Bacteria Attenuation Modeling and Source Identification in Kranji Catchment and Reservoir

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Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

This study was performed to determine the bacterial loading of Kranji Catchment and Reservoir and how this will affect planned recreational use of Kranji Reservoir. Field and laboratory work was conducted in Singapore during the month of January 2009 to characterize the concentration of bacteria at sampling locations in the drainage system of Kranji Catchment and in Kranji Reservoir. Using this data, a first-order attenuation model was constructed and used to evaluate attenuation of bacteria while traveling through the drainage network to the reservoir. GIS tools used this model to predict areas of potential concern in one specific sub-catchment of Kranji Catchment. The USEPA WASP modeling program was used to determine fate and transport of bacteria throughout Kranji Reservoir based on bacteria concentrations flowing into the reservoir.

These analyses led to the recommendation that farm run-off near the reservoir was the bacterial source of greatest concern. The relatively high concentrations coupled with short travel time, which diminishes opportunity for attenuation, resulted in high concentrations reaching the reservoir. Residential areas were found to contribute high concentrations of bacteria to the catchment, but due to relatively long travel times from the sources to the main body of the reservoir, have less of an effect on the bacterial concentrations of the main reservoir. Due to the uncharacteristically dry weather Singapore experienced during January 2009, the applicability of the results of this study to wet weather conditions is uncertain.

Thesis Supervisor: Peter Shanahan
Title: Senior Lecturer

Acknowledgments

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Introduction and Background

1 Executive Summary

The Kranji Reservoir is a drinking water reservoir managed by the Singapore Public Utilities Board (PUB). Located on the north side of the island, it was created by the damming of a natural estuary. The 6,000 hectare Kranji Catchment is primarily undeveloped, with some agriculture and residential uses. As part of the PUB's Active Beautiful and Clean Programme, PUB would like to use the Kranji Reservoir for recreation.

In preparation for these uses of the reservoir, the PUB commissioned a study by Nanyang Technological University (NTU) (2008) that sought to characterize the Kranji Reservoir and Catchment and develop a model to simulate the reservoir's water quality. The NTU (2008) study identified problem areas and suggested that further study identifying the sources of bacteria in the catchment and attenuation of bacterial levels in the reservoir were necessary before recreational use could be determined safe.

The study herein is the most recent follow-on to the aforementioned research. It has three main goals: to identify sources of bacteria, to model bacterial attenuation from the catchment to the reservoir, and to create a visual representation of this model.

In order to identify point sources of bacteria and study attenuation, the hydrology of the Kranji Catchment was mapped using a Geographic Information Systems (GIS) platform. The catchment drainage system was also mapped and sewage treatment plant (STP) locations within the catchment were identified. A representative group of STPs was then selected for further analysis along with forested, agricultural, and highly residential land use areas. The effluent of the STPs was characterized with regard to bacterial concentration and attenuation of these effluents was modeled using travel path and time. These results were used to identify contaminant source locations, delineate potential areas of additional sources in residential areas, and quantify relative impact on the catchment's bacterial profile.

The impacts of this bacterial loading on Kranji Reservoir were then modeled using a box model program. Reservoir dimensions, initial conditions, and hydrodynamic data were calculated and input into a network of differential segments for analysis. This resulted in spatial and time-variable predictions of bacterial concentrations throughout the influent rivers and reservoir. Additionally, a layout was created using GIS ArcMap and the time-variable predicted concentrations for the month of January 2009 were projected, by differential segment, throughout the reservoir to visually represent bacterial contamination and identify areas of high concern.

The relatively high bacterial concentrations attributable to farm run-off near the reservoir coupled with short travel times, which diminish opportunity for attenuation, resulted in high concentrations reaching the reservoir. Residential areas were found to contribute high concentrations of bacteria to the catchment, but due to relatively long travel times from the sources to the main body of the reservoir, to have less of an effect on the bacterial concentrations of the main reservoir.

2 Water Quality and Management in Singapore

Sections 2 through 4 of this thesis were written as part of a collaborative effort with Carolyn Hayek, Cameron Dixon, and Jean Pierre Nshimyimana.

Singapore is an island nation in Southeast Asia, just South of Malaysia (Figure 2.1).

Figure 2.1: Map of Southeast Asia with Singapore Highlighted (My Travel Guide 2008)

Singapore was established as a British port in 1819 due to its location and function as a hub for trade with India and China. After World War II, Britain felt that the country was too small to be a sovereign nation and instead granted it increasing liberties with time. Singapore joined the Federation of Malaya in 1963, but the union was short-lived due to internal conflicts. In contrast to the other federation members, Singapore's majority population was Chinese. This racial diversity spurred the call for a "Malaysian Malaysia," leading to several race riots in Singapore. Singapore exited the federation and became an independent nation in 1965.

Singapore has 4.4 million people and a water demand of 1.36 billion liters per day (Madslien 2008). While Singapore receives a significant amount of rainfall—approximately 2400 millimeters per year (Tortajada 2006)—it is considered water scarce. Singapore has no natural aquifers or lakes and due to its small size, there is little space to store that water for use.

Prior to becoming a sovereign nation, Singapore had negotiated treaties for water purchases from Malaysia to meet its water demand. The first treaty was signed in 1960 and expires in 2011, while a second treaty was signed in 1961 and expires in 2061. The two countries have already met to discuss the terms of new treaties that will take the place of these two once they have expired. However, Malaysia is demanding a price that is fifteen to twenty times higher than that negotiated under the previous contract, which was S$0.026 per ten cubic meters (Tortajada 2006).

In response to Malaysia's demands, the Prime Minister of Singapore has called for water self-

sufficiency by 2061, such that when the treaties on water exchange with Malaysia expire, there will no longer be a need to import water. Recognizing that meeting the country's water needs can be viewed as a problem of insufficient supply or one of high demand, the Public Utilities Board (PUB) has taken actions to both increase Singapore's internal water supply and to reduce the national water demand through a strategy known as "Water for All: Conserve, Value and Enjoy." By taking this two-pronged approach, Singapore is well on its way to becoming self-reliant in terms of its water needs.

The campaign for increasing supply is referred to as "Water for All." Singapore meets its water needs through a 'Four Taps' Strategy, with the four sources being: water imported from Malaysia, rainwater from local catchments, reclaimed wastewater (called 'NEWater'), and desalinated seawater. As of May 2007, approximately 40% (Morris 2007) of Singapore's water supply was coming from Malaysia. By increasing the capacity of the other three taps, all of which come from within the country, Singapore can reduce the percentage that is coming from Malaysia and thereby reduce its international dependence for meeting its water needs.

Rainwater catchments are an important part of the water supply for Singapore. Stormwater is collected through a network of drains, canals, and river channels and directed towards one of the nation's fourteen reservoirs. These reservoirs currently collect water from about half of Singapore's land surface. It is expected that additional catchments will be built by 2011 to bring the total catchment area from one half to approximately two thirds of the country's land surface. PUB has also taken measures to improve the quality of the water in the catchments through pollution controls such as public and private sewer maintenance, silt controls, regulation of industry, and gross pollutant traps. Each of these measures helps to improve water quality in the catchments by improving the quality of the water before it reaches the reservoir.

An important part of the "Conserve, Value and Enjoy" campaign is the ABC Waters Programme. PUB launched the ABC Waters Programme 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), and clean (of sufficient quality for domestic, industrial, and recreational uses). 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.

3 Site Description

Singapore is divided into three main catchment areas: the Western Catchment, the Central Catchment, and the Eastern Catchment. This study focuses on watershed management for the Kranji Reservoir and Kranji Catchment (Figure 3.1), which are located in the Western Catchment. The Kranji Catchment and Reservoir are in the northwestern corner of the island (1°25'N, 103°43'E).

Figure 3.1: Map of Singapore with Kranji Reservoir Highlighted (GoogleMaps 2008)

The Western Catchment encompasses the western third of the country and is home to about one million people or 27% of Singapore's total population (PUB 2008b). The catchment remained largely undeveloped until after Singapore achieved independence (PUB 2008b) and is currently an approximately equal mix of urban development, industrial development, and natural environment (PUB 2008a). Residential areas are concentrated on the southern edge of the catchment (PUB 2008b).

The Kranji Reservoir was created in 1975 by the damming of an estuary from the Johor Strait that separates the Malaysian mainland from Singapore. The reservoir is approximately 647 hectares in area and the catchment has four tributaries, Kangkar River, Tengah River, Peng Siang River, and Pangsua River.

The Kranji Catchment is approximately 6076 hectares in area. It is mostly undeveloped with some rural and manufacturing industry (PUB 2008b). Most of the land around the reservoir is designated as open space under current zoning regulations, with the exception of some agricultural land use, a small golf course to the west, and some light industry to the east (PUB 2008b).

While the Kranji Reservoir is strong in many aspects (including beauty, ecological uniqueness, and open spaces), the Western Catchment Masterplan (PUB 2008b) states that the Kranji sub-catchment currently has low visiting rates because of a combination of factors. First, the site is

relatively isolated since most of the sub-catchment is undeveloped. Second, public transportation is limited. Third, there are only two entry points (one on either side of the dam) and poor connectivity within the site. Finally, public recreational activities are limited. Current recreational opportunities include cycling, park visits, and minor fishing areas.

A proposal for improvements to the Kranji Reservoir has been made under the "Western Catchment Masterplan" (PUB 2008b). The proposed changes would be primarily made to the existing entrances to boost low visiting rates while still preserving the rich natural resources. The addition of a Kranji Reservoir Visitor Centre west of the dam will provide educational information and experiences on the wetlands and the reservoir. Minor changes to vegetation at the intake will also prime the location for bird watching and a bird observation tower. Also, the introduction of an electric 'eco-cruise' boat will help increase connectivity within the site.

Water quality improvements (through wetland construction near the intake channel) will enable kayaking along the water side and better fishing, barbecue, and picnic facilities east of the dam. PUB would like to increase recreational activities on the Kranji Reservoir further, but more information is needed about bacteriological levels in the water before activities that involve higher degrees of contact with the water can be introduced.

4 Previous Study of Kranji Reservoir

The Public Utilities Board (PUB) of Singapore would like citizens to be able to use Kranji Reservoir for a wider variety of recreational activities. The currently elevated bacterial loadings of the reservoir prohibit this type of use. Watershed protection efforts have already begun in many of the island nation's other catchments. Work investigating the Kranji Catchment by Nanyang Technological University (NTU 2008) in Singapore has focused on analysis of the water quality in the catchment. This analysis made use of seven sampling stations in the catchment and seven sampling stations within the reservoir, as seen in Figure 4.1. The study measured *E. coli* and *Enterococci* densities as the indicator bacteria for water quality. Table 4.1 presents the *E. coli* results from the NTU study. USEPA guideline concentrations for recreational waters can be expressed as a combination of single-sample maximum values and geometric means. Because Singapore's government does not have guidelines for *E. coli* levels, the NTU study used USEPA guidelines. The bold values in Table 4.1 indicate locations that exceed USEPA values (USEPA 1986).

Table 4.1: Kranji Reservoir and Catchment E. coli Data (Sept. 2005 to Sept. 2007) (NTU 2008)

Location	*E. coli* Density (MPN/100ml)				Sample Size
	Minimum	Maximum	Geometric Mean	Standard Deviation	
Reservoir Sampling Locations					
Station 1	1	**530**	18	150	17
Station 3	1	130	3.4	34	17
Station 4	1	140	3.5	33	14
3 Arm Junction	1	**1,800**	20	480	17
Peng Siang	8	**2,400**	100	840	14
Tengah	2	200	17	70	16
Kangkar	1	**700**	14	170	10
Catchment Sampling Locations					
KC1	110	**24,000**	**2,300**	5,700	17
KC2	1,300	**>24,000**	**7,700**	9,600	17
KC3	130	**6,900**	**630**	2,200	14
KC4	50	**8,300**	**320**	2,000	17
KC5	1,300	**24,000**	**2,200**	6,600	14
KC6	310	**4,100**	**1,600**	980	16
KC7	630	**13,000**	**1,200**	4,000	10

Note: **Bold** values exceed USEPA guidelines.

Table 4.1 shows that in the main body of the reservoir, the geometric means of the indicator bacteria fell below USEPA guidelines for every location. Stations 3 and 4, which are located at the north end of the reservoir, had the lowest geometric means. Even with acceptable geometric means, the reservoir water samples exceeded the single-sample maximum values for *E. coli* in four of the seven reservoir sampling locations. The single-sample maximum values were exceeded for both primary contact recreation and secondary contact recreation. The monitoring

stations located in the catchment had very high bacteria counts, exceeding USEPA guidelines for both geometric means and single-sample maximums at every location.

Figure 4.1: NTU Catchment and Reservoir Sampling Locations

The NTU study determined event mean concentrations (EMCs) for a variety of nutrients in seven sub-catchments, KC1 – KC7. (Please note that the naming convention for the sub-catchments in the NTU Study was CP. In our study, this has been replaced with KC (Kranji Catchment), as this is the most recent naming convention.) The NTU (2008) study collected samples that were analyzed for: ammonia (NH_3), nitrogen (N), nitrate (NO_3), nitrite (NO_2), total dissolved nitrogen (TDN), total nitrogen (TN), chlorophyll-a (Chl-a), total suspended solids (TSS), phosphate (PO_4), total dissolved phosphorous (TDP), total phosphorous (TP), TN/TP, silicon dioxide (SiO_2), total organic carbon (TOC), dissolved organic carbon (DOC), total inorganic carbon (TIC), and particulate organic carbon (POC). The contributors to the NTU study also mapped land use in each sub-catchment, as seen in Figure 4.2. As seen in Table 4.1, the KC2 sub-catchment had the highest levels of *E. coli*. KC5, KC1, and KC7 had substantially higher levels of *E. coli* than the remaining three sub-catchments. The study found that high bacterial loadings, as demonstrated by high levels of indicator bacteria, were correlated to a high percentage of development in the sub-catchment, as seen in Table 4.2.

Table 4.2: Land Use of Five Sub-Catchments and Mean Bacterial Concentration (NTU 2008)

Station	Location	Mean *E. coli* (MPN/100 mL)	Percentage Developed	Percentage Impervious
KC1	Bricklands	3,900	33	25
KC2	CCK AVE4	12,000	71	28
KC4	TG Airbase	1,200	1	0
KC6	AMK1	1,500	20	17
KC7	Sg Pangsua	3,500	40	23

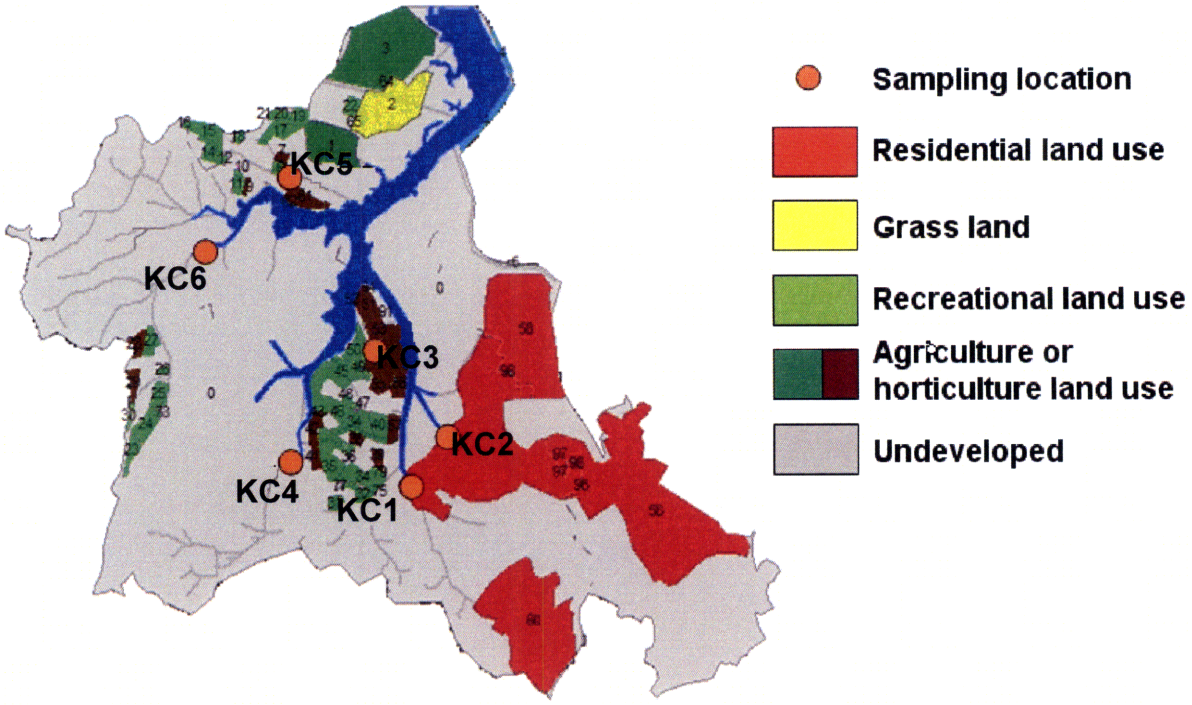

Figure 4.2: Land Use Map of the Kranji Catchment Exclusive of KC7 (NTU 2008) (KC7 is shown in Figure 4.1 and consists largely of residential land use.)

