See Figure 4.3 for land use distribution.

Table 4.1: Land use reclassification.

Singapore-Defined Land Use	SWAT Code
AGRICULTURE	AGRL
CEMETERY	FESC
CIVIC & COMMUNITY INSTITUTION	UINS
COMMERCIAL	UCOM
COMMERCIAL & RESIDENTIAL	UCOM
EDUCATIONAL INSTITUTION	UINS
HEALTH & MEDICAL CARE	UINS
LIGHT RAPID TRANSIT	UTRN
MASS RAPID TRANSIT	UTRN
OPEN SPACE	FESC
OPEN SPACE IN URBAN	FESC
PARK	FESC
PLACE OF WORSHIP	UINS
RESERVE SITE	RUBR
RESIDENTIAL	URHD
RESIDENTIAL WITH COMMERCIAL AT 1ST STOREY	URHD
ROAD	UTRN
SPECIAL USE	RUBR
SPORTS & RECREATION	FESC
TRANSPORT FACILITIES	UTRN
UTILITY	UIDU
WATERBODY	WATR

SWAT Land Use	SWAT Code
Commercial	UCOM
High-Density Residential	URHD
Institutional	UINS
Rubber trees	RUBR
Tall Fescue	FESC
Transportation	UTRN
Water	WATR

4.2.2 Soils

I was able to generate shapefiles delineating mapped soil series for Kranji Catchment by using maps provided by Ives (1977). I was able to define properties and parameters for the soil types present in the catchment from information given by Ives, as well as information given by Chia et al. (1991). See Figure 4.4 for soil series information.

Unfortunately, I was not able to obtain all the required values for all soil types. To fill in the gaps, I grouped the soils based on soil groups given in Chia et al. (1991). If a group was not defined for a particular soil, I used texture, hydrologic group, and drainage properties to assign the soil to an appropriate group. I used average values from each group to assign values where data was missing. See Table 4.2 for a summary of soil groups and characteristics. See Appendix B for complete soil groupings and characteristics.

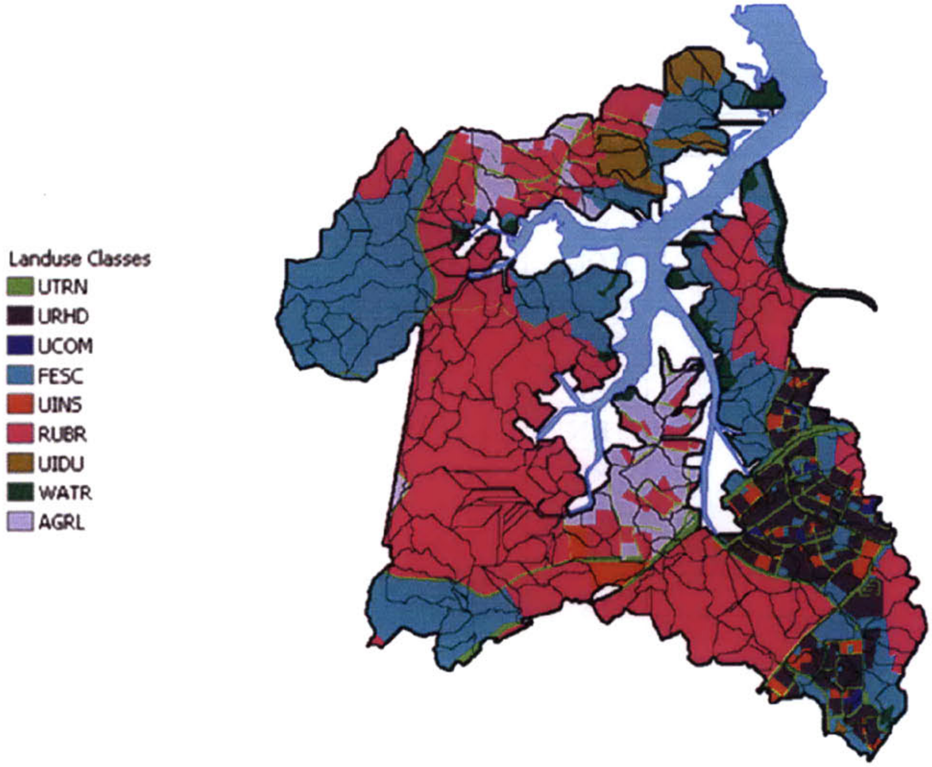

Figure 4.3: SWAT land use classes within Kranji Catchment.

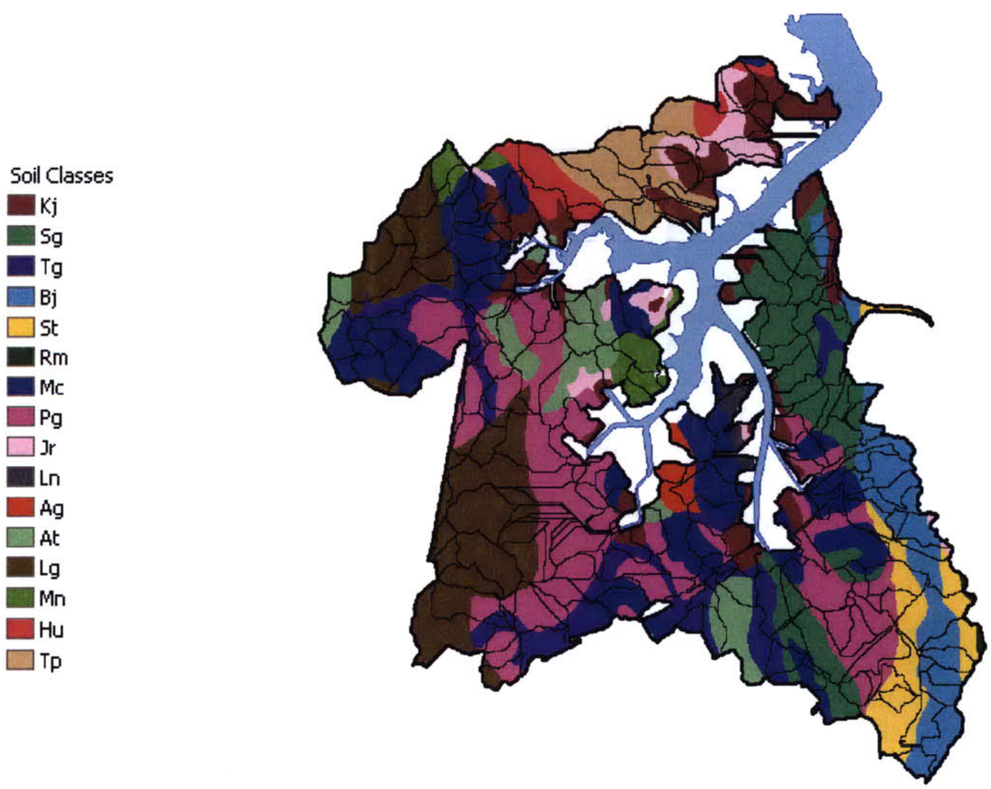

Figure 4.4: Soil classes within Kranji Catchment.

Table 4.2: Soil classes within Kranji Catchment. Soil group denotes soil type used to assign values for missing data.

Soil Name	Abbreviation	Drainage	Soil Texture	Hydrologic Group	Soil Group
Lokyang	Lg	Somewhat impeded drainage	sandy, sandy clay, and clay loams	C	Lg
Harimau	Hu	Well drained	sandy and sandy clay loam	B	Hu-Tp
Lam San	Ln	Moderately well drained	sand and sandy loam	B	Hu-Tp
Tengah	Tg	Somewhat impeded to poorly drained	heavy clay and silty clay loam	C	Hu-Tp
Tampoi	Tp	Well drained	sandy and sandy clay loams	B	Hu-Tp
Jurong	Jr	Poorly drained	granular clay and sandy loams, peaty loams, and organic clays	D	Kj
Kranji	Kj	Very poorly drained	silty and sandy clay loam, dark grey silty clay, and muck	D	Kj
Ayer Terjun	At	Moderately well drained	sandy clay and clay loam, and clay	C	At
Malacca	Mc	Moderately well drained	sandy and sandy clay loam	C	At
Munchong	Mn	Moderately well drained	clay loam and clay	B	At
Bukit Panjang	Bj	Moderately well drained	sandy clay loam	C	Rm
Rengam	Rm	Well drained	sandy and sandy clay loams	B	Rm
Sungei Kadut	St	Moderately well drained	sandy clay and clay loams and clay	C	Rm
Aik Hong	Ag	Well drained	sandy, clay, and sandy clay loam	B	Pg
Peng Siang	Pg	Well drained	sandy and sandy clay loams	B	Pg
Serdang	Sg	Well drained	sandy and sandy clay loams	B	Pg

4.2.3 Slope

ArcSWAT uses the DEM provided for watershed delineation to calculate slopes throughout the watershed. I chose to use two slope classes: 0%-3.1% and 3.1% and above, where 3.1% is the median slope within the catchment. See Figure 4.5 for slope definition.

4.2.4 HRU Definition Thresholds

ArcSWAT overlays the land use, soil type, and slope information to define HRUs. I chose to allow multiple HRUs in subbasins. As recommended by Winchell et al. (2009), I defined the threshold values for land use, soil type, and slope as 20%, 10%, and 20%, respectively. This means that if a land use covers more than 20% of the subbasin, a separate HRU is defined for that land use (e.g. for one land use: LU-A). If more than 10% of the subbasin is over a certain soil type, then a separate HRU is defined for that soil type and any previously defined land uses (e.g. for two soil types: LU-A\ST-A and LU-A\ST-B are created). If a slope class covers more than 20% of the subbasin, an HRU is defined for that slope class and any previously defined land uses and soil types (e.g. for two slope classes: LU-A\ST-A\SC-A, LU-A\ST-B\SC-A, LU-A\ST-A\SC-B, and LU-A\ST-B\SC-B are created).

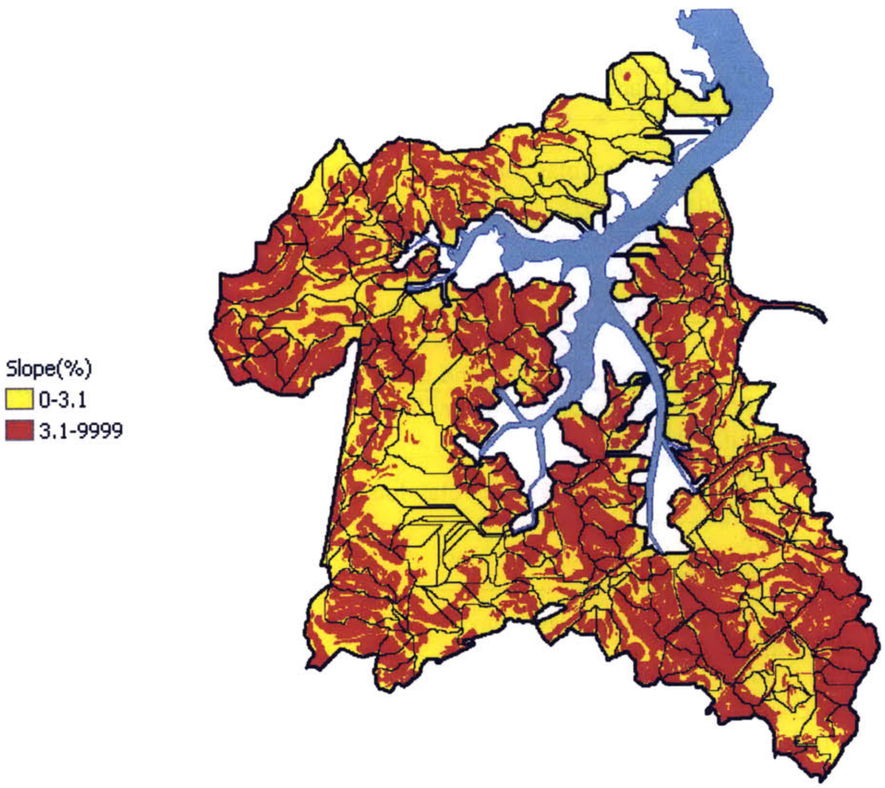

Figure 4.5: Slope classes within Kranji Catchment.

4.3 Weather Generator

During the SWAT simulation, weather is either simulated using SWAT's weather generator, or daily or sub-daily weather values are input by the user. For this study, SWAT's weather generator was used because there is no specific time period of interest. I am interested in the general behavior of water and bacteria within the catchment, which can be modeled using the weather generator, which generates weather based on the general behavior of the weather during a given month. Using weather data collected from the NTU-maintained meteorological station in Kranji Reservoir, I calculated average monthly values for SWAT-required weather inputs. See Appendix C for the weather values input into SWAT.

4.4 Bacteria Parameters

Most of the parameters described above primarily concern the physical behavior of water within the catchment and have only indirect effect on how bacteria behave within the flow. This section provides information on the parameters with direct effect on the fate and transport of bacteria. This section also describes the bacterial loads associated with point and non-point sources within the catchment.

SWAT allows for two different types of bacteria to be modeled, persistent and less persistent. In reality, the "less" is only used to distinguish between the two bacteria and has no actual bearing on their behavior in the model. For the sake of clarity, I modeled *E. coli* as the "persistent" bacteria and total coliforms as the "less persistent" bacteria. I used the results of my fieldwork (discussed above in Chapter 3) to assign values to these variables. SWAT does not allow for separate light and dark decay constants, so I had to combine the results of my light and dark attenuation studies into an effective decay constant, K_{eff}. Because bacterial decay is modeled as first-order and Singapore experiences approximately equal hours of light and dark, I combined the constants as:

$$C_t = (C_0*\exp[-K_L*0.5*t])*\exp[-K_D*.5*t] = C_0*\exp[-t*0.5*(K_L + K_D)] \quad (4.1)$$

which implies that:

$$K_{eff} = 0.5*(K_L + K_D) \quad (4.2)$$

where, t is the time in days, C_t is the concentration at time t, C_0 is the initial concentration, K_L is the decay constant for light conditions, and K_D is the decay constant for dark conditions. See Table 4.3 for effective decay constants.

Table 4.3: Effective decay constants for total coliforms and *E. coli*.

	Total Coliforms	*E. coli*
	k (day^{-1})	k (day^{-1})
Light	43 ± 27	63 ± 26
Dark	-23 ± 13	-29 ± 18
Effective	10	17

As discussed above, point source locations are input during the watershed delineation process. The point sources that I input are sewage treatment plants (STPs) within the catchment. These STPs are controlled by PUB, so I was able to calculate flow rate estimations from the information they provided. I used bacterial concentrations obtained from sampling done in January 2009, July 2009, and January 2010 to calculate bacterial loadings for a subset of STPs. Where data were not available for a particular STP, I used the average bacterial concentration from STPs on similar land uses to calculate a loading. See Appendix D for point-source values used in the model.

Another source of bacteria within the catchment is non-point source (NPS) contamination carried by runoff. From inspection of sampling data from January 2009, July 2009, and January 2010, it is apparent that most of the samples with the highest bacterial concentrations were from agricultural areas. That said, my most inaccurate set of parameters is that associated with land use—agricultural land in particular. From observations while in Singapore, I know that land categorized as "agriculture" encompasses everything from orchid farms to fish farms to small organic farms to chicken farms. Each of these land uses contributes differently to runoff loadings; however, I do not have data describing which areas within the "agriculture" area are used for which actual land use. I also do not have data characterizing loadings from each particular agricultural activity.

In an attempt to associate some form of NPS loading with agricultural land, I made two small adjustments to SWAT's default management practices for "Generic Agricultural Land." I changed the default fertilizer type to "Fresh Broiler Manure" because chickens are the only livestock I observed on the island and manure has bacterial loadings associated with it. I also changed the *E. coli* concentration in the fertilizer to 500,000 cfu/g fertilizer. This is the average of the values I found in the literature, which suggest that the *E. coli* concentration varies between 0 and 1,000,000 cfu/g fertilizer (Suslow, 1999). I know that total coliform concentration is higher than *E. coli* concentration, so I used 1,000,000 cfu/g fertilizer for total coliform concentration. This is by no means an accurate characterization of NPS pollution from agricultural areas; however, the necessary data are not yet available, and this is a parameter that is easily adjusted to refine results.

5 Model Results

My final model run produced five years of continuous daily output. The results from the first year were discarded as spin-up time; the ArcSWAT documentation suggests that this is sufficient to ensure that the hydrologic cycle is geared up (Winchell et al., 2009). SWAT outputs daily predictions of flow, total coliform and *E. coli* concentrations, runoff, precipitation, evapotranspiration, percolation, and temperature for each HRU, subbasin, and reach. These outputs are most dependent on the following model parameters: die-off rates for *E. coli* and total coliforms, concentrations of *E. coli* and total coliforms in fertilizer, and point source loadings of *E. coli* and total coliforms. Due to an input error, K_{eff} was doubled from the values calculated in Chapter 4. Since the magnitude of the error was within the range of uncertainty in the values, the model was not re-run after discovery of the error.

5.1 Presence/Absence Results

As discussed in Section 4.4 above, data were not available to parameterize exactly non-point sources of bacteriological contamination within Kranji Catchment. However, because of the sampling program that was previously conducted by students from NTU and MIT (Dixon et al., 2009), I know that there is a high concentration of bacteria coming from agricultural land either as runoff or as effluent from sanitary sewers. I attempted to capture runoff contamination by using the management options in SWAT to simulate routine application of fertilizer on all agricultural land. In Kranji Catchment, there are a variety of agricultural activities (orchid farming, fish farming, chicken farming, etc.) all taking place on land I classified simply as "Agricultural" in the model. Because the specific bacterial loading rates associated with these various activities are unknown, the model does not distinguish between different agricultural land uses. The rough estimation used to model non-point source pollution cannot be expected to provide accurate results in terms of loading magnitudes; however, it should provide a fairly accurate prediction of where contamination is present and where it is not.

As a first test of the model's performance, I evaluated the model's ability to predict the presence or absence of bacteria (not considering concentration magnitude). I am particularly interested in the bacterial loading to the reservoir. Because individual subbasins have very small areas and there are 266 of them, I decided to analyze more general catchment areas (from this point referred to as "subcatchments"). There are 49 whole-watershed outlets (outlets discharging directly to the reservoir) in the model. Using the watershed delineation provided by SWAT, I divided Kranji Catchment into 49 subcatchments corresponding to these outlets. Each of these subcatchments corresponds to a whole-watershed outlet in the model. Each subcatchment is composed of the SWAT-delineated subbasin(s) that are drained through the corresponding whole-watershed outlet. Figure 5.2 shows the delineation of the subcatchments and corresponding land uses. Table 5.1 shows predicted concentrations versus those observed in the field for some of these subcatchments. The subset of these results for which field data are available is summarized in Figure 5.1 in terms of the model's ability to predict the presence or absence of *E. coli* and total coliforms. A subcatchment was considered to be positive, for model predictions or sampling data, if average concentration exceeded 100/100mL.