The study of the Kranji Catchment also indicated that storm events contributed more bacteria to the water passing each station than did dry weather. This is to be expected, as higher bacteria levels are strongly associated with the first flush phenomenon, during which a storm event washes accumulated bacteria on the surface into the drainage system immediately. These findings demonstrate the need to examine the residential contribution to bacterial loading in the catchment. The bacteriological contribution of the individual sewage treatment plants in the catchment, of which there are 47 (Figure 4.3), also needs to be examined. The NTU study indicated the need to sample wet-weather as well as dry-weather concentrations.

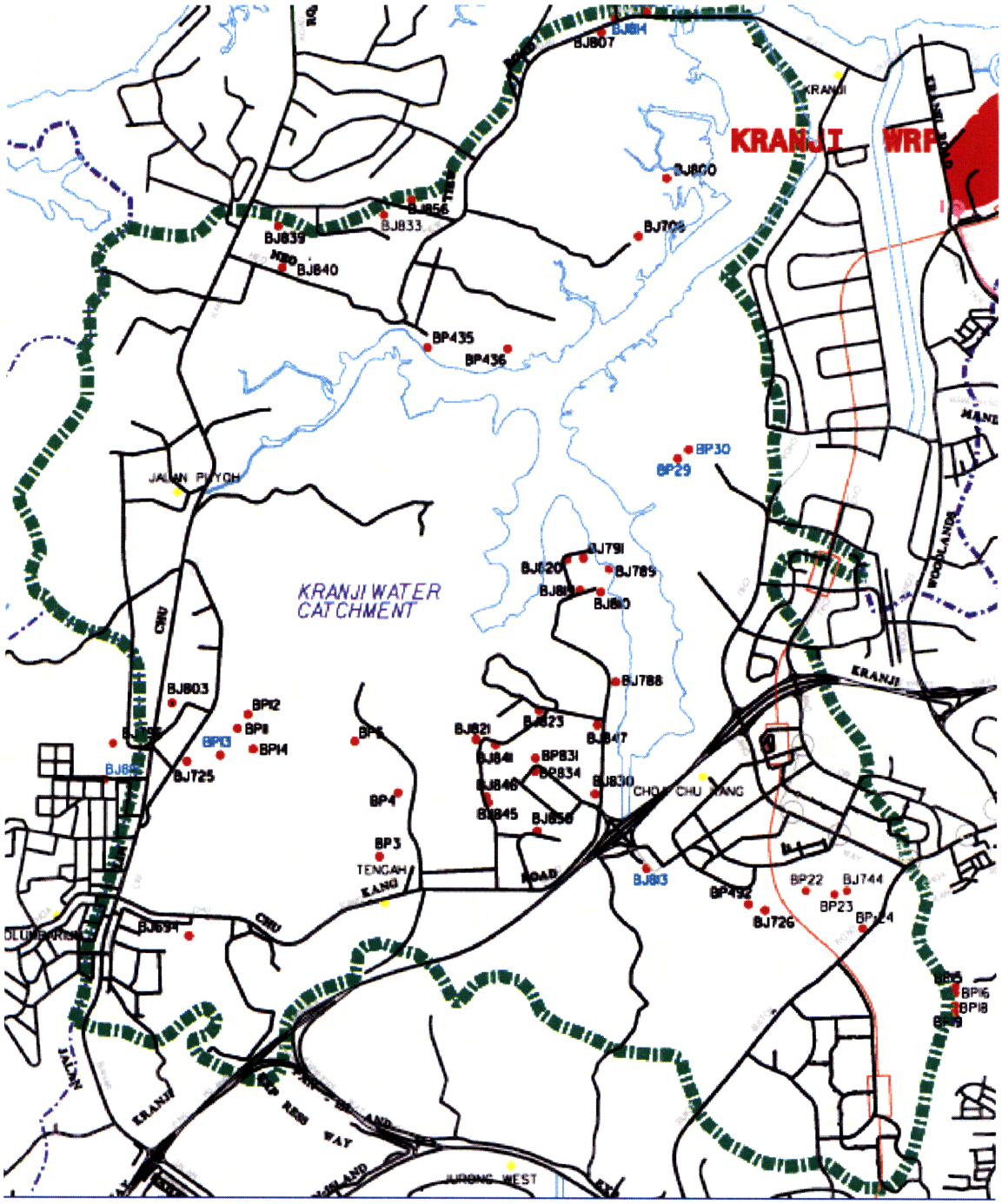

Figure 4.3: Kranji Catchment Sewage Treatment Plants (STPs) (Chua 2008)

The findings from the NTU (2008) study have contributed significantly to the knowledge of the catchment's characteristics and the bacterial loadings of the sub-catchments to Kranji Reservoir. Our study builds upon the findings of the NTU (2008) study by determining the bacterial contributions resulting from point and non-point sources in the sub-catchments and evaluating the fate and transport of the bacteria to Kranji Reservoir.

Field and Laboratory Work

5 Scope of Study

This study sought to characterize the *E. coli* concentrations in the drainage system in the Kranji Catchment and the attenuation experienced by the *E. coli* while traveling through the drainage system and being held in Kranji Reservoir. To this end, we conducted field and laboratory work during January 5-23, 2009 to measure *E. coli* concentrations within the catchment and reservoir.

We analyzed the data using first-order decay modeling, ArcGIS's ArcMap (ESRI 2008), and USEPA's Water Quality Analysis Simulation Program (WASP) (Wool et al. undated). The first-order decay model incorporated decay due to settling, natural mortality, and photolysis, as applicable. We used ArcMap to calculate distances in the catchment, which we then used to compute attenuation. We employed WASP to simulate the fate and transport of *E. coli* within the reservoir.

The objective of our fieldwork was to determine probable sources of bacterial contamination to the reservoir and catchment by sampling different locations around the catchment to find the highest concentrations of bacteria. The objective of our attenuation modeling was to determine if the bacteria from the sources found in the fieldwork die off substantially before reaching the reservoir. Locating where the highest concentrations of *E. coli* exist and whether or not these sources contribute high levels to the reservoir are important in determining appropriate measures to control the bacterial concentrations within the catchment. This also allows PUB to rank the importance of the sources that add bacteria to the reservoir.

The objective of our GIS analysis in sub-catchment KC2 was to determine future sites of additional study. We found possible areas of *E. coli* sources that can be sampled in future studies to characterize more fully the sub-catchment's bacterial loading.

The objective of our WASP modeling was to create a representation of the reservoir and catchment system to determine how it generally behaves. This will allow PUB to determine which areas of the reservoir might experience higher *E. coli* concentrations depending on the input of bacteria from the surrounding catchment and on the bacterial levels found in the reservoir upon sampling.

6 Fieldwork

6.1 Non-Point Source Sampling

Non-point sources of bacteria are characterized by the lack of specific origination points of the pollution. The NTU study indicated that residential runoff, a common non-point source, was a significant contributor of bacteria to the drainage system and, therefore, the reservoir (NTU 2008). We further explored these conclusions by collecting non-point source samples around the catchment in the drainage system.

6.1.1 Methods

Our team spent eleven days in January, 2009 taking 122 non-point source samples around the catchment, either via auto-samplers or grab-sampling. The auto-samplers were installed by NTU previously and collect samples from their locations by sucking water through a tube and depositing it in one of 22 bottles. The samplers also measure water level, rainfall, and stream velocity. They can be set to take samples at specific times or used to take a sample immediately. Grab sampling entails a team member collecting a sample in a Whirl-Pak bag by hand. To account for potential water quality changes due to diurnal variations in flow, we sampled sites at different times during the day and took a 22-hour round of hourly samples at KC2's auto-sampler, which is in a sub-catchment known to have high bacterial concentrations (see Figure 4.1 for location). For each sample, approximately 400-500 milliliters of surface water were collected in sterile plastic bags, chilled while being transported to the NTU laboratory, processed using membrane filtration and the Hach m-ColiBlue24® method within thirty hours, and incubated at 35 degrees Celsius for 23-25 hours. No appreciable precipitation occurred during the three weeks of fieldwork; therefore, no precipitation values were noted in the sampling.

We measured water temperatures at nine sampling locations within the catchment with a thermometer. We also measured flow at several sampling sites using a portable flow meter, but had reason to believe that the flow measurements were inaccurate and elected not to use them. We, instead, used flow and water-depth measurements from the auto-samplers' built-in flow meters, taking the average of January's data during the time we were conducting field work (January 7-22) as seen in Table 6.1. We expect these average values to be reasonably representative of flow during the entire period because of the lack of rainfall during our three weeks of field work. To illustrate this fact, we plotted the depths and velocities (in blue) with their averages (in orange) in Figure 6.1 and Figure 6.2, respectively. These graphs show that most of the data points lie near the averages. The outliers on January 14 are the result of a short rain event that is not representative of the three weeks, as seen in Figure 6.3. For our analysis in Section 10 below, the averages are a suitable estimate for use in computation.

Table 6.1: Auto-Sampler Flow Measurements

Station	Dates	Average Velocity (m/s)	Velocity Standard Deviation (m/s)	Average Depth (m)	Depth Standard Deviation (m)
KC2	1/7-1/22	0.2	0.043	0.06	0.014

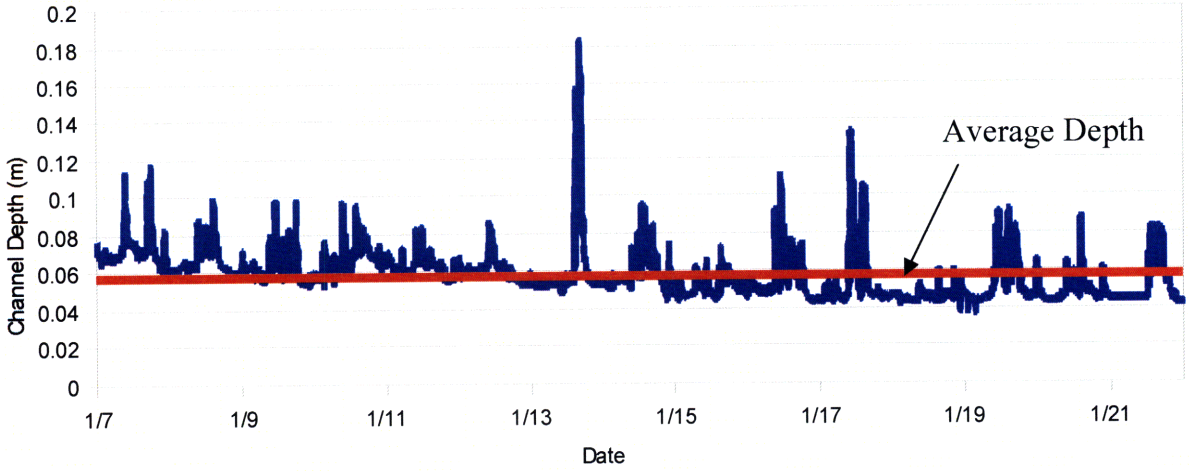

Figure 6.1: Channel Depth at KC2's Auto-Sampler

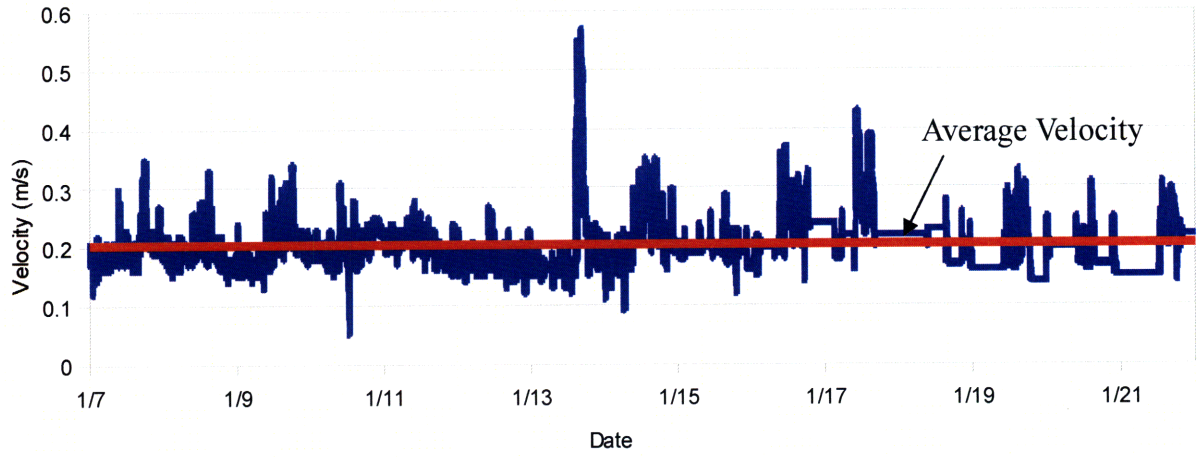

Figure 6.2: Velocity at KC2's Auto-Sampler

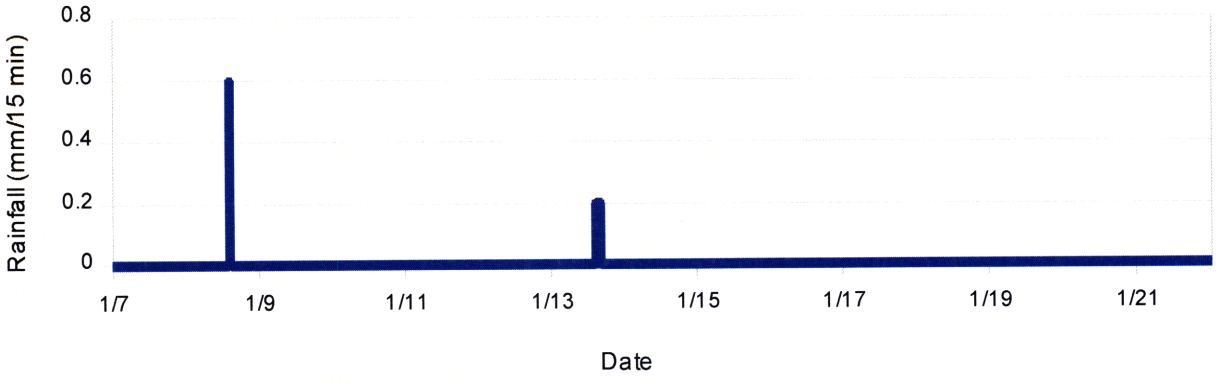

Figure 6.3: Rainfall at KC2's Auto-Sampler

6.1.2 Sampling Locations

Our team took approximately 122 non-point source samples within the Kranji Catchment, at auto-samplers, within the drainage system, and from run-off at a fish farm and a chicken farm. Sampling locations are shown in Figure 6.4.

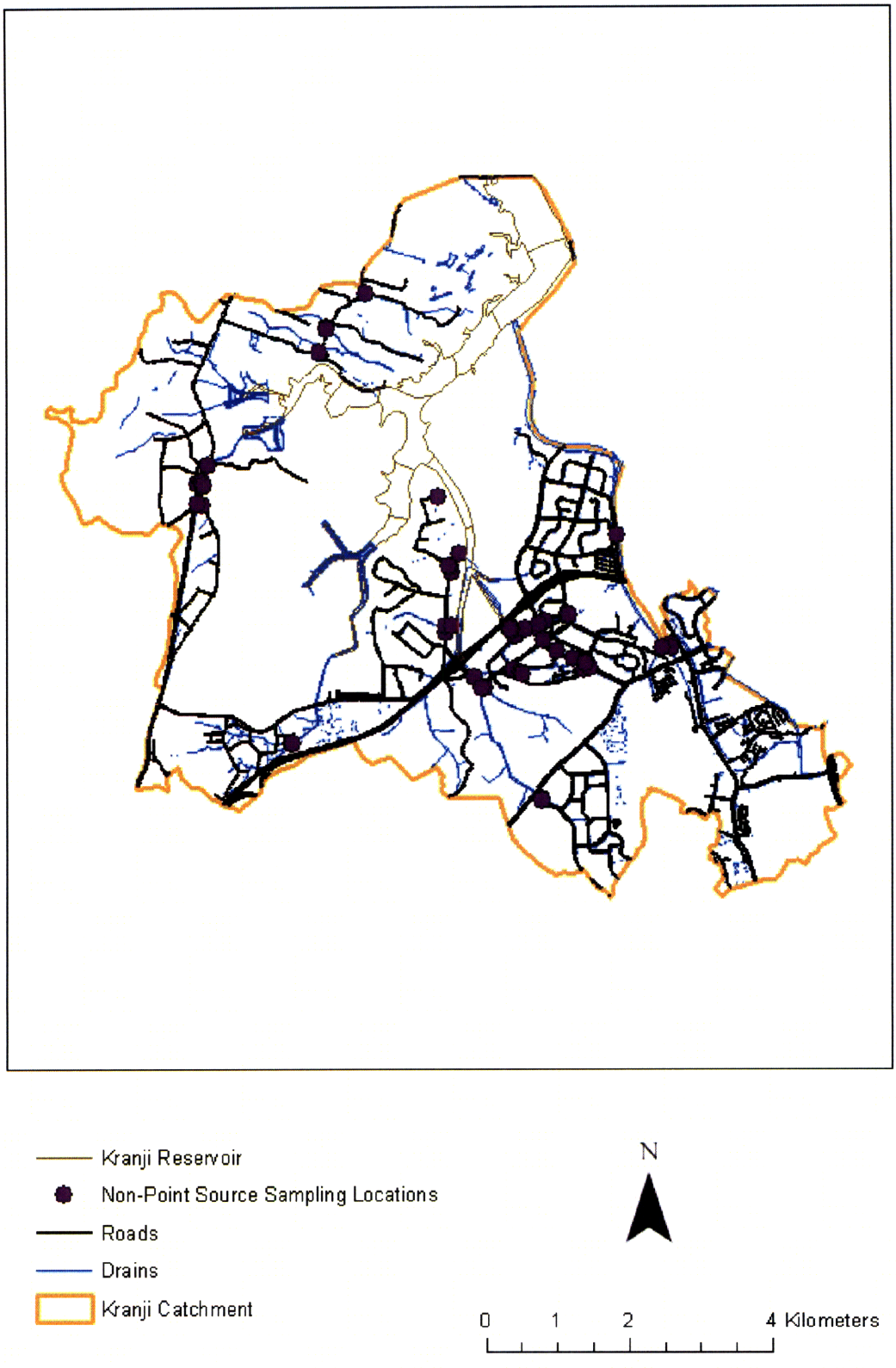

Figure 6.4: Non-Point Source Samples

6.1.3 Observations

In several of the sampling locations we made field observations, such as sheens on the water's surface or a sewage smell at the sampling site. These observations are included in the notes section in Appendix A. The sewage smell indicates that sanitary wastewater may be infiltrating the drains at these locations. This sewage smell may also be a product of people defecating in the drains. More study is needed to determine the exact causes of the sewage smell in these areas. The sheens may indicate small gasoline spills or road run-off getting in the drains. More study should be done to determine the sources of this potential contamination as well.

6.2 Point Source Sampling

Prior to our study, PUB suspected sewage treatment plant (STP) overflows to be the main source of bacterial pollution. Our team's point source sampling sought to determine the impact of a select few STPs within the catchment on the reservoir's and drainage system's bacterial loading.

6.2.1 Methods

We collected five point source samples from the effluent and influent of three STPs on January 20, accompanied by PUB officials. During sampling, approximately 400-500 milliliters of effluent from the septic or sedimentation tanks at these STPs were collected in sterile plastic bags, chilled until transported to the NTU laboratory, processed using membrane filtration and the Hach m-ColiBlue24® method within thirty hours, and then incubated at 35 degrees Celsius for 23-25 hours.

6.2.2 Sampling Locations

Our team sampled at selected STP effluent discharge points and one influent to an STP identified by PUB. We collected the five samples at three locations within the Kranji Catchment including a produce market/restaurant complex (Farmart), a very large chicken farm, and a fish farm. The sampling locations of all five samples are shown in Figure 6.5.

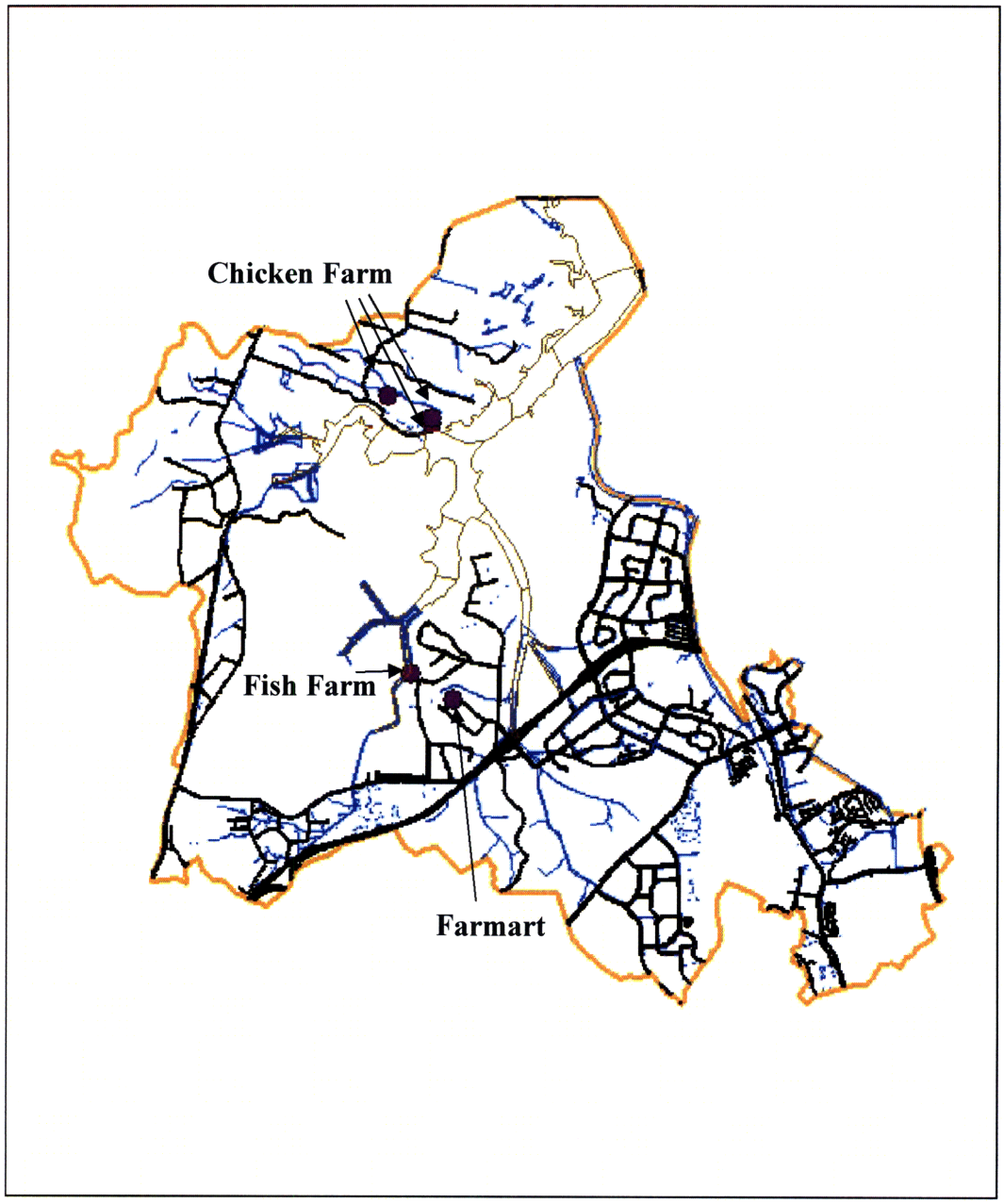

Figure 6.5: Point Source Samples

6.3 Reservoir Sampling

This section was written as part of a collaborative effort with Cameron Dixon.

Reservoir sampling occurred over the week of January 19 through January 23. We conducted the sampling to determine bacteria levels in the reservoir itself.

6.3.1 Methods

Our team collected water samples from a boat provided by PUB, using either Whirl-Pak bags or clean, sterile 1-liter containers for sample collection. We first removed the cap or opened the bag, and then placed the mouth of the container approximately ten centimeters beneath the surface of the water until the container was nearly full. We then sealed the pre-labeled container and placed it on ice in a cooler in the boat. The samples were kept on ice until analysis in the laboratory. Fourteen samples taken on January 19 and 20 were tested for *E. coli* by membrane filtration. The high turbidity of the reservoir rendered the samples unable to be analyzed using membrane filtration. Because of this, we discontinued *E. coli* testing after the second day.

6.3.2 Sampling Locations

Our team took water samples from select locations distributed within the reservoir. Figure 6.6 shows the sampling locations in the reservoir. Res-A is where the proposed boat launch and visitor's center will be located. Res-B and Res-C are in the same places as Station 3 and Station 1 from the previous reservoir study by NTU (2008), as can be seen in Figure 4.1. Res-D is located next to the proposed pavilion and dock. We chose sampling locations TG, KK, and PS to allow us to characterize their respective inflow arms of the reservoir.

Figure 6.6: Reservoir Sampling Locations

6.4 Domestic Wastewater Infiltration Testing

We conducted testing for inadvertent domestic wastewater hookups to drains using cotton pads to adsorb whiteners from detergent products carried in domestic wastewater. These whiteners fluoresce when held under a black light. We placed cotton pads in four drains in KC2 carrying reservoir-bound flow and left them for two days. We removed the pads and analyzed them for fluorescence under a black light. Any fluorescence would have likely been due to laundry detergents and, thus, would have indicated that human wastewater was contributing to the drain's flow. Due to the cotton pads also attracting a substantial amount of particulate matter, we could draw no conclusions from this test even after pulling them apart and rinsing them to try to remove some of the particulate buildup.

7 Laboratory Analysis

Our team completed three weeks of sampling, resulting in 148 samples, including seven blank samples. We used the Hach m-ColiBlue24® method to process the samples in order to delineate *E. coli* concentrations. This is a membrane filtration test that allows enumeration of total coliform and *E. coli* (fecal coliform) within 24 hours. After incubation, total coliform colonies appear red and *E. coli* appear blue and can be counted (Hach Company 1999).

We determined the reservoir *E. coli* levels using membrane filtration and the Hach m-ColiBlue24® method, but, because of the reservoir's high turbidity, *E. coli* levels at those sampling sites are uncertain. Because some dilutions of the samples showed no *E. coli* colonies, however, an upper limit can be determined for the *E. coli* concentration of those samples.

We used the resulting bacterial colony counts to find the waters' total coliform and *E. coli* concentrations, based on the dilution used in the analysis. We mapped all of the sampling locations using GIS.

7.1 Preliminary Results

Total coliform concentrations ranged from 1800 in a KC2 drain to 167 million in the run-off of a fish farm. *E. coli* concentrations ranged from 87 in a KC2 drain to 29 million at a location draining directly into the reservoir downstream from KC1's auto-sampler. A selection of the sampling results can be found in Table 7.1. The complete results including duplicates and blanks can be found in Appendix A. Maps of the results can be seen in Figure 7.1 (for non-point sampling results) and Figure 7.2 (for point source sampling results).

Table 7.1: E. coli Concentrations at Selected Sampling Points

Sample Name	Date	Time	*E. coli* Concentration (CFU/100 mL)	Location
22.7-44.8-A	01/12/09	11:34	520,000	KC2 Drainage System
22.8-44.7	01/09/09	12:50	9,000	KC2 Drainage System
22.9-44.3-18	01/22/09	18:00	2,300	KC2 Drainage System
22.9-44..3-1	01/22/09	01:00	150,000	KC2 Drainage System
23.8-43.4-A	01/20/09	16:00	830,000	Chicken Farm Sedimentation Tank Entrance
23.8-43.4-B	01/20/09	16:05	<120[1]	Chicken Farm Sedimentation Tank Exit
23.0-43.6	01/20/09	17:55	>200,000,000[2]	Farmart Sedimentation Tank Exit
23.2-43.3	01/20/09	17:15	1,500	Fish Farm Sedimentation Tank Exit
25.0-43.1	01/20/09	15:15	3,700	Chicken Farm Sedimentation Tank Exit

[1] This number is an estimate. The sample showed zero *E. coli* for a 1:100 dilution. Neither a 1:1 nor a 1:10 dilution was performed. The test performed is only valid for *E. coli* counts between 12 and 200.
[2] This number is an estimate. The sample showed greater than 200 *E. coli* for a 1:1,000,000 dilution. No higher dilutions were analyzed. The test performed is only valid for *E. coli* counts between 12 and 200.