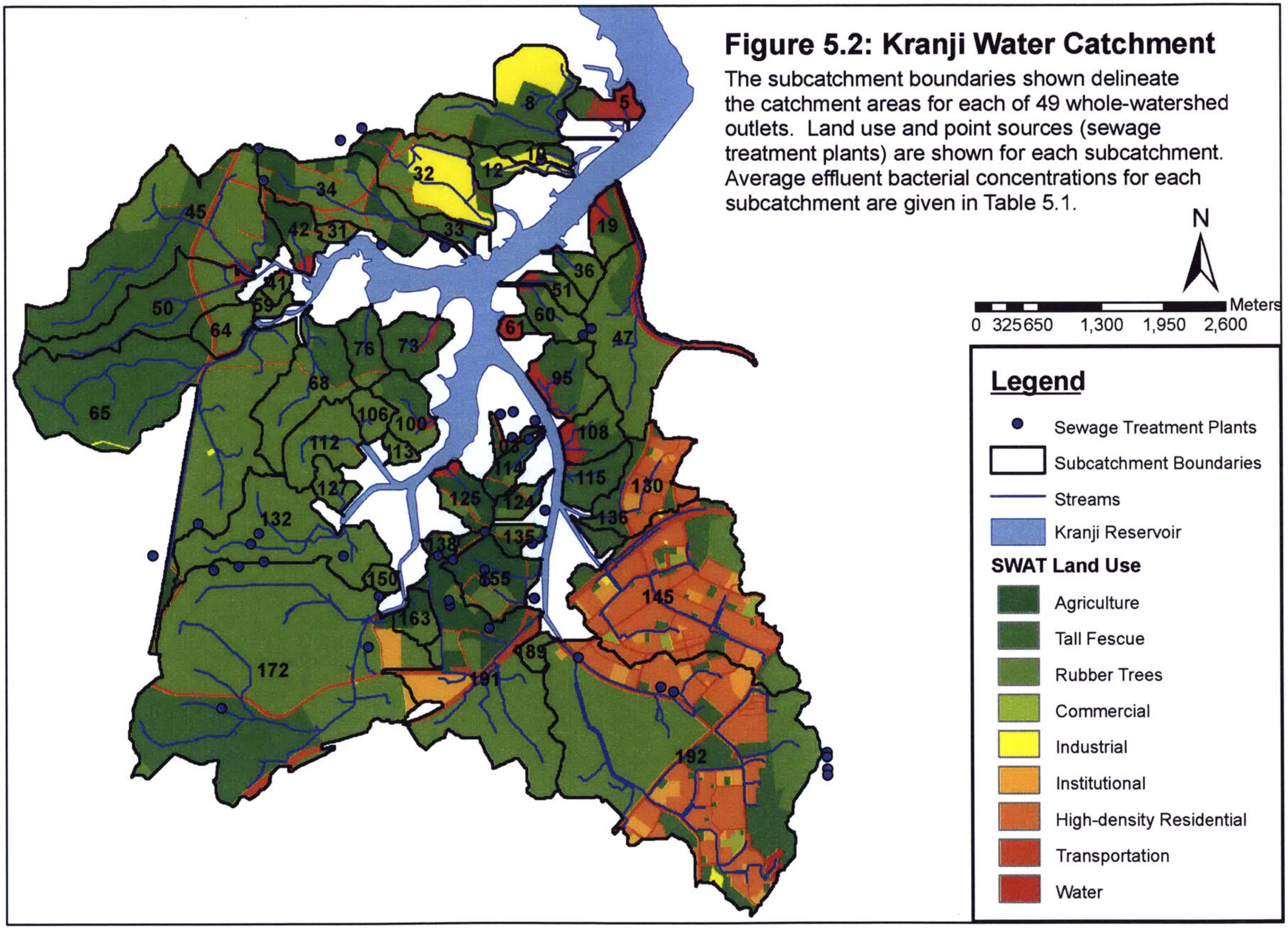

Figure 5.2: Kranji Water Catchment

The subcatchment boundaries shown delineate the catchment areas for each of 49 whole-watershed outlets. Land use and point sources (sewage treatment plants) are shown for each subcatchment. Average effluent bacterial concentrations for each subcatchment are given in Table 5.1.

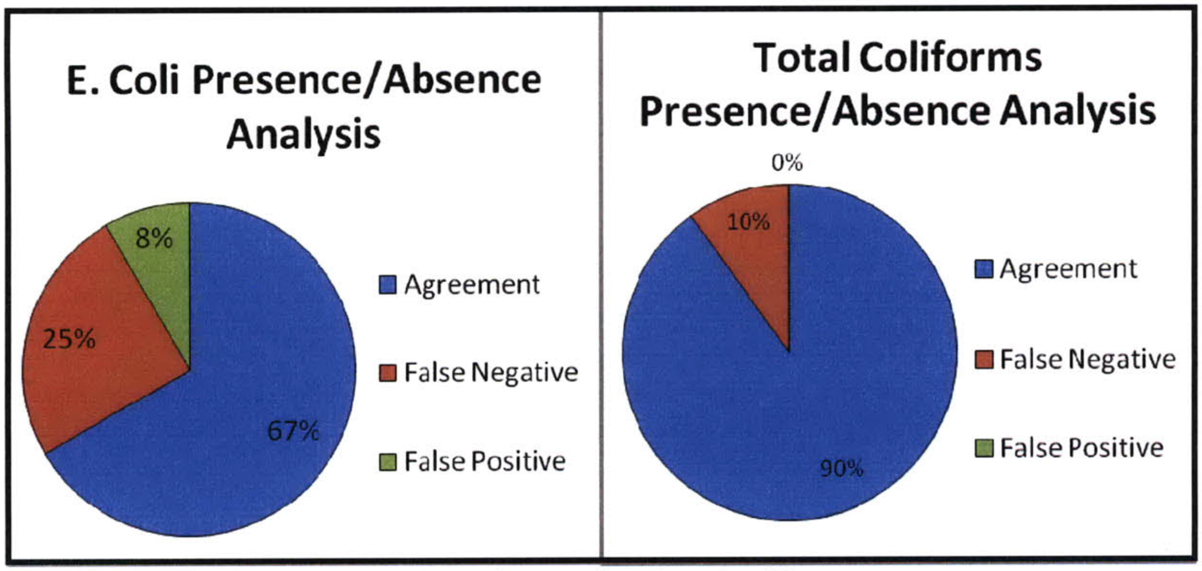

Figure 5.1: Presence/absence analyses for *E. coli* and total coliforms.

Figure 5.1 shows that, for subcatchments with sampling data, the model accurately predicts presence or absence of *E. coli* 67% of the time and total coliforms 90% of the time. The model accurately predicted positive *E. coli* and total coliform presence in 10 subcatchments each. Even though the model simulates them as two separate bacteria, total coliform concentration is actually a sum of the concentrations of all coliform bacteria, including *E. coli*. This means that total coliforms should be predicted at least as often as *E. coli*, if the model is making accurate presence/absence predictions. This condition is fulfilled in that equal numbers of subcatchments were predicted to have *E. coli* and total coliforms. A false negative occurs when the model predicts the bsence of bacteria, but the field data show bacteria to be present above the 100/100 mL threshold. A false positive occurs when the model predicts bacteria to be present, but the field data show bacteria to be absent. False negatives are predicted more often than false positives. This could indicate that die-off rates are too low, that there are there are sources in the real catchment that are not simulated by the model, or that the source concentrations simulated in the model are too low. Where there is a basis for comparison, the model agrees with the field observations more often than not. The model will require more refinement to make more accurate predictions, but this is a good foundation to work from.

5.2 Drain Discharges to the Reservoir

It is also important to evaluate the model's prediction of the magnitude of loading to the reservoir. The model does show a good ability to make qualitative predictions of the presence or absence of bacteria; however, as seen in Table 5.1, quantitative agreement between model predictions and field observations is poor. This is likely the result of several factors, the most important of which is that the specific loading rates for individual agricultural land uses are not available in general, let alone for Singapore specifically. More information is needed to characterize management practices for the particular agricultural activities carried out in the catchment and to develop appropriate loading rates. Additionally, more information is needed to understand the relative contributions of point and non-point sources to bacterial loads. These factors are discussed further in the following sections, which evaluate two specific subcatchments with different compositions.

Table 5.1: Comparison of predicted and observed concentrations.

	Average *E. coli* Concentration (#/100 mL)		Average Total Coliform Concentration (#/100mL)	
Subcatchment	Model	Samples	Model	Samples
8	1,000,000	---	20,000,000	---
10	5,000	---	2,000,000	---
31	1	---	500	---
32	30	390	300	68,000
33	0.2	---	200	---
34	4,000,000	52,233	800,000,000	3,379,200
41	0.003	---	9	---
42	30,000	62	80,000	3,690
47	400	---	1,000,000	---
50	0	23	0	---
60	100,000	---	100,000,000	---
65	20	3,271	200	44,100
100	500	---	600,000	---
103	5,000,000,000	---	10,000,000,000	---
113	1,0000	---	60,000	---
114	10,000,000	6,440	300,000,000	129,970
124	40,000,000	7,373	200,000,000	184,950
125	60,000	---	100,000	---
127	70	---	20,000	---
130	100	---	80,000	---
132	400,000	---	200,000,000	---
135	600,000,000	---	2,000,000,000	---
138	600,000	---	100,000,000	---
145	0	70,445	0	7,054,700
150	30,000	---	20,000,000	---
155	100,000,000	7,395,400	700,000,000	41,519,000
163	70,000	---	7,000,000	---
172	10,000,000	254	20,000,000,000	16,070
191	400,000	176,970	5,000,000	---
192	2,000,000	4,478	3,000,000,000	69,040

Note: Model results were rounded to one significant digit. Subcatchments highlighted in gray are discussed in the text. "---" signifies that samples were either not taken within the subcatchment or that no valid sampling results were obtained from within the subcatchment.

5.3 Model Results for Subcatchment 42

The geographic location of subcatchment 42 (sub 42) is shown in Figure 5.2; it is located in the northwest quadrant of Kranji Catchment. Sub 42 contains no point sources. Its land use composition can be seen in Figure 5.3.

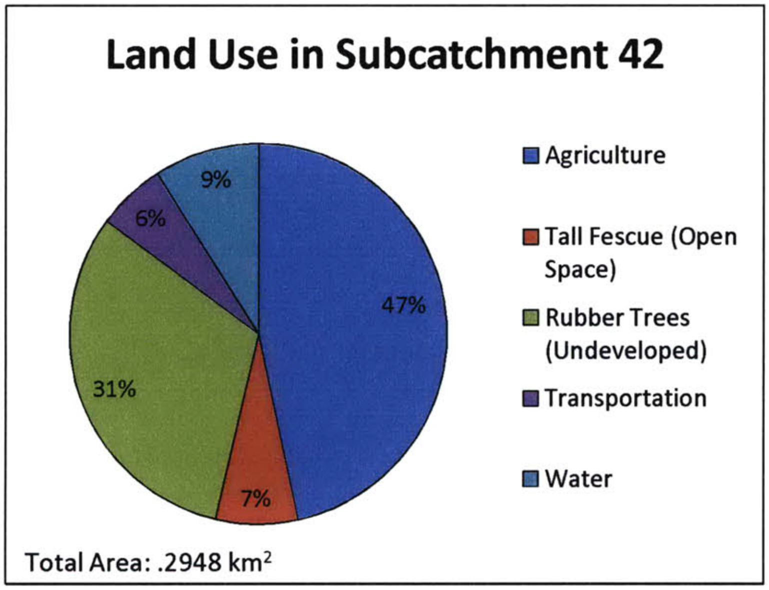

Figure 5.3: Land use distribution in subcatchment 42.

Because sub 42 contains no point sources, any bacteriological contamination must be originating from a non-point source (at least in the case of the model). For the model, this means the contamination is coming from agricultural land, which, as shown in Figure 5.3, comprises 47% of sub 42. Because of this, one would expect to see a non-point source signal in the model results; that is, one would expect to see higher bacterial loadings with higher flow (corresponding to higher precipitation, higher runoff, and higher subsurface contributions). Also, one would expect to see higher loadings with lower temperatures because SWAT models bacterial decay rate as a function of temperature (Neitsch et al., 2005):

$$K_T = K_{20}\theta^{T-20} \quad (5.1)$$

where, K_T is the first-order bacterial decay constant at temperature T, in degrees Celsius; K_{20} is the first-order bacterial decay constant at 20°C, which the user inputs into the model; and θ is the temperature adjustment factor for bacterial die-off/growth, with a default value of 1.070, which was used in my simulations. The temperature dependence can also be observed in Figure 5.4, which shows bacterial loading as a function of temperature within sub 42. Figure 5.4 shows a clear decreasing trend in maximum observed bacterial loading with increasing temperature. Both the non-point source loading signal and the temperature dependence of the decay constant contribute to the explanation of the model results for sub 42, which are shown in Figure 5.5

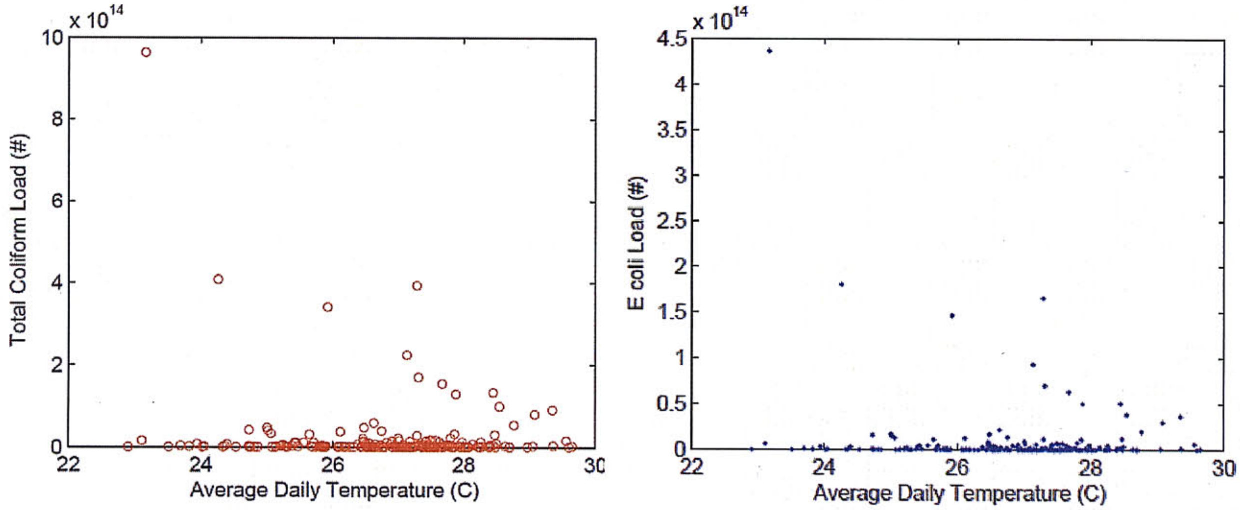

Figure 5.4: Predicted bacterial loadings as a function of temperature in subbasin 42.

The daily *E. coli* (blue) and total coliform (red) loadings are shown in the bottom panel of Figure 5.5. The loading plot does not look continuous because on most of the days there is very little to no loading; it is a log plot, so these points do not appear on the graph. There are intermittently some individual days with bacterial loading (the dots) and a few time periods for which loadings appear more continuous and are present over the course of a few days (lines). One of the reasons for the periods of no-load is that there is often very low flow out of the subcatchment; for example, in Figure 5.5 between lines A and B there is very little flow. During that time, the temperature is also elevated. Low flow implies low runoff, which implies that there would not be much mobilization of bacteria from non-point sources, while elevated temperature implies higher die-off rates, as discussed above. The discontinuous nature of the loadings plot is primarily due to these two factors. Conversely, where loadings are present continuously for time periods of a few days, there is higher flow and lower temperatures. This occurs, for example, in the model output along line E, where the temperature is a local minimum and the flow is a local maximum. The model output between lines C and D shows a trend similar to that along line E. The temperature during this period is very low, but so is the flow. The loading is highest at the beginning and end of this time period, which is also when temperature and flow are highest. When the flow decreases, so does the temperature, which is why the loading appears as continuous as it does (had temperature remained high as flow decreased, loading would have dropped off of the plot sooner). Because the highest loading in this period occurs when the temperature and flow rate are highest, I believe that, in periods of low flow in the model, flow rate is a more important factor than temperature in determining predicted loading to the reservoir. Higher temperature should indicate lower concentration; however, flow was also slightly elevated at the same time as temperature. The outgoing concentration was definitely highest during the time period when flow was highest, regardless of temperature.