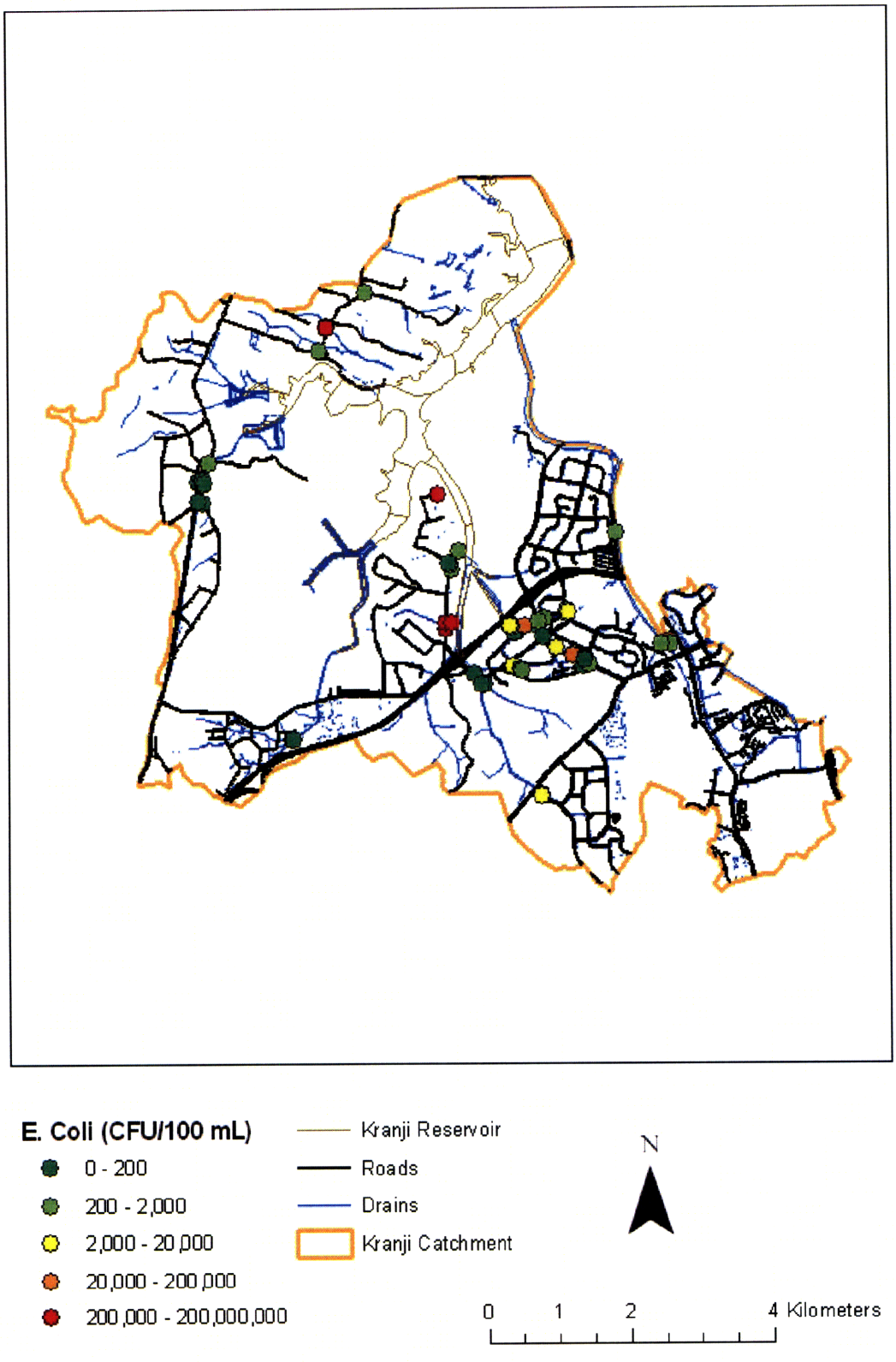

Figure 7.1: Non-Point Source Sampling Results

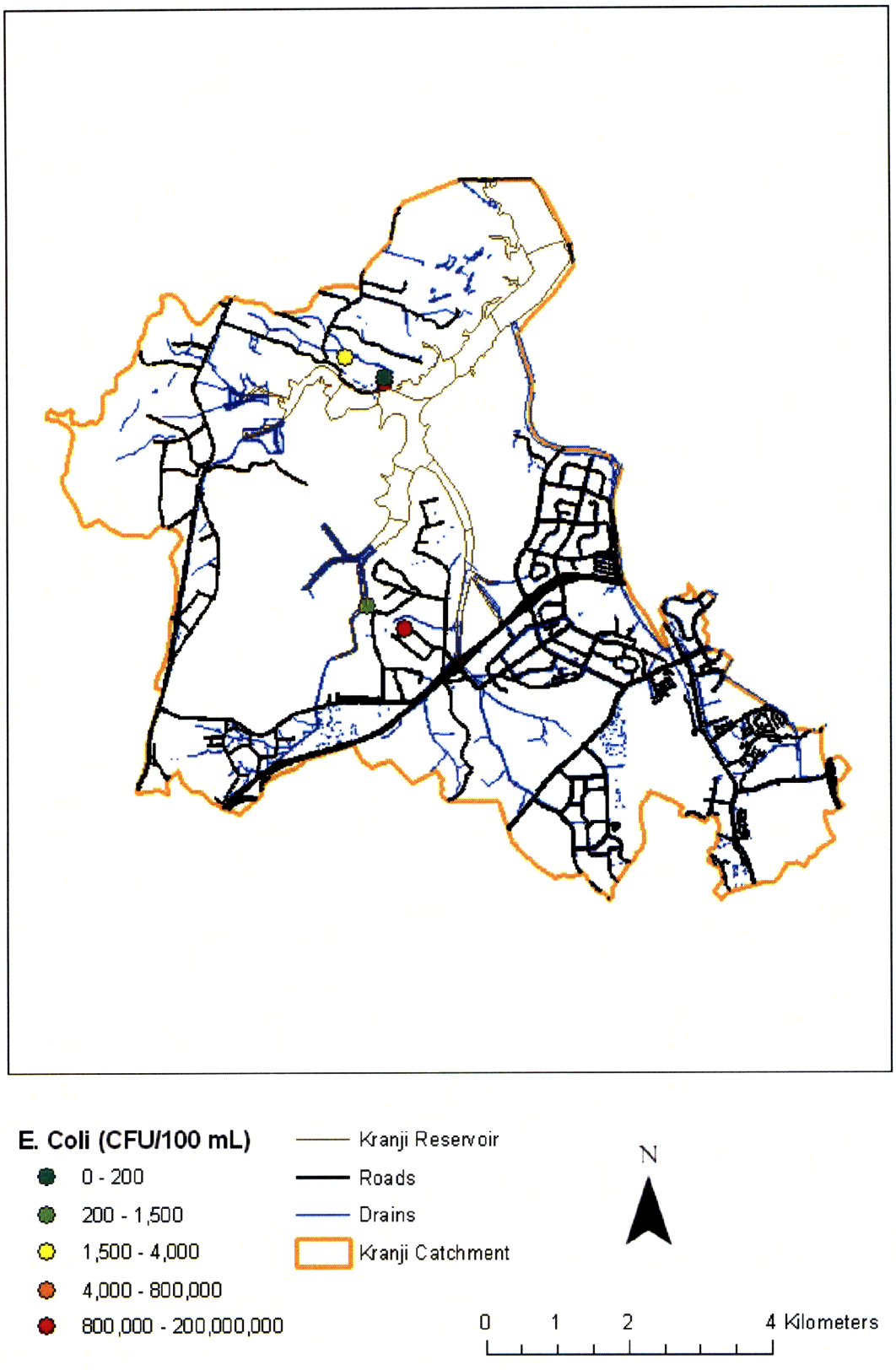

Figure 7.2: Point Source Sampling Results

We also conducted a 22-hour round of sampling at auto-sampler KC2 to evaluate the variability of *E. coli* concentrations over time. This test showed that *E. coli* concentrations can vary substantially over time, as seen in Figure 7.3. This variability could also be a result of intrinsic variability in bacteria sampling.

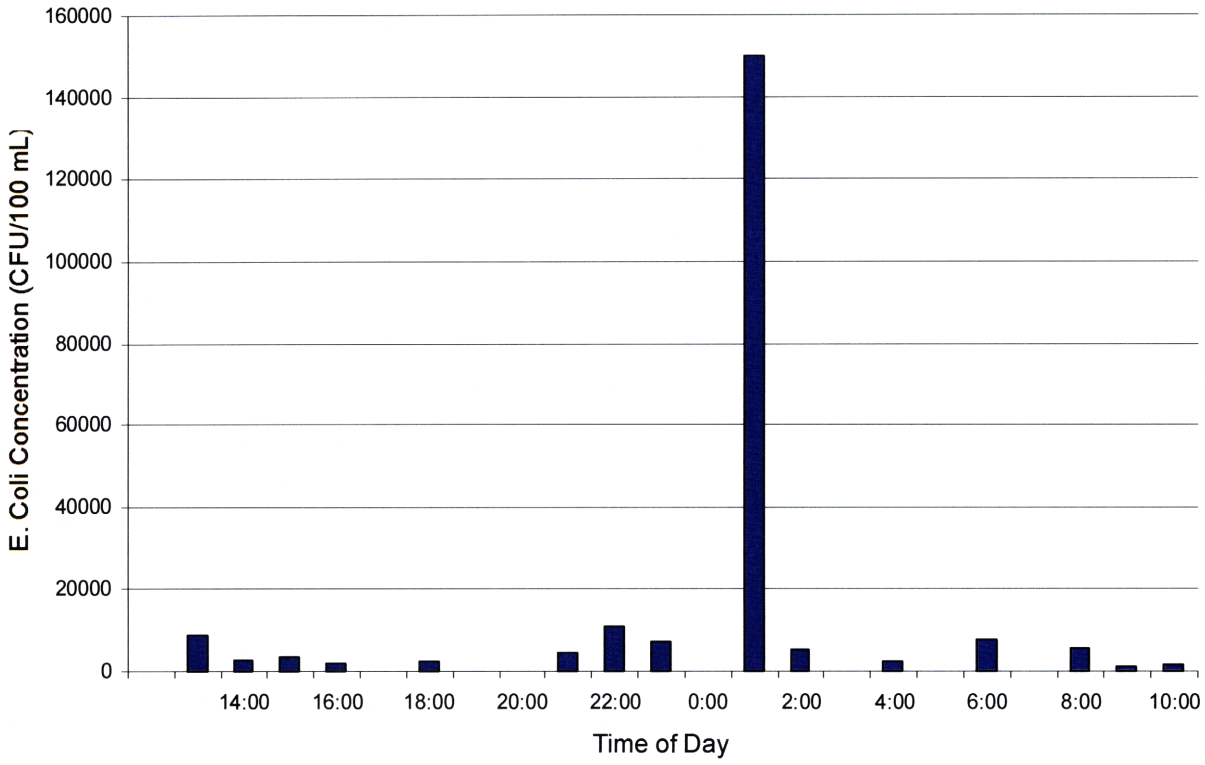

Figure 7.3: 22-Hour Round of Sampling at KC2's Auto-Sampler

The reservoir *E. coli* readings are shown in Table 7.2. Due to high turbidity in the reservoir, we could not read the non-diluted samples. These *E. coli* concentrations are based on the fact that samples diluted one-to-ten showed no *E. coli*. These concentrations are estimates.

Table 7.2: Reservoir Sampling Data

Date	01/19/09	01/20/09
Sample Name	*E. coli* Concentration (CFU/100 mL)	
23.7-43.4	<10	<10
23.9-44.0	<10	<10
24.7-43.7	<10	<10
24.7-43.5	<10	<10
24.8-42.8	<10	<10
25.9-44.5	<10	<10
26.1-44.2	<10	<10

8 Field and Laboratory Quality Control and Quality Assurance

This section was written as part of a collaborative effort with Carolyn Hayek, Cameron Dixon, and Jean Pierre Nshimyimana.

Quality assurance (QA) is the standard program and policies adopted for field and laboratory operation that define the measures necessary to produce defensible data of known precision and accuracy. Quality control (QC) is the set of processes adopted to ensure the quality of analytical data produced (Eaton et al. 2005).

8.1 Initial Demonstration of Competency

Each member of our research team completed an initial demonstration of capability to conduct each test that was performed in this project (Eaton et al. 2005). We examined our field and laboratory notes to ensure that every member of our team used the same protocols and found no inconsistencies.

8.2 Collection and Preservation of Samples

The MIT research team collected samples that were small enough by volume to be transported to the lab easily but still large enough to be used in the analysis, ranging from 400 milliliters to one liter. We handled samples in a way that prevented deterioration, contamination, or any other result that would have compromised them before analysis, by collecting them in sterile Whirl-Pak bags or 1-liter bottles and transporting them in coolers with ice. We made certain of the cleanliness and quality of all sampling equipment and used only clean sample containers. Following the procedures of Eaton et al. (2005), all bottles being reused were either bleached and soaked in deionized water or baked at 450 degrees Celsius to ensure cleanliness.

Following procedures from Eaton et al. (2005), we filled sample containers without pre-rinsing with sample, leaving a space for aeration. To minimize the potential for biodegradation, samples were then chilled, but not frozen, in coolers until transported to the laboratory.

8.2.1 Proper Labeling

Our team made a record of every sample collected and identified each bottle/container with a unique sample number, team name, sample type (if DNA), date, hour, minute and exact location collected, which were written on the sample's label. Other data such as water temperature, weather conditions, water level, and stream flow were recorded in the field logs. We used GPS to determine sample locations.

8.2.2 Laboratory and Field Blanks

A blank is a water sample that has no initial concentration of bacteria. This blank is used to evaluate instrument performance and the accuracy of testing. We took blank samples with our sample batches on the third, fourth, fifth, sixth, and seventh days of sampling. On these days, we took approximately one blank sample for every eight field samples. All blanks contained zero *E.*

coli and zero total coliform, as can be seen in Table 8.1, demonstrating the lack of outside contamination experienced by the samples in the study.

Table 8.1: Laboratory and Field Blanks

Date	Sample Name	Time	Total Coliform (CFU/100 mL)	Total *E. coli* (CFU/100 mL)
1/12/2009	Blank	12:55	0	0
1/12/2009	Blank	11:38	0	0
1/13/2009	Blank	14:30	0	0
1/14/2009	Blank	11:08	0	0
1/14/2009	Blank	12:30	0	0
1/15/2009	Blank	11:50	0	0
1/16/2009	Blank	12:43	0	0

8.2.3 Duplicate Sampling

At specific sampling sites, our team took two samples (a sample and a duplicate sample). Following the procedures of Eaton et al. (2005), the duplicate sample was taken in the field in the same way the original sample was taken. The duplicate was processed in the laboratory like the original sample was processed. We took duplicate field samples with our sample batches on the second, third, fourth, fifth, sixth, seventh, and tenth days of sampling. On these days, we took approximately one duplicate sample for every nine field samples, resulting in ten duplicate samples.

We evaluated our duplicate samples based on quality assurance goals published by Oregon's Department of Environmental Quality (2001). To achieve these goals, the relative percent difference between the original sample and the duplicate sample should be less than 25 for samples with values greater than five times the detection limit, or sixty Colony Forming Units per one hundred milliliters. For samples with values less than or equal to sixty Colony Forming Units per one hundred milliliters, the absolute difference between the same dilution of the two samples should be less than two times the detection level, or 24 Colony Forming Units per one hundred milliliters. If our samples do not achieve these goals, we have qualified them with a J, indicating they are an estimate.

To analyze the accuracy of our duplicate sampling, we used Equation 8.1 (Eaton et al. 2005) to calculate the relative percent difference of the two samples with the same dilution, as seen in Table 8.2. We also calculated the absolute difference of the two samples with the same dilution, as applicable, as seen in Table 8.2.

$$\frac{[original]-[duplicate]}{([original]+[duplicate])/2}\times 100 \qquad (8.1)$$

Table 8.2: Duplicate Samples

Date	Sample Name	Time	*E. coli* Dilutions				Total *E. coli* (CFU/100 mL)	Relative Percent Difference	Absolute Difference (CFU/100 mL)	Qualifier
			10^2	10^3	10^4	10^6				
1/9/2009	22.9-44.3-D	10:30	34	21	1		12,200	NA[3]	13	
1/9/2009	22.9-44.3-D	10:30	47	0	1		4,700			
1/12/2009	22.7-44.9-B	11:50	TNTC	TNTC	158		1,580,000	NA	155	J[4]
1/12/2009	22.7-44.9-B	11:50	TNTC	17	3		17,000			
1/13/2009	22.6-44.4-A	14:25	18	5	0		1,800	NA	7[5]	
1/13/2009	22.6-44.4-A	14:25	11	2	2		uncertain			
1/14/2009	22.7-44.9-B	10:35	10	1	0		uncertain	NA	3[5]	
1/14/2009	22.7-44.9-B	10:35	7	0	0		uncertain			
1/14/2009	23.0-43.8-B	12:27	TNTC	TNTC	TNTC		TNTC	0[6]	NA[7]	
1/14/2009	23.0-43.8-B	12:27	TNTC	TNTC	TNTC		TNTC			
1/15/2009	24.0-42.0-D	14:55	6		4	0	uncertain	NA	6[5]	
1/15/2009	24.0-42.0-D	14:55	0		0	0	uncertain			
1/15/2009	21.7-44.5	11:50	37	4	0		3700	NA	7	
1/15/2009	21.7-44.5	11:50	30	8	0		3000			
1/16/2009	23.0-43.8-B	11:15	TNTC		TNTC	29	29000000	NA	25	J[4]
1/16/2009	23.0-43.8-B	11:15	TNTC		TNTC	4	uncertain			
1/16/2009	22.6-44.4-A	12:45	21		0	0	2100	NA	11[5]	
1/16/2009	22.6-44.4-A	12:45	10		1	0	uncertain			
1/21/2009	22.8-45.5-A	16:30	70		21	5	108500	NA	49	J
1/21/2009	22.8-45.5-A	16:30	21		7	4	2100			

TNTC: Too Numerous To Count
NA: Not Applicable
J: Estimated Value

[3] The relative percent difference analysis is not applicable to values less than sixty Colony Forming Units per one hundred milliliters.
[4] One of the values is not in the valid range of twelve to two hundred; therefore, this absolute difference is only an estimate.
[5] One or both of the values is not in the valid range of twelve to two hundred; therefore, the absolute difference is only an estimate.
[6] The values are not in the valid range of twelve to two hundred; therefore, the relative percent difference is only an estimate.
[7] The absolute difference analysis is not applicable to values greater than sixty Colony Forming Units per one hundred milliliters.