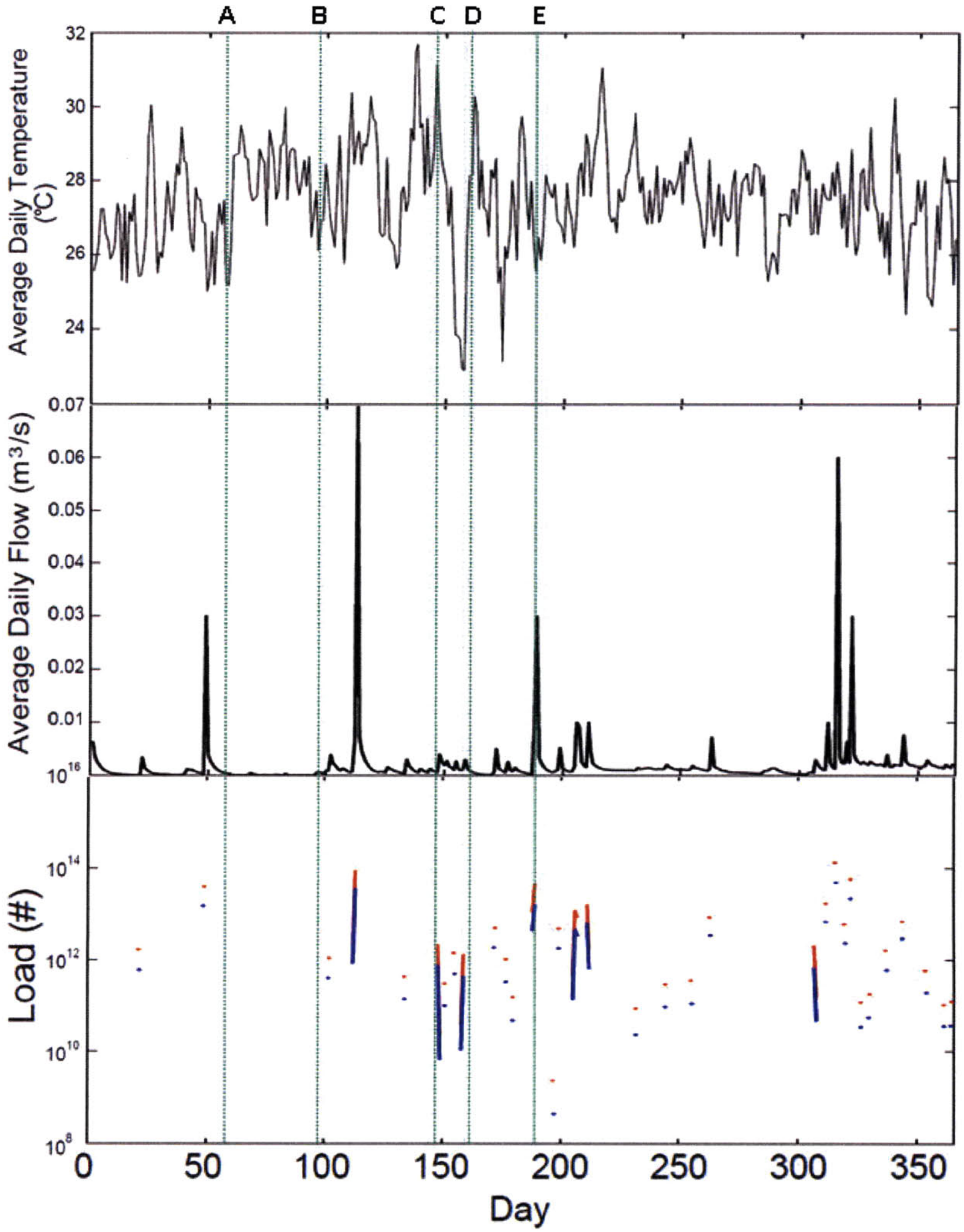

Figure 5.5: These plots show daily bacterial loading, daily average temperature, and daily average flow rate predictions for sub 42 in model year 3. The red lines and dots represent total coliform loading, the blue lines and dots represent *E. coli* loading.

For this subcatchment, the model predicts average bacterial concentrations that are much higher than those observed in the field (Table 5.2). There could be a variety of reasons for this. One explanation is that the non-point source loadings that I introduced are too high. Another explanation is that the bacterial decay rates I measured and used in the model could be too low. This over-prediction of concentration could also be due to the bacteria being mobilized from the fertilizer too easily; the sorption coefficient could be too low. There are many possible explanations for the model predicting excess concentration; however, more information is needed to determine the cause.

Table 5.2: Average bacterial concentrations in sub 42.

Average *E. coli* Concentration (#/100 mL)		Average Total Coliform Concentration (#/100mL)	
Model	Samples	Model	Samples
30,000	62	80,000	3,690

5.4 Model Results for Subcatchment 192

The geographic location of subcatchment 192 (sub 192) is shown in Figure 5.2; it is located in the southeast quadrant of Kranji Catchment, as shown in Figure 5.2. Sub 192 contains three sewage treatment plants (STPs), shown below in Table 5.3.

Table 5.3: Estimated flow rates and loadings from point sources in subcatchment 192.

STP Number	Flow Rate (L/day)	Total Coliform Load (#/day)	*E. coli* Load (#/day)
BJ 813	1,375	975,000,000	3,437,500
BP 492	300,000	208,800,000,000	750,000,000
BJ 726	60,000	41,760,000,000	150,000,000

The land use distribution for sub 192 is shown in Figure 5.6. As shown in Figure 5.6, sub 192 contains no agricultural land. This means that the only sources of bacterial contamination that are modeled within the subcatchment are point sources, thus I would expect to see a point-source signal. Such a signal is characterized by an almost constant loading with concentrations fluctuating as a function of flow, with higher flow yielding higher dilutions and lower concentrations. This dilution can be seen in Figure 5.7; it is particularly obvious along lines A, B, and C. Bacterial loading, as shown in Figure 5.8, is not constant, as one would expect, but varies over several orders of magnitude. This is due primarily to the same temperature dependency discussed above, for subcatchment 142. Between lines D and E in Figure 5.8, temperature is relatively high and bacterial loadings are relatively low. This is again because the die-off rate increases with increasing temperature. Conversely, between lines F and G, temperature is relatively low and bacterial loadings are relatively high. This dependency explains the lack of a strong point-source signal.

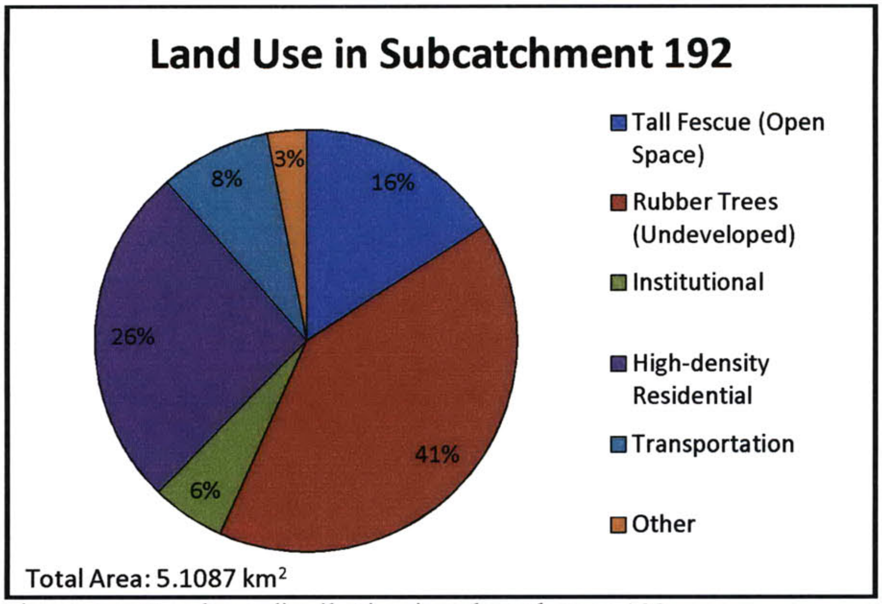

Figure 5.6: Land use distribution in subcatchment 192.

For sub 192, the model predicts concentrations that are much higher than those observed in the field (Table 5.4). There are several possible explanations for this over-prediction. The point source loading estimates in Table 5.3 could be too high; samples were only collected for a small subset of the STPs. The resulting concentration data from these samples was applied to non-sampled STPs with similar surrounding land uses. All of the STP's listed in Table 5.3 use the concentrations measured at BJ 813 to estimate daily bacterial loadings—this leaves much room for error. Additionally, the model requires that STPs be located on one of the streams defined during watershed delineation. In reality, these STPs are not located in the same location the model uses and travel time for bacteria in the drain could be longer, leading to reduced concentrations in the field observations. Another explanation is that the bacterial decay rates I measured and used in the model could be too low. More information on the actual concentrations in STP effluent, more accurate stream definition, and more refined die-off rates would yield a more refined model prediction.

Table 5.4: Average bacterial concentrations in sub 192.

Average *E. coli* Concentration (#/100 mL)		Average Total Coliform Concentration (#/100mL)	
Model	Samples	Model	Samples
2,000,000	4,478	3,000,000,000	69,040

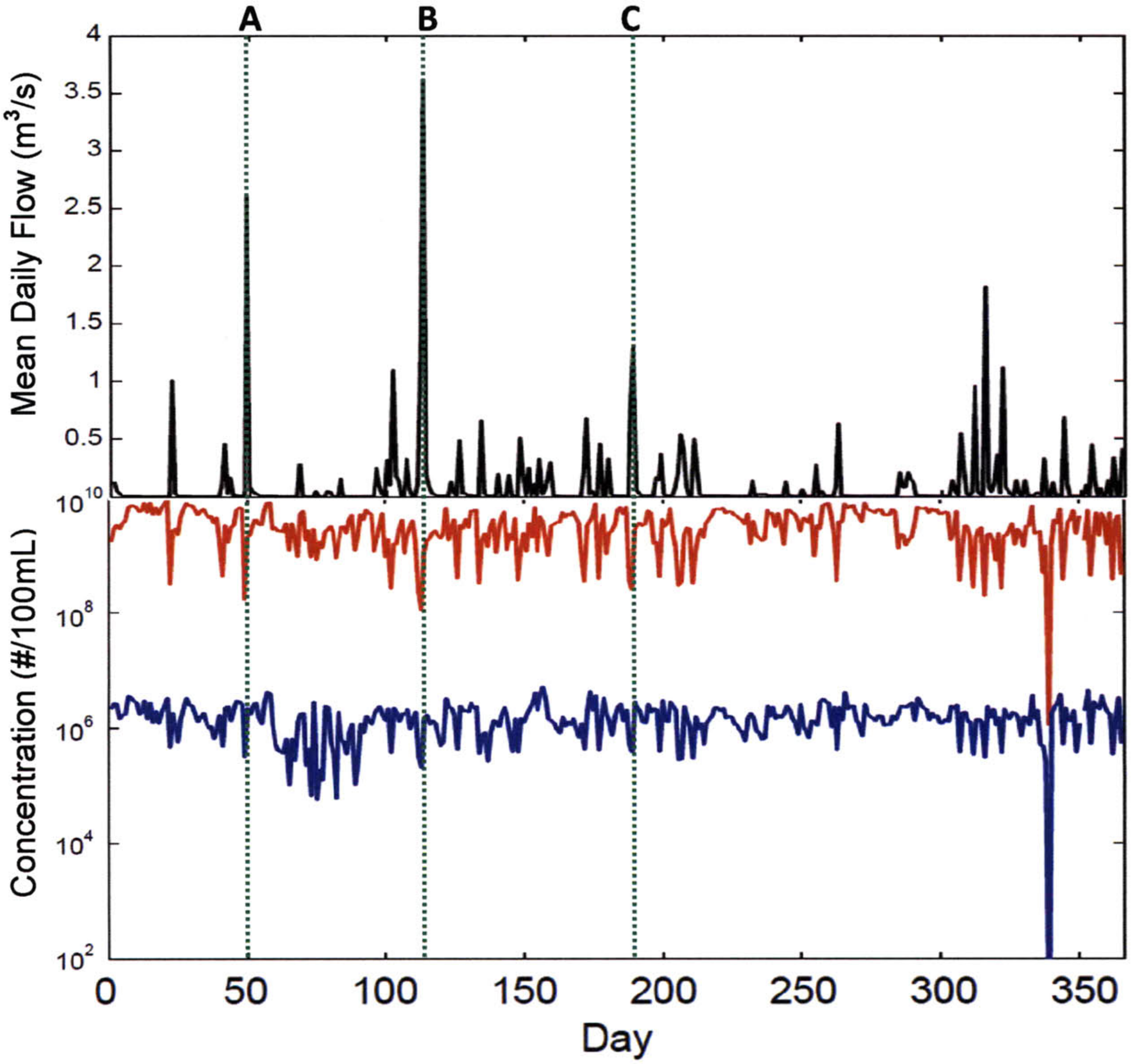

Figure 5.7: Comparison of predicted daily average flow to predicted daily average bacterial concentrations (*E. coli* concentration is shown in blue and total coliform concentration is shown in red) for subcatchment 192 in model year 3.

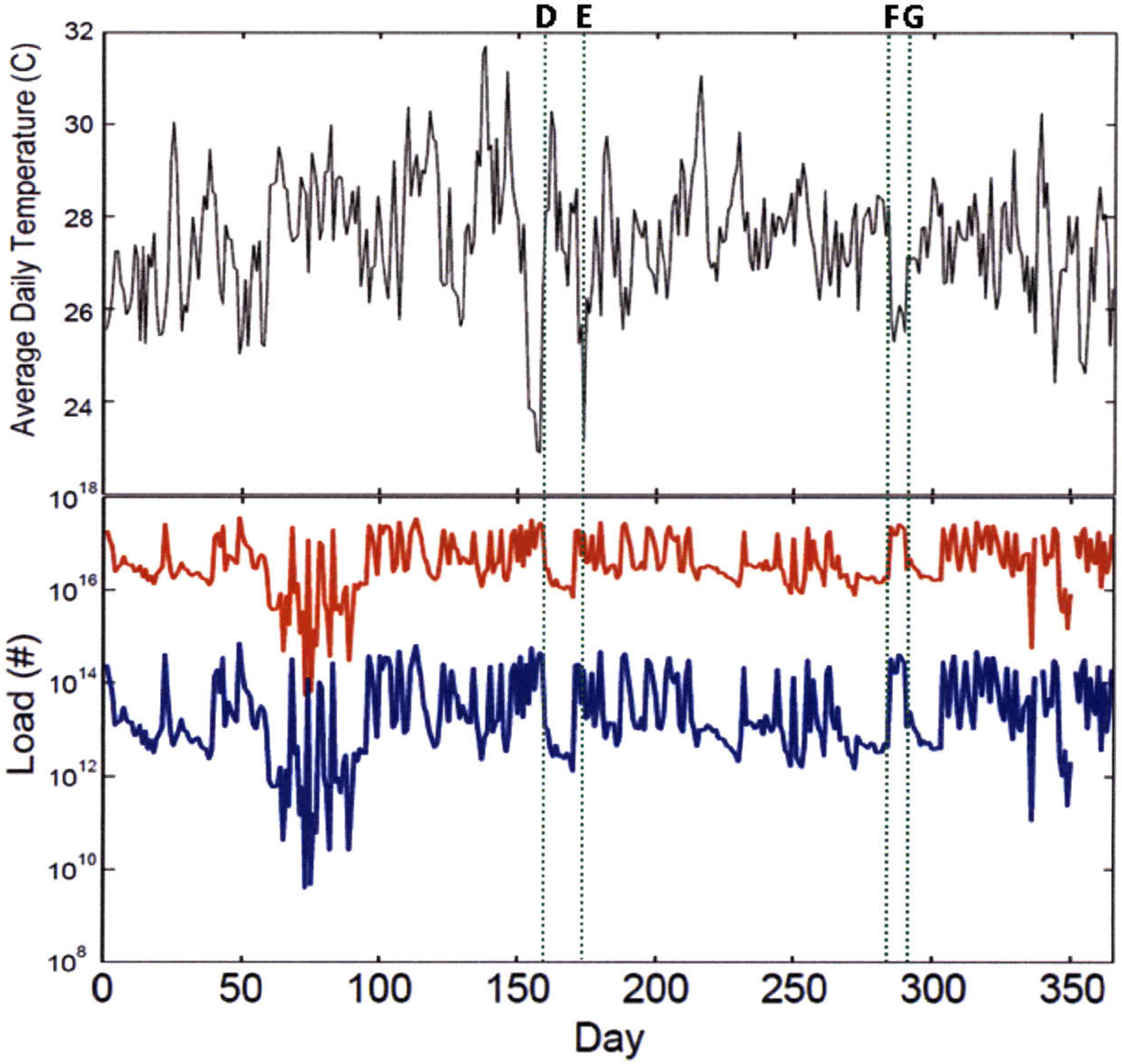

Figure 5.8: Comparison of predicted average daily temperature and average daily bacterial load (*E. coli* load is shown in blue and total coliform load is shown in red) for subcatchment 192 in model year 3.

6 Conclusions

6.1 Attenuation Study

The results from my attenuation study definitely suggest that further investigation is warranted concerning behavior of tracer bacteria in the Singaporean environment. My results indicate that at the particular times of my study and in that particular reach, *E. coli* and other coliform bacteria were dying in sunlit conditions and growing in dark conditions. Additional attenuation studies should be conducted in different reaches, over longer travel times, and at different times of day in order to further develop our understanding of how these bacteria behave. A study by Bellair et al. (1977) found that the rate of die-off of fecal coliform bacteria varied directly with light intensity in a study conducted at an ocean outfall for a sewage treatment plant in Australia. This result may have been amplified by the salinity of the water; high salinity can act to amplify the effects of solar radiation (Bowie et al., 1985). However, even if the results are amplified, the base indication is still that light intensity is an important factor in bacterial die-off, which agrees with the results of my attenuation study. My results show that, in the environment of the study, sunlight is one of the dominant factors, if not the dominating factor, affecting bacterial die-off. Further investigation should be conducted to better understand the behavior *E. coli* and other coliform bacteria in the Singaporean environment.

6.2 SWAT

6.2.1 Model Utility

For the most part, I found the ArcSWAT interface easy to use. I only encountered a few issues using ArcSWAT. It is not always easy to locate specific variables within the interface. Also, ArcSWAT does not always allow the user to set variables to the desired value; bounds set on field inputs are not always sufficiently broad.

SWAT requires huge amounts of data and input variables; these are not always easy to come by. However, there is a link between ArcSWAT and the SWAT2005 database, which makes it fairly simple to use SWAT's pre-defined inputs for various land uses, soil types, and management practices. In terms of time commitment, I may have been able to reach the same conclusions using just the watershed delineation, point source estimates, and sampling data, without the need for SWAT. In terms of output, SWAT gives well-organized results in an easy to use format. That said, output volume could be reduced by eliminating field redundancy between tables and within the same table (e.g. subbasin area only needs to be output once per subbasin).

One concern with using SWAT is its ability to model bacterial fate and transport in Singapore. The results of my attenuation study show that "decay" is very different in sunlit versus dark conditions. If the SWAT time step were shorter than a day, then it would be very important to model day and night differently. This would require changing some of SWAT's components—not an easy task. However, because the time step is at least a day, the decay rate can be modeled as an effective decay rate, as opposed to two separate rates. Decay rates vary over the course of a day; if the time step is a day or longer, the effects of the different decay rates can be averaged over that time period. If the time step is shorter than one day, the modeled decay rate would have to be dependent on the time of day, a functionality that SWAT does not currently possess.

6.2.2 Recommendations

This run of the model is like a first draft—more refinement and more information are needed before it will make accurate predictions; however, the framework is in place. The model did a good job of qualitatively predicting presence or absence of bacteria within the subcatchments, but quantitatively its performance was poor. This is mainly the result of a general lack of information about the bacterial loading rates associated with specific agricultural activities within Kranji Catchment. Another contributing factor is uncertainty about loadings from and locations of point sources. Travel time is also an important factor in downstream bacterial concentrations; the higher the resolution of the watershed delineation, the more accurate the travel times. If the stream network can be further refined and fitted to the real drainage network, bacterial travel times will be more accurate, leading to better predictions of concentration downstream. A more in-depth sampling program might be undertaken for STPs for which there are no bacterial sampling results. It would also be prudent for this sampling program to look at temporal variability of STP effluent to ensure that the samples taken correctly characterize the loading. In order to better evaluate the accuracy of the model, it would also be prudent to conduct a sampling program in those subcatchments with no field observations. Refinement of the attenuation study results will also enhance the accuracy of the model. There are many opportunities to refine the model, and there is a good framework in place. With more information, SWAT could provide valuable insights into the behavior of bacteria within the catchment and the bacterial loading to Kranji Reservoir. I think that SWAT definitely warrants more work in the future because it has the potential to be a very useful tool for predicting behavior of bacteria within Kranji Catchment.