As the table demonstrates, only a single sample with *E. coli* values between twelve and two hundred (Sample 22.8-45.5-A) did not meet our quality assurance goals. This indicates the relative accuracy of our testing procedures. The discrepancies exhibited by sample 22.8-45.5-A and its duplicate can be attributed to errors in our sampling or analysis methods. They could also be the result of problems with our analysis media. Hach has discontinued sale of their m-ColiBlue24® broth due to lack of sensitivity in random testing of the product. Communication with Hach revealed that the discontinued m-ColiBlue24® gave lower than expected concentrations of *E. coli* (Hach Customer Service 2009); therefore, we have assumed that even if this is a problem in our study, our values are still valid, but may be taken as conservatively low. Another possible source of the discrepancies is the natural variation in bacteria concentrations in a water body. Fluctuations in concentration are more common in flowing water (e.g. streams and drains) which is where many of our samples were taken. Also, because duplicate sampling consists of taking two separate samples of the water, the second sample could have more sediment due to stirring of the water body while taking the first sample (Thompson 2009). These effects would contribute additional *E. coli* to a sample.

8.2.4 Split Sampling

Split sampling entails analyzing the same sample more than once. We did not conduct any split sampling in our analysis.

Analysis

9 Theoretical Modeling of Bacterial Attenuation

9.1 Bacterial Attenuation through the Drainage System

The fate of bacteria in the environment has been studied extensively. Because *E. coli* is less sensitive to environmental stresses than other pathogens, it has been used in many of these studies as a conservative indicator of bacterial levels in recreational waters (Bowie et al. 1985). To find the expected attenuation as bacteria travel through the drainage system of Kranji Catchment, factors that influence bacterial die-off must be determined and modeled. These factors can be categorized as physical, physiochemical, or biochemical-biological (Bowie et al. 1985).

The physical factors that affect bacterial decay include photo-oxidation, adsorption, flocculation, coagulation, sedimentation, and temperature. Only photo-oxidation, or photolysis, temperature, and adsorption onto particles and sedimentation of those particles have been quantitatively shown to correlate to bacterial die-off. It has been postulated that ultraviolet light damages cell DNA, and, as such, sunlight kills off bacteria as effluent travels from the source (Bowie et al. 1985). Because much of the drainage system in Singapore is exposed to light, photolysis die-off will have a significant effect on the attenuation of bacteria from their sources to Kranji Reservoir. Temperature is also an important contributor to die-off rates of bacteria as quantified by Mancini (1978). Sedimentation will also have a significant effect on the die-off of bacteria in the drainage system, and needs to be incorporated into a model of bacterial disappearance in Kranji Catchment and Reservoir.

The physiochemical factors that influence bacterial decay include osmotic potential, pH, chemical toxicity, and redox potential. Increased salinity enhances the ability of solar radiation to increase the decay rate of bacteria. While heavy metal content and pH appear to affect disappearance rates, the exact manner in which these mechanisms contribute to the overall decay rates of bacteria is difficult to quantify and not fully understood in some cases (Bowie et al. 1985). Because of this and the fact that Kranji Reservoir is a freshwater body, these physiochemical factors will not be considered when modeling bacterial die-off in the drainage system.

The biochemical-biological factors that affect the decay rate of bacteria include nutrient levels, presence of organic substances, predators, bacteriophages, algae, and presence of fecal matter (Bowie et al. 1985). While nutrient levels, predation, and algae appear to affect disappearance rates for bacteria, the synergies and mechanisms for these effects are not fully quantifiable. Except for the natural mortality effects on bacteria disappearance, these biological factors will not be incorporated into the attenuation model for Kranji Reservoir.

Traditionally bacterial die-off has been modeled using a simple first-order decay equation, as seen in Equation 9.1.

$$C_t = C_0 e^{-kt} \tag{9.1}$$

In Equation 9.1, C_t is the concentration of bacteria at time, t. C_0 is the initial concentration of bacteria. The variable t is the time, and k is the decay constant.

The decay constant is typically determined experimentally using sample concentrations. The decay constant can also be found empirically, taking into account natural die-off, sedimentation, and photolysis, as discussed in Thomann and Mueller (1987). The total loss rate, k, is found by combining the loss rates for natural mortality, k_1, photolysis, k_p, and sedimentation, k_s, as Equation 9.2 shows (Mills et al. 1985).

$$k = k_1 + k_p + k_s \tag{9.2}$$

Bacteria naturally die just as any other living organism. This natural die-off needs to be incorporated into any rate constant for bacterial disappearance. Bacterial survival is heavily dependent on temperature, salinity, and solar radiation. Mancini (1978) developed a model to incorporate these factors empirically. Mancini used published mortality rates of bacteria and plotted decay rates versus temperatures to find a model that describes bacterial die-off in both seawater and freshwater. The rate constant for natural mortality of bacteria can be modeled with Equation 9.3, where T [degrees Celsius] is the water temperature (Mancini 1978).

$$k_1 = (0.8 + 0.006(\%seawater))1.07^{(T-20)} \tag{9.3}$$

Because Kranji is a freshwater reservoir and the drainage system of Kranji Catchment is presumed to have low salinity, the equation for natural mortality can be rewritten to exclude salinity, and the loss rate due to natural mortality, k_1 [per day], can be written as Equation 9.4.

$$k_1 = (0.8)1.07^{(T-20)} \tag{9.4}$$

As discussed above, ultraviolet light increases disappearance rates of bacteria. Thomann and Mueller (1987) developed an equation to describe die-off from photolysis using the findings of a study of the effect of sunlight on die-off rates of bacteria by Gameson and Gould (1974) and the fact that solar radiation is attenuated by water and, therefore, decreases with depth below the water surface. Light decay can be modeled with Equation 9.5, where α is a proportionality constant that has been determined by Thomann and Mueller (1987) from Gameson and Gould's data (1974) to be approximately unity. I_{ave} [kilocalories per centimeter squared] is the average light energy experienced by the bacteria.

$$k_p = \alpha I_{ave} \tag{9.5}$$

Light energy, I, can be modeled with respect to the depth of water according to the Beer-Lambert Law, Equation 9.6, where I_0 [kilocalories per square centimeter] is the average daily amount of incoming light energy at the surface of the water. The variable k_e [per meter] is an extinction coefficient dependent on turbidity (amount of particulate matter in the water) and color. The value of k_e can be approximated as 0.55 times the concentration [milligrams per liter] of total suspended solids (TSS) in the water. The variable z [meters] is the depth below the water surface (Chapra 1997).

$$I(z) = I_0 e^{-k_e z} \tag{9.6}$$

For an open channel of depth H [meters], I_{ave} can be found by integrating Equation 9.6 over the depth of the channel, as seen in Equation 9.7 (Chapra 1997).

$$I_{ave} = I_0 \frac{1 - e^{-k_e H}}{k_e H} \tag{9.7}$$

By incorporating these equations, a die-off constant due to photolysis, k_p [per day], can be created. Thomann and Mueller (1987) did this as can be seen in Equation 9.8.

$$k_p = \alpha I_0 \frac{1 - e^{-k_e H}}{k_e H} \tag{9.8}$$

In addition to natural die-off and die-off due to photolysis, sedimentation of bacteria adsorbed to particles has an effect on the fate and transport of bacteria in a system. Bacteria can adsorb onto particles of sediment, which allows the bacteria to settle out of water as the particles settle. This settling loss rate is dependent on the fraction of bacteria that attaches to particles in the water, the settling velocity of these particles, and the depth of the channel. The loss rate due to sedimentation, k_s [per day], can be modeled using Equation 9.9, where H is the channel depth. F_P is the fraction of bacteria that are attached to particles as modeled by Equation 9.10, and v_s [meters per day] is the settling velocity of the particles (Chapra 1997).

$$k_s = F_P \frac{v_s}{H} \tag{9.9}$$

The fraction of bacteria that adsorb to particles is dependent on the amount of particles in a water body, or the total suspended solids (TSS), and the partition coefficient associated with the bacteria and the particles involved. Equation 9.10 models the fraction of bacteria attached to particles. K_d [liters per milligram] is a partition coefficient and [TSS] [milligrams per liter] is the suspended solids concentration (Chapra 1997).

$$F_P = \frac{[TSS]K_d}{1 + [TSS]K_d} \tag{9.10}$$

Using the studies of Mancini (1978) and Thomann and Mueller (1987), die-off modeling can be done empirically for natural mortality, photolysis, and sedimentation. The drainage system in Kranji Catchment's KC2 sub-catchment was one-dimensionally modeled using the first-order decay equation (Equation 9.1), with the loss rate, k, incorporating natural mortality and sedimentation. This gives the attenuation from each sampling point to Kranji Reservoir via the drainage system.

9.2 Travel Time and Flow Data

Dry weather flow in channels can be described using Manning's equation for channel flow

(Equation 9.11).

$$v = \frac{R_h^{2/3} S_0^{1/2}}{n} \tag{9.11}$$

R_h [meters] is the hydraulic radius of the water in the channel and v [meters per second] is the velocity of the flow in the channel. The variable, n, is the roughness coefficient that describes the roughness of the surface of the channel sides and bottom. S_0 is the slope of the channel (Thomann and Mueller 1987).

Travel time for a parcel of water can be determined using Equation 9.12.

$$t = \frac{d}{v} \tag{9.12}$$

The variable d [meters] is the distance traveled and t [seconds] is the time taken to travel that distance. By measuring distances between sampling points and the reservoir in ArcMap, determining velocity through the system, and using Equation 9.12, we can determine travel time from the source to the reservoir.

10 Model Development

10.1 Assumptions

For our model development, we focused on sub-catchment KC2. We chose this one because we were able to take many more samples in KC2 than in any other sub-catchment. Because this sub-catchment is mostly residential, there was easy access to many of the drains. This sub-catchment was also highlighted in the NTU study (2008) as a suspected heavy contributor to the bacterial loading of the reservoir, since high concentrations of bacteria were found at its auto-sampler. Because KC2 is a newer residential area, the drain size and shape were relatively uniform throughout the drainage system.

For sub-catchment KC2, we made several assumptions regarding flow through the drainage system and the decay constant. Because the channels throughout the drainage system are relatively similar in cross-sectional area and depth, we assumed that the velocity of the water was constant in all parts of the drainage system. Because no substantial rain events occurred during the month and the standard deviation in the measured velocities was only 0.043 meters per second, we assumed the velocity of the channel was constant over time for our eleven days of fieldwork (January 7-22, 2009). We determined this velocity was approximately 0.2 meters per second, as seen in Table 6.1: Auto-Sampler Flow Measurements.

Because a very high percentage of KC2's drainage system is underground, the decay constant for KC2 did not include die-off due to sunlight, but only decay due to natural die-off and settling. Decay due to natural die-off (Equation 9.4) is dependent on water temperature. Because Singapore experiences relatively constant mean monthly temperatures, ranging from 26 degrees Celsius to 28 degrees Celsius throughout the year (The Weather Channel 2008), the water temperature in the drainage system can be assumed to be relatively constant. Based on observations and two temperature measurements in the covered drains, we assumed the water temperature to be constant at 26 degrees Celsius. Using this temperature, we computed the decay due to natural die-off as 1.2 per day.

To determine the decay due to settling (Equation 9.9), we estimated the average depth of water in the drainage system to be the average depth of water at KC2's auto-sampler, 0.06 meters, as seen in Table 6.1: Auto-Sampler Flow Measurements. Because there were no significant rain events during our field work, the standard deviation in the depth of the water in the channel was only 0.014 meters. Based on observations and depth measurements, we estimated that the depth of the water in the channels is relatively uniform throughout the drainage system. The particle settling velocity is 0.00002 meters per second, or about 2 meters per day, as approximated from a study by Jamieson (2005). The partition fraction was taken to be 0.44. This is the fraction of bacteria found to adsorb to 45-75 micron particles in Jamieson's study. Using this settling velocity, depth, and partition coefficient, we computed the decay due to settling in KC2 as approximately 10 per day, which dominates the decay constant.

10.2 Attenuation Model

The percentage of living bacteria as a function of time can be characterized by Equation 9.1. To describe the attenuation of the bacteria in KC2's drainage system, we combined the two

decay constants above. We computed the decay through the drainage system as 10 per day. The bacterial attenuation through the drainage system can be modeled with Equation 10.1. Distance, *d* [meter], must be multiplied by the decay constant (approximately 10 per day) and divided by the velocity (approximately 0.2 meters per second), which gives the coefficient of 0.0008 [per meter] in Equation 10.1.

$$1 - \frac{C}{C_0} = 1 - e^{-0.0008d} \qquad (10.1)$$

This equation can be used to determine how much bacteria should be lost as bacteria travel through the drainage system of sub-catchment KC2. This can be used to predict bacteria levels within the system if all bacteria originate from a single source. This can, therefore, be used to identify locations of potential bacterial sources. Locations that exhibit significantly higher bacteria levels than predicted by the model will indicate an area containing an additional bacterial source.

10.3 Model Verification

Lee Li Jun and Por Yu Ling, undergraduate students at Nanyang Technological University, conducted a test on March 25, 2008 to verify and calibrate our theoretical model. They collected two samples near KC2's auto-sampler. The locations of these points are shown in Figure 10.1. The results of this sampling can be seen in Table 10.1.

Figure 10.1: KC2 Sampling Points for Model Calibration (GoogleMaps 2009)

Table 10.1: Model Calibration Sampling Results

Sampling Points	*E. coli* Concentration (CFU/100 mL)	Velocity (m/s)
Upstream Point	350,000	0.23
Downstream Point	190,000	0.23

The distance between these two points is approximately 150 meters. Using the velocity measured by the auto-sampler at 15:15 on March 25, 2009, 0.23 meters per second, we computed the travel time between the upstream point and the downstream point as approximately 11 minutes. Using

this travel time in Equation 9.1), we computed the bacterial decay constant, k, as approximately 81 per day to produce the die-off observed in the field. This is substantially more attenuation than our model predicts. Because this length of drain is exposed to sunlight, an additional 0.2 per day of decay (from Equation 9.8) would need to be added to our theoretical decay, however this is insufficient to explain the observed discrepancy between field observations and the attenuation rate computed in section 9. The additional attenuation observed in the field could be due to inaccuracies in the parameters, an incomplete theoretical model, or equation or sampling inconsistencies.

Because this test was conducted only once, we will use the theoretical decay constant of 10 per day in this study. This will give a conservatively low estimate of attenuation until further study can be done to fully calibrate the attenuation model of KC2's drainage system.

11 Mapping Sampling Data with ArcGIS

11.1 Mapping of Sampling Data

Our team mapped both the non-point source and point source sampling points, along with other geographic data and infrastructure, using ArcGIS's ArcMap, Figure 6.4 and Figure 6.5.