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Appendices

Appendix A: Attenuation Study Results

Study	Sample Name	Travel Time (min)	Most Probable Number (MPN)						Decay Rate (hr^{-1})					
			Dilution: 1:10		Dilution: 1:100		Dilution: 1:10,000		Dilution: 1:10		Dilution: 1:100		Dilution: 1:10,000	
			TC	EC	TC	EC	TC	EC	TC	EC	TC	EC	TC	EC
Light Study	TTL01.U		N/A	24,196	N/A	32,550	733,000	52,000						
	TTL01.D	8.92	N/A	N/A	N/A	22,470	471,000	75,000	N/A	N/A	N/A	2.49	2.97	-2.46
	TTL02.U		N/A	N/A	N/A	155,310	1,664,000	161,000						
	TTL02.D	9.37	N/A	N/A	N/A	120,330	1,266,000	86,000	N/A	N/A	N/A	1.63	1.75	4.01
	TTL03.U		N/A	17,329	N/A	17,850	197,000	31,000						
	TTL03.D	10.66	N/A	12,997	198,630	15,530	389,000	10,000	N/A	1.62	N/A	0.78	-3.83	6.37
	TTL04.U		N/A	14,136	N/A	14,140	228,000	N/A						
	TTL04.D	10.62	N/A	8,664	173,290	7,890	201,000	20,000	N/A	2.77	N/A	3.30	0.71	N/A
	TTL05.U		N/A	17,329	N/A	19,350	292,000	N/A						
	TTL05.D	9.90	N/A	8,664	198,630	11,120	327,000	20,000	N/A	4.20	N/A	3.36	-0.69	N/A
Dark Study	TTD01.U		N/A	3,448	N/A	2,410	256,000	10,000						
	TTD01.D	10.02	N/A	2,909	198,630	3,730	292,000	N/A	N/A	1.02	N/A	-2.62	-0.79	N/A
	TTD02.U		N/A	2,310	N/A	1,750	369,000	N/A						
	TTD02.D	10.31	N/A	2,909	N/A	2,280	480,000	N/A	N/A	-1.34	N/A	-1.54	-1.53	N/A
	TTD03.U		N/A	3,076	141,360	2,560	121,000	N/A						
	TTD03.D	9.49	N/A	3,873	N/A	2,790	432,000	10,000	N/A	-1.46	N/A	-0.54	-8.04	N/A
	TTD04.U		N/A	1,191	241,960	1,730	285,000	N/A						
	TTD04.D	9.79	N/A	1,334	198,630	1,850	309,000	10,000	N/A	-0.69	1.21	-0.41	-0.50	N/A

TC stands for Total Coliforms and EC stands for *E. coli*. Sample names ending in "U" denote upstream samples, and sample names ending in "D" denote downstream samples. Sampling results labeled as "N/A" had invalid readings.

Appendix B: Soils of Kranji Catchment

Soil properties obtained from Chia et al. (1991). Colors denote soil groupings used to provide input values for missing data.

					Layer 1								
Soil Name	Abbreviation	Number of Soil Layers	Hydrologic Group	Maximum Depth	Bottom Depth (mm)	Bulk Density (g/cm^3)	Available Water Capacity (mm H_2O/ mm soil)	Saturated Hydraulic Conductivity (mm/hr)	Organic Carbon Content (% soil wt)	% Clay	% Silt	% Sand	% Rock
Lokyang	Lg	4	C	1500	90	1.04	44.14	162	1.9	29	25	46	0
Harimau	Hu	4	B	940	140	1.19	37.44	360	1.6	18	4	77	1
Lam San	Ln	4	B	970	100	1.20	37.99	360	1.4	17	3	78	3
Tengah	Tg	4	C	970	100	1.20	37.99	360	1.4	17	3	78	3
Tampoi	Tp	4	B	1000	60	1.21	38.54	360	1.1	16	2	78	4
Jurong	Jr	2	D	1500	450	1.04	44.14	151	1.9	29	25	46	0
Kranji	Kj	2	D	1500	450	1.04	44.14	151	1.9	29	25	46	0
Ayer Terjun	At	4	C	1350	70	1.08	44.14	252	2.1	29	47	24	0
Malacca	Mc	4	C	1350	70	1.08	44.14	252	2.1	29	47	24	0
Munchong	Mn	4	B	1350	70	1.08	44.14	252	2.1	29	47	24	0
Bukit Panjang	Bj	4	C	1600	80	1.13	40.74	456	2.3	28	2	70	0
Rengam	Rm	4	B	1600	80	1.13	40.74	456	2.3	28	2	70	0
Sungei Kadut	St	4	C	1600	80	1.13	40.74	456	2.3	28	2	70	0
Aik Hong	Ag	3	B	1000	190	1.18	37.64	116	1.8	19	2	79	0
Peng Siang	Pg	3	B	1000	190	1.18	37.64	116	1.8	19	2	79	0
Serdang	Sg	3	B	1000	190	1.18	37.64	116	1.8	19	2	79	0

					Layer 2								
Soil Name	Abbreviation	Number of Soil Layers	Hydrologic Group	Maximum Depth	Bottom Depth (mm)	Bulk Density (g/cm^3)	Available Water Capacity (mm H_2O/ mm soil)	Saturated Hydraulic Conductivity (mm/hr)	Organic Carbon Content (% soil wt)	% Clay	% Silt	% Sand	% Rock
Lokyang	Lg	4	C	1500	270	1.38	32.84	30.6	0.5	37	28	35	0
Harimau	Hu	4	B	940	280	1.45	29.44	21.6	0.5	22	4	72	2
Lam San	Ln	4	B	970	205	1.49	28.44	21.6	0.5	24	2.5	71.5	2
Tengah	Tg	4	C	970	205	1.49	28.44	21.6	0.5	24	2.5	71.5	2
Tampoi	Tp	4	B	1000	130	1.53	27.44	360	0.5	26	1	71	2
Jurong	Jr	2	D	1500	1500	1.27	39.74	99.24	1.1	62	29	9	0
Kranji	Kj	2	D	1500	1500	1.27	39.74	99.24	1.1	62	29	9	0
Ayer Terjun	At	4	C	1350	240	1.34	35.44	48.6	1.3	33	44	23	0
Malacca	Mc	4	C	1350	240	1.34	35.44	48.6	1.3	33	44	23	0
Munchong	Mn	4	B	1350	240	1.34	35.44	48.6	1.3	33	44	23	0
Bukit Panjang	Bj	4	C	1600	340	1.4	31.34	156.6	0.3	38	1	61	0
Rengam	Rm	4	B	1600	340	1.4	31.34	156.6	0.3	38	1	61	0
Sungei Kadut	St	4	C	1600	340	1.4	31.34	156.6	0.3	38	1	61	0
Aik Hong	Ag	3	B	1000	600	1.41	29.94	21.6	0.5	23	4	73	0
Peng Siang	Pg	3	B	1000	600	1.41	29.94	21.6	0.5	23	4	73	0
Serdang	Sg	3	B	1000	600	1.41	29.94	21.6	0.5	23	4	73	0

Soil Name	Abbreviation	Number of Soil Layers	Hydrologic Group	Maximum Depth	Layer 3								
					Bottom Depth (mm)	Bulk Density (g/cm^3)	Available Water Capacity (mm H_2O/ mm soil)	Saturated Hydraulic Conductivity (mm/hr)	Organic Carbon Content (% soil wt)	% Clay	% Silt	% Sand	% Rock
Lokyang	Lg	4	C	1500	540	1.47	30.24	14.4	0.3	44	28	28	0
Harimau	Hu	4	B	940	530	1.52	27.54	180	0.3	26	3	67	4
Lam San	Ln	4	B	970	485	1.545	27.04	72	0.35	27	1.5	65.5	6
Tengah	Tg	4	C	970	485	1.545	27.04	72	0.35	27	1.5	65.5	6
Tampoi	Tp	4	B	1000	440	1.57	26.54	21.6	0.4	28	0	64	8
Jurong	Jr	2	D	1500									
Kranji	Kj	2	D	1500									
Ayer Terjun	At	4	C	1350	600	1.33	36.14	21.6	0.8	54	33	13	0
Malacca	Mc	4	C	1350	600	1.33	36.14	21.6	0.8	54	33	13	0
Munchong	Mn	4	B	1350	600	1.33	36.14	21.6	0.8	54	33	13	0
Bukit Panjang	Bj	4	C	1600	680	1.34	34.34	100.8	0.4	40	3	57	0
Rengam	Rm	4	B	1600	680	1.34	34.34	100.8	0.4	40	3	57	0
Sungei Kadut	St	4	C	1600	680	1.34	34.34	100.8	0.4	40	3	57	0
Aik Hong	Ag	3	B	1000	1000	1.43	30.84	14.4	0.4	31	2	67	0
Peng Siang	Pg	3	B	1000	1000	1.43	30.84	14.4	0.4	31	2	67	0
Serdang	Sg	3	B	1000	1000	1.43	30.84	14.4	0.4	31	2	67	0

Soil Name	Abbreviation	Number of Soil Layers	Hydrologic Group	Maximum Depth	Layer 4								
					Bottom Depth (mm)	Bulk Density (g/cm^3)	Available Water Capacity (mm H_2O/ mm soil)	Saturated Hydraulic Conductivity (mm/hr)	Organic Carbon Content (% soil wt)	% Clay	% Silt	% Sand	% Rock
Lokyang	Lg	4	C	1500	1500	1.47	32.64	18	0.2	57	33	10	0
Harimau	Hu	4	B	940	940	1.53	26.64	4.86	0.2	34	1	48	17
Lam San	Ln	4	B	970	970	1.52	27.24	99.24	0.25	32.5	0.5	49	18
Tengah	Tg	4	C	970	970	1.52	27.24	99.24	0.25	32.5	0.5	49	18
Tampoi	Tp	4	B	1000	1000	1.51	27.84	92.43	0.3	31	0	50	19
Jurong	Jr	2	D	1500									
Kranji	Kj	2	D	1500									
Ayer Terjun	At	4	C	1350	1350	1.27	39.74	18	1.1	62	29	9	0
Malacca	Mc	4	C	1350	1350	1.27	39.74	18	1.1	62	29	9	0
Munchong	Mn	4	B	1350	1350	1.27	39.74	18	1.1	62	29	9	0
Bukit Panjang	Bj	4	C	1600	1600	1.39	31.94	72	0.3	43	2	55	0
Rengam	Rm	4	B	1600	1600	1.39	31.94	72	0.3	43	2	55	0
Sungei Kadut	St	4	C	1600	1600	1.39	31.94	72	0.3	43	2	55	0
Aik Hong	Ag	3	B	1000									
Peng Siang	Pg	3	B	1000									
Serdang	Sg	3	B	1000									

Appendix C: Weather Data

Monthly average values for variables taken by SWAT that are used by the weather generator to simulate weather. Values calculated from three years of weather data from a PUB weather station in Kranji Reservoir.

Month	Mean Daily Maximum Air Temperature (°C)	Mean Daily Minimum Air Temperature (°C)	Standard Deviation of Daily Maximum Air Temperature (°C)	Standard Deviation of Daily Minimum Air Temperature (°C)	Mean Total Monthly Precipitation (mm)	Standard Deviation of Daily Precipitation (mm)	Skewness of Daily Precipitation (mm)
January	29.2	24.3	1.8	0.6	155	74	7
February	30.9	25.4	1.5	0.7	56	9	5
March	31.4	25.5	1.1	0.7	97	7	2
April	31.3	25.2	1.4	1.0	254	17	3
May	30.8	25.1	1.2	1.0	139	11	3
June	30.2	25.0	1.2	3.4	190	13	3
July	30.1	25.2	1.2	1.2	238	15	2
August	30.0	25.2	1.2	1.1	71	5	3
September	30.2	24.8	1.1	0.8	95	10	3
October	30.8	25.2	0.8	0.9	49	7	4
November	30.38	24.6	1.1	0.69	109	15	3
December	29.2	24.3	1.7	3.39	369	39	5

Month	Probability of a Wet Day Following a Dry Day	Probability of a Wet Day Following a Wet Day	Average # of Days with Precipitation	Maximum Half-hour Rainfall (mm)	Average Daily Solar Radiation ($MJ/m^2/day$)	Average Daily Dewpoint Temperature (°C)	Average Daily Wind Speed (m/s)
January	0.2414	0.7097	15.5	55	18,760	23.1	2.9
February	0.3182	0.6190	10.5	34	19,714	23.5	3.4
March	0.2424	0.5909	11.0	25	19,053	23.8	2.7
April	0.3043	0.7838	18.5	38	14,262	24.2	1.6
May	0.5333	0.7692	19.5	16	12,432	24.4	1.5
June	0.5172	0.4839	15.5	47	12,290	24.1	1.6
July	0.2609	0.8205	19.5	36	11,914	24.2	1.7
August	0.3704	0.5926	13.5	8	11,927	24.1	1.7
September	0.3333	0.5789	9.5	27	12,636	23.9	1.4
October	0.0625	0.7000	5.0	22	11,276	24.0	1.3
November	0.6154	0.6774	15.5	59	13,663	23.9	1.5
December	0.3500	0.7895	19.0	31	11,673	23.7	2.4

Appendix D: Point Source Inputs

Values used for sewage treatment plants (point sources) in SWAT. Flow rates estimated using values from Metcalf and Eddy (1977).

STP NO	TYPE OF PREMISES (PUB Data)	CAPACITY (PUB Data)	Flow Rate (L/day)	CONCENTRATIONS		LOADINGS		Source of Concentration Estimate
				Total Coliforms (#/100mL)	*E. coli* (#/100mL)	Total Coliforms (#/day)	*E. coli* (#/day)	
BJ 708	BBC FAR EAST RELAY STN	20	1,100	69,600	250	765,600,000	2,750,000	BJ813
BJ 694	ENV - PARSI CEMETERY	10	550	69,600	250	382,800,000	1,375,000	BJ813
BJ 810	FARM	10	550	16,448,694	1,232,181	90,467,819,750	6,776,999,167	BJ821, BJ856, BJ820, BJ830, BP435, BP436
BJ 821	FISH FARM	10	550	1,080,000	5,750	5,940,000,000	31,625,000	Sampled
BJ 831	FISH FARM	10	550	1,080,000	5,750	5,940,000,000	31,625,000	BJ821
BP 16	MINDEF - BT GOMBAK CAMP	50	15,000	69,600	250	10,440,000,000	37,500,000	BJ813
BP 18	MINDEF - BT GOMBAK CAMP	20	6,000	69,600	250	4,176,000,000	15,000,000	BJ813
BP 19	MINDEF - BT GOMBAK CAMP	15	4,500	69,600	250	3,132,000,000	11,250,000	BJ813
BP 15	MINDEF - BT GOMBAK CAMP	50	15,000	69,600	250	10,440,000,000	37,500,000	BJ813
BJ 726	MINDEF - KEAT HONG CAMP	200	60,000	69,600	250	41,760,000,000	150,000,000	BJ813
BP 492	MINDEF - KEAT HONG CAMP	1000	300,000	69,600	250	208,800,000,000	750,000,000	BJ813
BP 30	MINDEF - KRANJI CAMP	25	7,500	69,600	250	5,220,000,000	18,750,000	BJ813
BJ 813	TEMPLE	25	1,375	69,600	250	975,000,000	3,437,500	Sampled
BJ 800	TRANSMISSION STN	10	550	101,400,000	18,481,500	557,700,000,000	101,648,000,000	Sampled

STP NO	TYPE OF PREMISES (PUB Data)	CAPACITY (PUB Data)	Flow Rate (L/day)	CONCENTRATIONS		LOADINGS		Source of Concentration Estimate
				Total Coliforms (#/100mL)	*E. coli* (#/100mL)	Total Coliforms (#/day)	*E. coli* (#/day)	
BP 29	MINDEF - KRANJI CAMP	25	7,500	69,600	250	5,220,000,000	18,750,000	BJ813
BJ 725	MINDEF - LIM CHU KANG CAMP	1200	360,000	69,600	250	250,560,000,000	900,000,000	BJ813
BP 12	MINDEF - TENGAH AIRBASE	50	15,000	69,600	250	10,440,000,000	37,500,000	BJ813
BP 13	MINDEF - TENGAH AIRBASE	50	15,000	69,600	250	10,440,000,000	37,500,000	BJ813
BP 14	MINDEF - TENGAH AIRBASE	10	3,000	69,600	250	2,088,000,000	7,500,000	BJ813
BP 3	MINDEF - TENGAH AIRBASE	1500	450,000	69,600	250	313,200,000,000	1,125,000,000	BJ813
BP 4	MINDEF - TENGAH AIRBASE	30	9,000	69,600	250	6,264,000,000	22,500,000	BJ813
BP 5	MINDEF - TENGAH AIRBASE	30	9,000	69,600	250	6,264,000,000	22,500,000	BJ813
BP 11	MINDEF - TENGAH AIRBASE	40	12,000	69,600	250	8,352,000,000	30,000,000	BJ813
BJ 856	NURSERY	25	1,375	2,643,500	1,093,500	36,348,125,000	15,035,625,000	Sampled
BJ 819	NURSERY	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 820	NURSERY	10	550	2,673,500	2,123,500	14,704,250,000	11,679,250,000	Sampled
BJ 823	NURSERY	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 830	NURSERY	25	1,375	12,268,500	3,318,490	168,692,000,000	45,629,237,500	Sampled
BJ 833	NURSERY	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 839	NURSERY	20	1,100	5,861,833	2,178,496	64,480,166,667	23,963,463,333	BJ856, BJ820, BJ830
BJ 840	NURSERY	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830

STP #	TYPE OF PREMISES (PUB Data)	CAPACITY (PUB Data)	Flow Rate (L/day)	CONCENTRATIONS		LOADINGS		Source of Concentration Estimate
				Total Coliforms (#/100mL)	*E. coli* (#/100mL)	Total Coliforms (#/day)	*E. coli* (#/day)	
BJ 841	NURSERY	20	1,100	5,861,833	2,178,496	64,480,166,667	23,963,463,333	BJ856, BJ820, BJ830
BJ 845	NURSERY	25	1,375	5,861,833	2,178,496	80,600,208,333	29,954,329,167	BJ856, BJ820, BJ830
BJ 846	NURSERY	25	1,375	5,861,833	2,178,496	80,600,208,333	29,954,329,167	BJ856, BJ820, BJ830
BJ 847	NURSERY	25	1,375	5,861,833	2,178,496	80,600,208,333	29,954,329,167	BJ856, BJ820, BJ830
BJ 850	NURSERY	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 834	NURSERY	20	1,100	5,861,833	2,178,496	64,480,166,667	23,963,463,333	BJ856, BJ820, BJ830
BJ 788	ORCHID FARM	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 789	ORCHID FARM	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 791	ORCHID FARM	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 796	ORCHID FARM	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BJ 803	ORCHID FARM	10	550	5,861,833	2,178,496	32,240,083,333	11,981,731,667	BJ856, BJ820, BJ830
BP 435	POULTRY FARM	10	550	20,000,000	21,850	110,000,000,000	120,175,000	Sampled
BP 436	POULTRY FARM	25	1,375	60,026,667	830,000	825,367,000,000	11,412,500,000	Sampled
BJ 645	PUB - KRANJI DAM	50	2,750	69,600	250	1,914,000,000	6,875,000	BJ813
BJ 807	SINGAPORE TELECOMS	40	2,200	69,600	250	1,531,200,000	5,500,000	BJ813
BJ 814	SINGAPORE TURF CLUB	25	1,375	69,600	250	957,000,000	3,437,500	BJ813