We received GIS data that described the Kranji Catchment, the buildings on the island, the drainage system of Singapore, the island's elevation, and the Kranji Reservoir from Prof. Lloyd Chua and Syed Alwi Bin Sheikh Bin Hussien Alkaff at NTU. This data was in differing spatial coordinates, so we had to project all of the data layers into the same World Geodetic System of 1984, Universal Transverse Mercator (UTM) zone 48N. This is the appropriate zone for Singapore (Franson Technology 2009). Our team did this using the projection tool in ArcMap.

We then mapped our sampling data from a spreadsheet, using the add x-y data tool. This tool plots data using latitudes and longitudes in the same projection as the rest of the layers in the map. Because our data's longitude and latitude readings were only accurate to three decimal places, the sampling points had to be moved, using ArcMap's editor tool, to align them with the appropriate drains in the mapped drainage system. Also, because we took several samples at the same sampling point, we used the editor tool to move these points to allow for full visibility of every sample's location. These points were displaced only minimally so it would be clear that they belonged to the same sampling location.

11.2 KC2 Data Analysis with ArcGIS

Our team used ArcGIS's ArcMap to calculate the distances over which the samples experienced attenuation. We then used Equation 10.1) to compute the attenuation and expected *E. coli* concentrations from these distances.

For sub-catchment KC2, we used the average *E. coli* concentrations at each of the 29 different sampling locations in the drainage system. Our samples included multiple samples at each location over the three weeks of sampling and our samples were not taken at the same time of day or day of the week. To account for this variation, we used average concentrations in our computations. Averaging the concentrations helped us filter out the temporal fluctuations in the *E. coli* concentrations at different sampling locations.

The drainage system layer in ArcMap had gaps between line segments and, therefore, we had to redraw the drainage system using the editor tool. Then, we used ArcGIS's ArcCatalog to create a network dataset out of this fully connected redrawn drainage system. Using this network dataset, our team employed the network analyst tool in ArcMap to calculate the route lengths between upstream sampling locations and the closest downstream sampling point.

We performed our analysis on separate groups of sampling points and the point immediately downstream of these points. This created thirteen groups of upstream points (ranging from one to five points). One of these groups of upstream points and their immediate downstream point is shown in Figure 11.1. The upstream points are shown as squares and the downstream point is shown as a circle. The samples travel downstream from the squares along the drainage system to

the circle. The dark lines indicate roads.

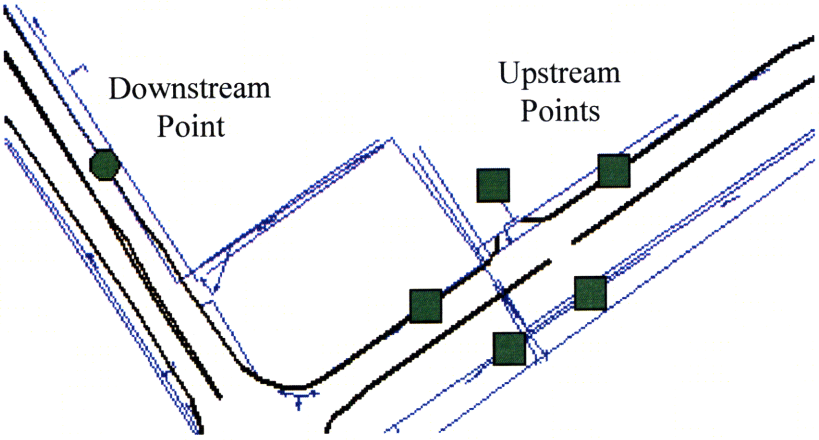

Figure 11.1: Group of Upstream Points and Downstream Point

Using Equation 10.1, we computed the expected *E. coli* concentration in water from each upstream point as it traveled through the drainage system to the downstream point. We then averaged these concentrations to account for the fact that the samples mixed as they traveled through the system to the downstream point. Finally, we compared this resulting average concentration to the measured concentration at the closest downstream sampling point. Where these predicted concentrations were substantially less than the measured concentrations, we hypothesized that additional *E. coli* sources existed in the drainage system between the upstream points and the downstream point. These areas of potential sources in sub-catchment KC2 are indicated in Figure 11.2.

11.3 Attenuation from the Ten Samples with the Highest Concentrations using ArcGIS

The samples with the ten highest concentrations, in order according to sample name instead of in order of concentration since some locations have several different concentrations, are 22.7-44.9-B, 22.9-43.8-B, 22.9-43.8-D, 23.0-43.6, 23.0-43.8-B (on two different dates and two as duplicates), and 23.9-43.8 (on two different dates) as can been seen in Appendix A.

Our team used ArcGIS's ArcMap to calculate the distance from these sampling points to the reservoir via the drainage system. We could not do this using ArcMap's network analyst tool as we did for KC2's drainage system because, due to the poor connectivity between segments in the original drainage layer, it would entail drawing entirely new drainage systems for each location. We instead used ArcMap's measure tool to calculate the distance between each sampling location and the reservoir, as seen in Figure 11.3.

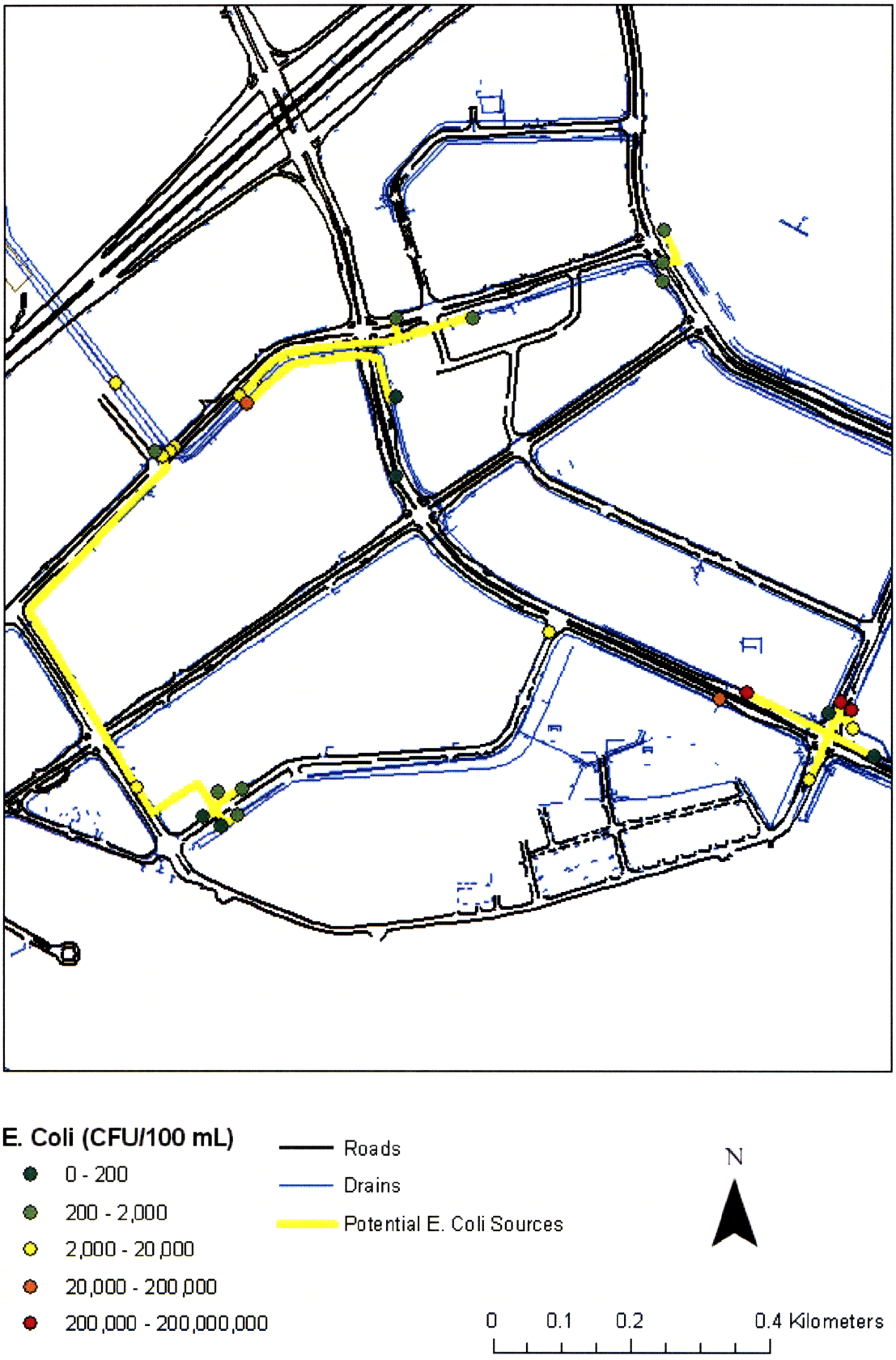

Figure 11.2: Potential E. coli Sources in KC2

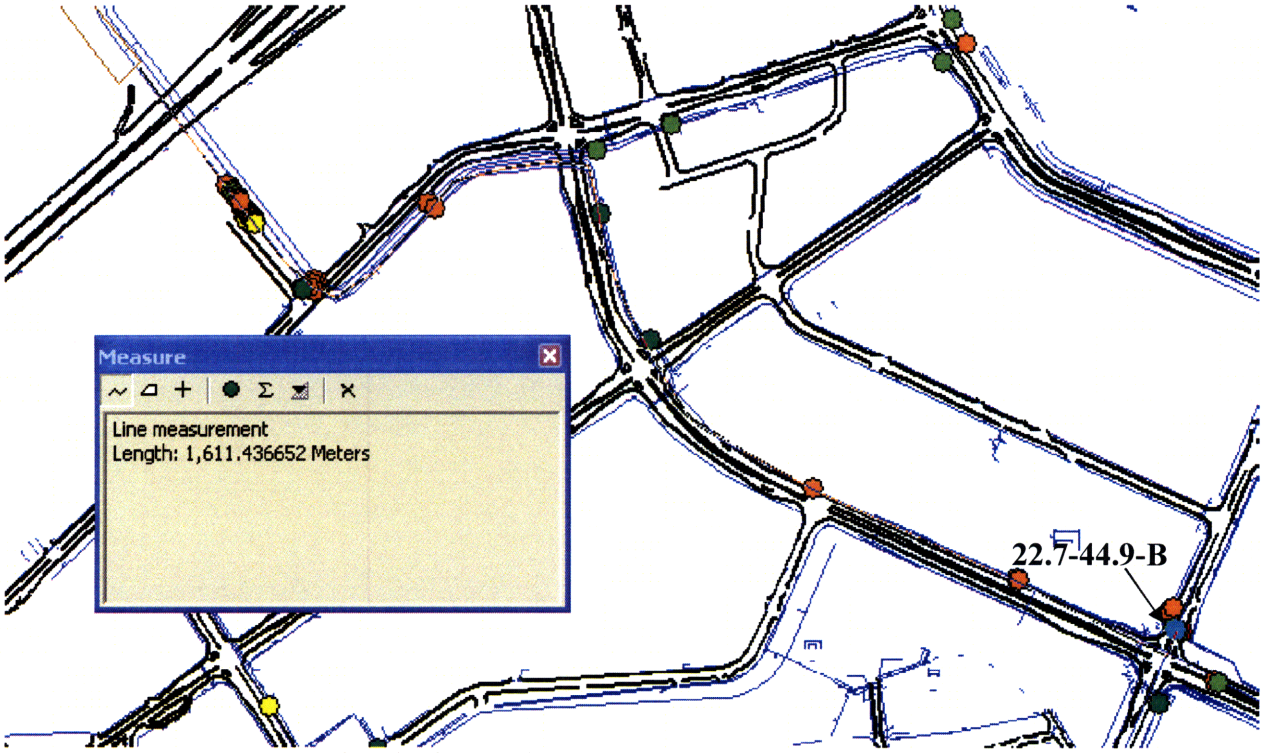

Figure 11.3: Measure Tool Calculating the Distance from 22.7-44.9-B to Kranji Reservoir

Sampling location 22.7-44.9-B is located in KC2's drainage system, enabling us to use Equation 10.1 to calculate attenuation from this point to the reservoir since this equation was developed with data from KC2. For the other five sampling locations, however, we do not know the velocity of the flow, channel depth, or TSS concentration because there are no auto-samplers between them and the reservoir. The drains along which these samples traveled were exposed to sunlight, but, as demonstrated in Section 10.3, this does not contribute significantly to the decay constant. We, therefore, have made the assumption that a conservatively low estimate of attenuation for these ten samples can be computed using Equation 10.1, assuming the same decay constant and travel velocity as KC2's drains. This is the best estimate that can be made until further investigation to determine flow, depth, and TSS concentration data can be conducted at the remaining five sampling locations.

Table 11.1 shows the *E. coli* concentrations for the ten samples, the distance along the drainage system from these sampling locations to the reservoir, and the percentage of attenuation in the *E. coli* that should be seen at the reservoir for each sample.

Table 11.1: Distances from the Samples with the Ten Highest Concentrations to the Reservoir

Sample Name	*E. coli* Concentration (CFU/100 mL)	Distance to Reservoir (m)	*E. coli* Attenuation (%)
23.9-43.8 (1)	200,000,000	70	6
23.0-43.6	200,000,000	180	10
23.0-43.8-B (1)	29,000,000	70	5
22.9-43.8-B	21,000,000	200	10
23.9-43.8 (2)	2,000,000	70	6
23.0-43.8-B (2)	2,000,000	70	5
23.0-43.8-B (3)	2,000,000	70	5
23.0-43.8-B (4)	2,000,000	70	5
22.7-44.9-B	1,580,000	1,600	70
22.9-43.8-D	1,450,000	190	10

Note: Numbers in parentheses indicate multiple samples at the same locations, either on multiple days or as duplicates.

As Table 11.1 indicates, most of the samples with the highest concentrations experience very little attenuation as they travel from their sources to the reservoir. This is because most of these locations are very close to Kranji Reservoir.

12 Reservoir Modeling

12.1 Introduction

In addition to modeling the drainage system, we also modeled the reservoir to characterize more adequately the Kranji Reservoir's potential for recreational use. To do this we used a box model to create a representative model of the reservoir system that could be used to understand general processes going on. The model utilized estimated flows and loading rates to predict *E. coli* concentrations throughout the reservoir. We then used these results to identify problematic areas and diagnose potential causes for the predicted elevated contamination.

12.2 Model Description

The USEPA's multi-dimensional Water Quality Analysis Simulation Program (WASP) (Wool et al. undated) was adapted to the Kranji reservoir to predict flow and mixing behavior of coliform in the reservoir. The model output is a forecast of contaminant, in our case *E. coli*, concentrations. WASP is a box model, which is an analytical tool that divides a body of water into segments and uses the principles of conservation of mass to calculate the exchange of flows and mass between segments (Adams unpublished). We built first-order decay of *E. coli* bacteria into the model.

12.3 Parameters and Data

We configured the box model to represent the reservoir in two dimensions, longitudinal and lateral. We then used available field sampling stations, of which there are 14 in the Kranji Reservoir, to guide segment definition in the box model of the reservoir system, as shown in Figure 12.3 (on page 47). The Kranji Reservoir has five auto-samplers monitoring the three rivers that flow into the reservoir from the south (see Figure 12.2). Auto-samplers KC1, KC2, and KC3 monitor flows entering Peng Siang river, and auto-samplers KC4 and KC6 monitor flow entering the Tengah and Kangkar rivers, respectively. Three sampling stations were previously positioned, one in each of the three rivers, to mark locations for taking grab samples. These stations, named after the rivers in which they are located, are Station Peng Siang, Station Tengah, and Station Kangkar (see Figure 4.1). Flows going directly into the main reservoir were monitored by an auto-sampler located in the KC7 sub-catchment, by grab samples taken where the KC5 auto-sampler was previously located, and at four additional sampling stations, Station 1, Station 3, Station 4, and Station 3 Arm Junction, positioned in the main reservoir. These sampling locations can be seen in Figure 4.1.

The number, size, and location of segments of a box model are usually determined by the availability of data and it is best if each WASP model segment corresponds to a field location at which data are collected (Adams unpublished). In the Kranji Reservoir, data was available at 14 sampling locations and so we constructed our segments so that each had at least one sampling location within it, but no more than one if it was possible. This is because the more segments a model employs, the greater the spatial resolution will be in the bacterial concentration results. In this way, better spatial resolution allows more specific identification of areas predicted to have high bacterial concentrations. In order to maintain model stability within the restrictions our reservoir system flows and geometry imposed, the greatest number of segments we could define

was 11. These are KC1KC2, KC3PS, KC4, Station Tengah, KC6, Station Kangkar, Station 3 Arm Junction, KC5S1, KC7, Station 3, and Station 4 as shown in Figure 12.3 (on page 47).

We positioned the segments in the reservoir so that the upstream edge of each segment coincided with its respective sampling location. Field data were then used to set initial conditions of the corresponding downstream WASP model segments. Boundaries were also specified. We placed boundaries on the upstream end of each of the influent rivers (at the southern end of segments KC1KC2, KC4, and KC7, and at the western end of KC3PS, KC5S1, and KC6) and at the dam at the northern end of the reservoir (at the northern edge of Station 4's segment). The sequence of boundaries and segments, as they proceed toward the reservoir outlet, can be seen in Figure 12.1.

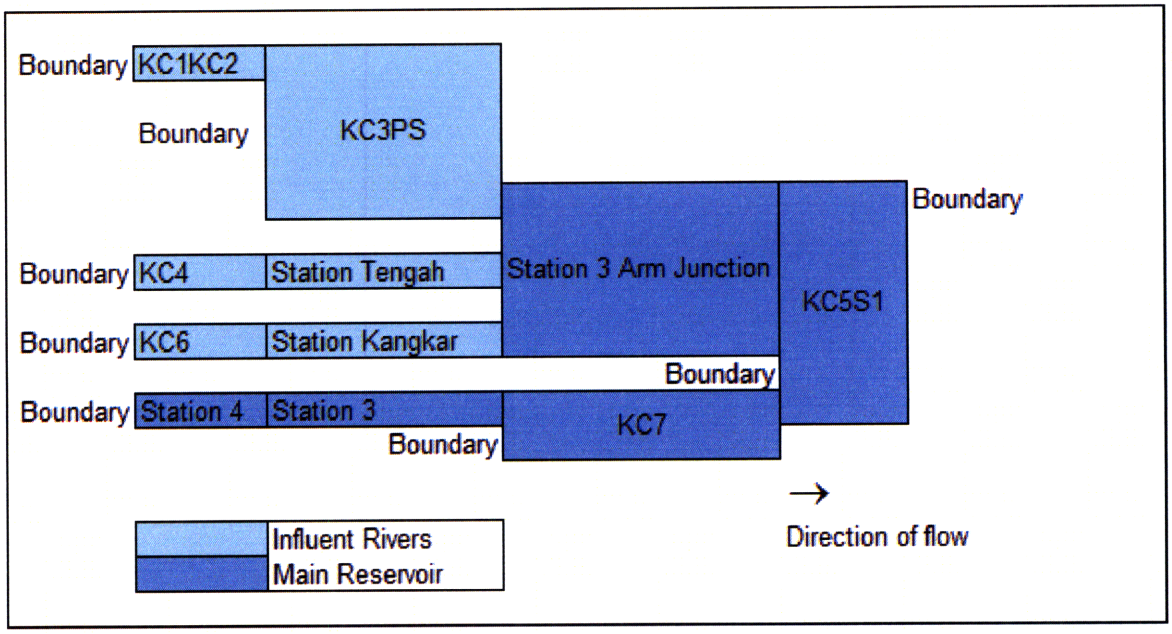

Figure 12.1: Kranji Reservoir Box Model Segment Sequence and Direction of Flow

12.4 Physical Reservoir Characteristics and Geometry

WASP requires the physical characteristics of the reservoir to model bacterial attenuation effectively. These include water body geometry and bottom roughness. We calculated the length and width of each segment using ArcMap's measure tool. The depth of each segment located in the concrete drainage system upstream of the influent rivers and main reservoir (i.e. KC1, KC2, KC3, KC4, KC6, and KC7) was taken from drain cross-section measurements completed in the 2004-2007 NTU study (NTU 2008). The average depth of each segment in the influent rivers and main reservoir (i.e. Station KC3PS, Station Tengah, Station Kangkar, Station 1, Station 3, Station 3 Arm Junction, Station 4, KC5, and KC7) was estimated based on available bathymetric data and observed topography, from values measured in a University of Western Australia study as well as from sampling depth data provided in the 2004-2007 NTU study (Antenucci et al. 2007, NTU 2008). We then calculated the cross-sectional area of each segment using the measured widths and estimated average depths. We calculated the volume of each segment by multiplying the cross-sectional area by segment length. These values are shown in Appendix D. We used these values to define the size and geometry of each reservoir segment in the model.

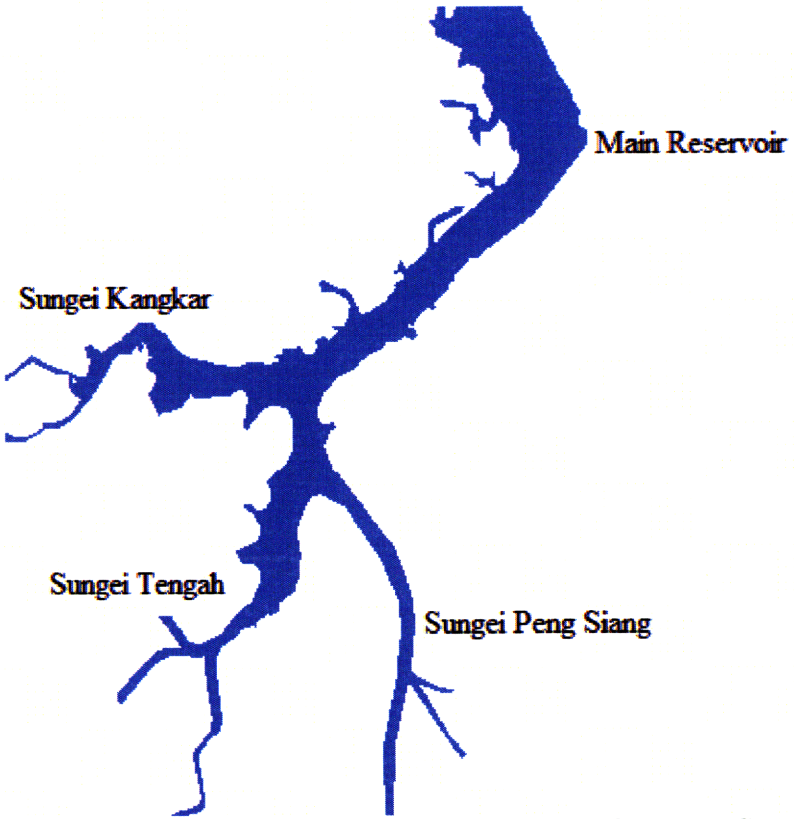

Figure 12.2: Kranji Reservoir and Influent Tributaries, Sungei (River) Kangkar, Tengah, and Peng Siang

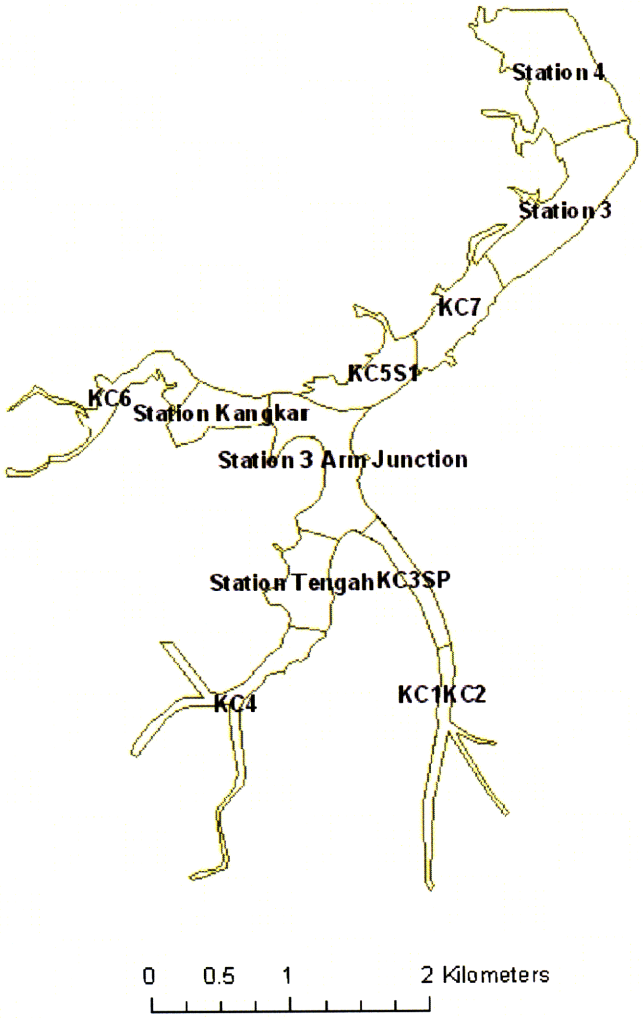

Figure 12.3: Kranji Reservoir Segments as Defined in WASP

We also assigned a Manning roughness coefficient to each of the segments. Under optimum conditions, rivers with firm soil bottoms, like those in the upstream segments at KC1, KC2, KC3, KC4, and KC6, would have roughness coefficients of 0.025-0.032 (Arcement and Schneider 1989). The riverbeds in the Kranji Catchment, however, likely had a significant amount of settled material on them. This would make the roughness greater than that of a smooth riverbed. We therefore adjusted the coefficient according to USGS guidance for minor degradations in channel bed conditions, which specified an additional 0.005 be added to the base coefficient (Arcement and Schneider 1989). This gave a minimum estimated Manning roughness of 0.03 for the upstream segments.

Manning roughness was also estimated for the main reservoir. The base Manning coefficient of 0.025-0.032 for soil beds was used again and then adjusted for non-uniformity (evidenced in bathymetric profiles from Antenucci et al. 2007) and observed degraded bed conditions. The USGS guidance specifies adding 0.005 for bed degradation and an additional 0.003 for variations in geometry (Arcement and Schneider 1989). Observations made while taking soil cores in the main reservoir lead us to believe that sediment in the reservoir was significantly less consolidated than sediment in the influent rivers. This would increase the roughness. We used the upper limit of the smooth soil bed range as the base roughness coefficient, adjusted as specified, and estimated the main reservoir's Manning roughness coefficient to be 0.04.

12.5 Flow and Dispersion Data

Influent flows for the catchment were not available, however outflows from the reservoir were, so to approximate the inflows needed to run our simulation we assumed that flows into the reservoir equaled flows out. Pumping rates for reservoir outflows were not available for the period during January 2009 when we conducted our field studies; however, flow rates from a previous year were substituted in order to construct a representative scenario. We obtained daily pumping rate records for water being pumped from the Kranji reservoir to various treatment facilities in 2005 (Chua 2009). The daily outflows from the reservoir for the month of January 2005 were averaged and this average flow, calculated as approximately 0.8 cubic meters per second, was partitioned between each of the inflowing boundary segments. To approximate the percentage of total flow assigned to each of the individual segments, flow data that was available (flow data for the month of January 2009 was known for the upstream boundaries of KC1KC2, KC4, KC6, and KC7) was used as a basis for the channels with auto-samplers and for estimating flows for boundaries that did not have auto-samplers reading flows. We then scaled up these base flows to compensate for additional runoff influent to segments downstream from where the auto-sampler took flow readings. Scaling was done based on relative surface area of segments under the assumption that a greater segment surface area corresponds to a larger sub-catchment area draining into the segment. The upstream boundaries for Station 4 and KC5S1 were not known however a small flow needed to be estimated for the upstream boundaries of both to simulate the flow that would be traveling to the outflow being pumped from the reservoir at segment KC5S1. This flow was assumed to be much smaller than the flow coming from the southern end of the reservoir (i.e. from segment Station 3 Arm Junction) due to the fact that Station 4 and KC7 both lack influent rivers, whereas Station 3 Arm Junction had three rivers flowing into it from the south (see Figure 12.3). For dimensions and hydrodynamic values used, the reader is referred to Appendix D.

We also needed to estimate longitudinal velocity in each segment. We did so by dividing each segment's flow by its cross-sectional area. The segments that route flow into the reservoir through the three main southern rivers can be modeled as open channel flow. This allows us to compute longitudinal dispersion in each of these segments using Elder's method (1959), Equation 12.1 (Adams unpublished) where E_L [meters squared per second] is the longitudinal dispersion, u^* [meters per second] is the shear velocity (approximated as 0.05 times u, where u is the mean velocity), and H [meters] is the depth. Using dimensions and velocity from the Station Kankar segment, we computed a minimum longitudinal dispersion of 0.0003 square meters per second, which we used as a representative value throughout the reservoir.

$$E_L = 5.9Hu^* \qquad (12.1)$$

Reservoirs are generally considered to function as "reactor vessels," a generic term for any natural or man-made tank or water body that receives and discharges water. In these water bodies, a transformation occurs that causes the effluent characteristics to be altered from their initial influent characteristics (Adams unpublished). Longitudinal dispersion, additional to that due to flow, can be caused in a closed body of water by wind blowing along the water's surface. We considered this to be a factor in the two northernmost segments of the reservoir, segments Station 3 and Station 4, due to their interaction with the confining seawall on the northern edge of segment Station 4. This additional dispersion can be calculated by considering dispersion to be created by an equal-but-opposite exchange flow between adjacent segments. Such a formulation is in fact the mechanism by which dispersion is modeled in WASP. This relationship is captured in Equation 12.2, where E_L [meters squared per second] is the longitudinal dispersion coefficient, Q_{ex} [meters cubed per second] is the equal-but-opposite exchange flow between segments, L [meters] is the length between adjacent segment centroids, and A [meters squared] is the cross-sectional area of the segment (Wool et al. undated).

$$E_L = Q_{ex}L / A \qquad (12.2)$$

To compute flow we assumed that the wind pushes the water northward up the reservoir at a velocity 0.03 times the wind speed (Stolzenbach et al. 1977). This would create a flow toward the seawall at the water's surface and an equal and opposite flow returning south along the bottom of the reservoir. Because this dispersion was an estimate, for simplicity, we assumed that the velocity profile of the water due to wind speed was linear with the surface water moving at 0.03 times the wind speed, the water at the reservoir bottom moving at 0.03 times the wind speed in the opposite direction, and at a speed of zero meters per second at the middle of the profile. The flow, Q, can then be computed by Equation 12.3, where U_w [meters per second] is the wind speed.

$$Q_{ex} = (A / 2)(0.03U_w / 2) \qquad (12.3)$$

Plugging Equation 12.3 into Equation 12.2, we get Equation 12.4.

$$E = 0.03W_s L / 4 \qquad (12.4)$$

Using an average local wind speed for January 2009 of 0.004 meters per second (The Weather Channel 2009) and a segment length of 1000 meters, we calculated a dispersion of one square meter per day.

12.6 Bacterial Concentrations

Initial and boundary concentrations of *E. coli* were also input into the model. As mentioned above, by positioning the segments in the reservoir so that at least one sampling location was located within each model segment, we were able to co-locate sample concentrations with segment input concentrations in the model. This allowed us to use the sample concentrations obtained from field work as bacterial concentrations for each segment. Initial concentrations for segments at the upstream edges of the reservoir were calculated (from drainage system samples) using our model from Section 10. We calculated attenuation of bacterial concentrations using the travel time from the upstream sampling locations to each of the reservoir system's influent boundaries. Initial concentrations for in-reservoir segments were obtained from samples taken at the sampling stations during the 2007 NTU study (NTU 2008). Boundary concentrations, which are the continuous bacterial inputs flowing into the system through each identified boundary, were defined with the sample concentrations obtained during our January 2009 fieldwork. We incorporated all valid sample concentrations with their respective sampling date and time for each sampling location into the boundaries of our simulation. For data on inflowing concentrations used in our simulation, the reader is referred to Appendix A.

12.7 Reservoir Decay Constants

The bacteria in the reservoir experience decay through three mechanisms, natural mortality, settling, and photolysis (Equation 9.2). The decay experienced by the bacteria due to photolysis is governed by Equation 9.8, which is repeated here for convenience.

$$k_p = \alpha I_0 \frac{1 - e^{-k_e H}}{k_e H} \tag{9.8}$$

The daily average solar radiation at the surface of the water in the reservoir, I_0, for use in Equation 9.8, is the total solar flux at the Earth's surface (5.9 x 10^{-6} kilocalories per square centimeter per second) (Hanson 1976) multiplied by the number of seconds of daylight in a day. This value for solar flux is based on the latitudinal zone 0-2.5 degrees north, in which Singapore is located. This method takes daily averages of cloud cover into account when estimating solar flux reaching the Earth's surface. Singapore has twelve hours of daylight daily because it is near the equator. This gives an I_0 of 0.26 kilocalories per square centimeter.

For use in Equations 9.8 and 9.9 repeated below, we assumed the depth, H, of each reservoir segment is constant. For use in Equation 9.8, we assumed k_e is proportional to the mean value of the concentration of total suspended solids for the reservoir, 13.9 milligrams per liter (NTU 2008). This gives a value of 7.6 per meter for k_e.

The loss of bacteria to settling is governed by Equation 9.9, repeated here.

$$k_s = F_P \frac{v_s}{H} \qquad (9.9)$$

For use in Equation 9.9, the particle settling velocity, v_s, is 0.00003 meters per second, or three meters per day, as approximated from a study by Jamieson (2005) which evaluated suspended particle sizes (45-75 microns) comparable to those in Kranji Reservoir. The partition fraction, F_p, was estimated to be 0.34. This is the fraction of bacteria found by Jamieson (2005) to adsorb to 45-75 micron particles. These two values give decay due to settling, k_s, of 0.1. Summing these decay rates, we calculated a total decay constant, k, of 1.39 per day for the reservoir.

12.8 Results

12.8.1 Concentrations per Segment

The results of the bacterial attenuation simulation predicted that fairly high *E. coli* concentrations persist throughout the reservoir, as indicated in Table 12.1. Mean *E. coli* concentrations were highest in segment KC1KC2 (Figure 12.3), averaging over four times the values predicted in the remaining segments. This is likely due to the heavier loading coming from the residential area located between the two tributaries that make up that segment. KC1KC2 also has relatively low volume compared to other segments in the catchment. This would prevent any significant dilution and is therefore another possible factor causing the high bacterial concentrations predicted there. The segment downstream from KC1KC2, KC3PS, was predicted to have dramatically reduced concentrations. This segment is characterized by a larger volume and flow, due to the additional flow entering the western boundary of the segment from the KC3 sub-catchment. Dilution therefore, along with loss associated with greater travel time experienced by loads flowing from KC1KC2, may be causing the reduction in concentration there.

Table 12.1: Predicted Minimum, Maximum, and Mean Concentrations in Reservoir Simulation

Segment	*E. coli* Concentrations (CFU/100 mL)			
	Minimum	Maximum	Mean	Standard Deviation
KC1KC2	600	630,000	21,000	80,000
KC3PS	2,100	20,000	5,000	1,900
KC4	2	5,400	4,600	360
Station Tengah	320	5,700	4,700	320
KC6	2,000	7,800	3,700	1,700
Station Kangkar	810	5,900	4,700	320
KC5S1	4,400	21,000	4,800	440
Station 3 Arm Junction	1,700	6,400	4,800	320
KC7	4,400	42,000	4,800	590
Station 3	1,300	5,600	4,700	300
Station 4	6	5,600	4,700	330

Mean modeled *E. coli* concentrations in the remaining segments were relatively uniform, ranging from 3700 to 4800 Colony Forming Units per one hundred milliliters, compared to the 21000

Colony Forming Units per one hundred milliliters predicted in KC1KC2. Although these concentrations are significantly lower than those predicted in KC1KC2, they are still much higher than the maximum value, 126 Colony Forming Units of *E. coli* per one hundred milliliters, USEPA guidelines stipulate for recreational freshwaters (USEPA 1986). These segments experience less flow and loads than KC1KC2 and often have much higher volumes. This would increase the efficacy of dilution in reducing contamination. These segments are also located hundreds to thousands of meters downstream from bacteria sources which would increase the travel time the bacteria experience, increasing loss due to decay and sedimentation. These factors would act to decrease concentrations in segments which may explain the lower concentrations predicted in them.

12.8.2 Time Variable Analysis

Again, because intensive *E. coli* sampling during our field work was not possible, our team used concentrations from the 2007 NTU study on Kranji Reservoir as representative initial concentrations for the simulation (NTU 2008). All boundary concentrations, used to set bacterial loads, were determined in our January 2009 fieldwork (Appendix A). The initial conditions of the reservoir specified at the beginning of the simulation (i.e. for the simulated date of January 1, 2009) indicate a much more heterogeneous distribution of *E. coli* concentrations, show in the left image in Figure 12.4, than our prediction of concentrations after running the simulation for 31 days, shown in the right image in Figure 12.4. The initially non-uniform concentrations were predicted to attenuate and disperse throughout the reservoir as also indicated in the simulated concentration output data as discussed in Section 12.8.1 above. The relative uniformity of the predicted concentrations highlights the relatively steady bacterial loads and flow that the reservoir received during our sampling, a result of the lack of rain events during the time our sampling was completed. This would have diminished the intermittent spikes in inflowing bacteria that occur during rain storms, producing more spatially uniform concentrations. A portion of the uniformity may also be due to the nature of the model. By modeling the reservoir as a network of fully mixed tanks (i.e. segments), we introduced a high level of mixing into the system. Absent significant inputs, such mixing would eventually result in evenly distributed concentrations of bacteria. This situation is very similar to the one predicted at the end of the simulation, pictured in the right image of Figure 12.4.

We also focused our temporal analysis on diurnal variations in concentration distributions. Figures 12.5 through 12.10 below show how changes in *E. coli* concentration originating from the residential KC2 sub-catchment affect downstream concentrations in Sungei Peng Siang and the reservoir. The effect is most clearly depicted in Figures 12.8, 12.9, and 12.10, which show the concentrations sampled at KC2's auto-sampler at times 0:00, 4:00, and 8:00, on January 22, 2009. As more concentrated flows move out of the KC1KC2 segment, concentrations in the KC3PS segment, which is experiencing no other bacterial loading during this time, become elevated. By the time these flows have reached the following segment, Station 3 Arm Junction, this effect however, is no longer visually discernable in the spatial analysis.

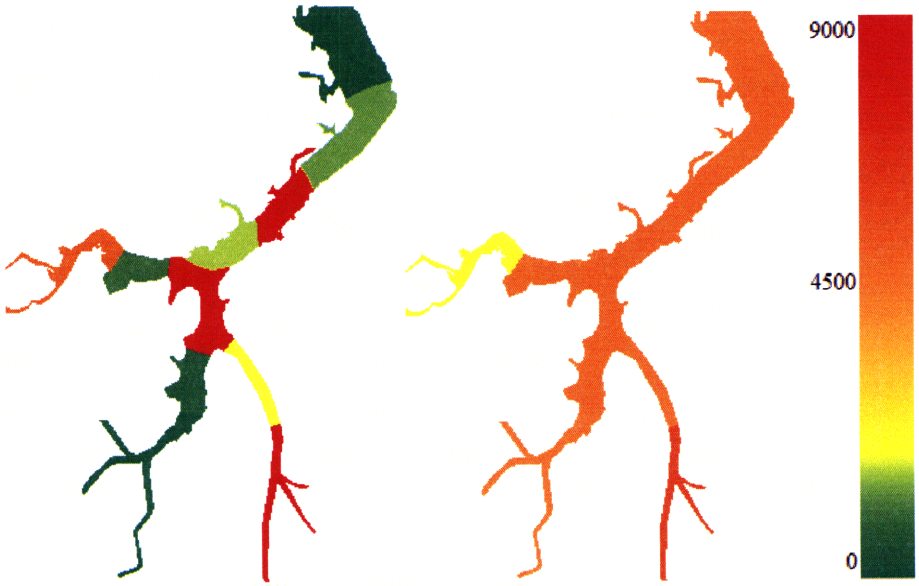

Figure 12.4: Initial Condition (Left) and Predicted Final Condition at 31 Days (Right). Color scale indicates bacterial Concentration in CFU/100 mL

Figure 12.5: Predicted Concentration Distribution for January 21, 13:00, Inflow Concentration: 8,850 CFU/100 mL

Figure 12.6: Predicted Concentration Distribution for January 21, 16:00, Inflow Concentration: 5,200 CFU/100 mL

Figure 12.7: Predicted Concentration Distribution for January 21, 20:00, Inflow Concentration: 9,870 CFU/100 mL

Figure 12.8: Predicted Concentration Distribution for January 22, 00:00, Inflow Concentration: 32,130 CFU/100 mL

Figure 12.9: Predicted Concentration Distribution for January 22, 4:00, Inflow Concentration: 34,130 CFU/100 mL

Figure 12.10: Predicted Concentration Distribution for January 22, 8:00, Inflow Concentration: 43,600 CFU/100 mL

12.8.3 Diagnosis of Problematic Areas

The 31-day attenuation simulation completed in this study predicted that fairly uniform concentrations would result throughout the reservoir over time absent significant input concentration spikes. It also showed that, although very high concentrations were often predicted in the upper reaches of the drainage system and even into the three southern influent rivers, these higher concentrations became relatively negligible by the time the flows with which they were associated reached the main reservoir. This indicates that if elevated *E. coli* concentrations are originating far enough upstream of the main reservoir to allow for sufficient die-off and sedimentation, distances of approximately 1500 to 2000 meters, these sources do not need to be addressed as primary obstacles to water recreation in the main reservoir.

At the same time, this aspect of the simulation shows that sources nearer to the rivers, at distances of approximately 100 to 200 meters from the banks, as in segment KC1KC2, were seen to have an immediate and almost continuous impact on water quality. Despite very high bacterial concentrations observed discharging to the main reservoir, this elevated impact was not predicted in the larger segments located there. This is most likely due to the very large volume of the main reservoir segments, some of which were 200 times the volume of that of the smallest river, Peng Siang (Appendix D). Although the predicted concentrations in these segments were much lower than observed concentrations in the influent to these segments, it is important to note that the simulated concentrations are averages and that concentrations near the banks of the reservoir, especially near the farm sources, would not have much time to decay, nor be diluted through mixing caused by deeper water and greater flow (Hemond and Fechner-Levy 2000). This would allow much higher concentrations to exist along the shores of the reservoir.

The WASP simulation predicts that bacterial concentrations during the month of January 2009 would have been highest in KC1KC2 but high enough in the remaining segments to make water recreation inadvisable throughout the entire reservoir. In order to further narrow down stretches of most concern within the reservoir, more in-reservoir sampling will need to be completed at additional sampling locations to enable more detailed modeling so that the dynamics of mixing and attenuation can be better understood.

13 Conclusions and Recommendations

13.1 Conclusions

Our study provided several insights into the bacterial loading of Kranji Catchment and Reservoir. Our sampling in January showed which specific sites in the catchment have high levels of *E. coli*. By determining the attenuation experienced by the bacteria as it travels through the drainage system, we were able to hypothesize which areas in the catchment are of greatest concern with respect to bacterial loading on the reservoir. Our analysis of attenuation showed that sites closest to the reservoir, like farm run-off sites, pose a greater threat than sites that are far from the reservoir, even if the bacterial concentration is high at those farther sites. Our GIS analysis determined areas in sub-catchment KC2 where further study may reveal additional *E. coli* sources.

Our WASP analysis confirmed the results of the GIS analysis, predicting that *E. coli* sources located far upstream were not of great concern once they had reached the main reservoir. This was the result of the increased decay experienced by bacteria with longer distances to travel, and thus longer travel time. Likewise, high concentrations of bacteria originating near the reservoir were predicted to immediately impact the segments into which they flowed. This affirms the results of the GIS analysis by also indicating that sources located near the reservoir are of greatest concern to Kranji Reservoir water quality. The WASP simulation also predicted that concentrations would be fairly uniform throughout the reservoir. This was not observed to be so during 2005 sampling, however, and is likely the result of two factors. The first is the extremely dry weather the catchment experienced during our sampling which resulted in more uniform flows and fewer inflowing concentration spikes caused by rainfall events. The second is the limited number of samples obtained within the main reservoir. This prevented us from more fully assessing spatial and temporal variations of bacterial concentrations.

13.2 Recommendations

Our recommendations for PUB are to confine and/or treat farm run-off to lower the bacterial concentrations flowing into the reservoir. This would also diminish odors near the reservoir to improve recreational experiences at the reservoir. Further investigation into areas of high *E. coli* concentrations would find additional places that could benefit from source treatment.

Bacterial concentrations predicted throughout the reservoir were consistently high, with segments KC1KC2 and Station KC3PS shown to be the highest. The primary sources of contamination were suspected to be the high-density residential land that lies around this area of the catchment. Our recommendation is therefore to restrict all water recreation in the Peng Siang River that these segments comprise until bacterial contamination coming from this area can be reduced. Bacterial concentrations throughout the remaining segments in the reservoir were also consistently high. This may be partially due to coarsely defined data, however. Because it is not possible to determine exact locations of greatest threat at this time, our recommendation for the main reservoir is again to restrict water recreation until more spatially specific data is available and the bacterial concentrations by location are better understood.

13.3 Limitations and Further Study

Our study is based exclusively on dry weather sampling. Because the characteristics of the drainage system, bacterial loading, and the reservoir will be very different during and after a storm event, a wet weather study should be conducted to determine the applicability of our analyses on wet weather situations.

Our attenuation model is based on theoretically derived coefficients. A verification study to determine attenuation in the field would most likely modify our model. A study like this would entail measuring *E. coli* concentrations at an upstream point and a point downstream, with no additional drains entering and a measured distance between them. Taking several samples over time would improve the model's accuracy.

Our GIS modeling of KC2 bacterial sources could be vastly improved by collecting additional samples within the sub-catchment, focusing on the areas we highlighted in Figure 11.2. This method could also be applied to other sub-catchments. A detailed survey of the drains resulting in a new, more useful shapefile would be very helpful.

Our sampling data was severely limited in the reservoir due to heavy concentrations of total suspended solids. This made membrane filtration, the sample processing method we were prepared to use, impossible. If a most probable number (MPN) method were used in future studies, far more *E. coli* concentration data would become available for the reservoir. Bathymetric data for the reservoir was also incomplete. This forced our team to use averages based on limited depth profiles for the in-reservoir attenuation simulation. More accurate bathymetric data allows more accurate dispersion, decay, and hydrodynamic parameters to be used in simulations. Additional sampling locations and reservoir geometry data would make a future study more spatially specific and therefore more useful in diagnosing threats to public safety during recreational activities.

The WASP model is limited in that it is only a representative model and is only as good of a representation as the amount of data we put into it. A further study using the WASP model should entail collecting much more data within the reservoir itself and from any streams seen to contribute directly to the reservoir. A spatially intensive survey within the reservoir would be particularly useful. This will give a more accurate view of the fate and transport of the bacteria as it goes through the reservoir.

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Appendix A
Sampling Data

Date	Sample Name	Sub-Catchment	Time	Coliform Dilutions						Total Coliform	E Coli Dilutions						Total E Coli (CFU/100	Entero	DNA	Temperature (degrees C)	STP	Latitude	Longitude	Notes
				1	10	100	1000	10000	1000000		1	10	100	1000	10000	1000000								
1/7/2009	22.3-42.9	KC4	11:45	TNTC	TNTC	120				12000	error	error	0				error		no		no	1.373	103.715	auto-sampler
1/7/2009	23.4-43.8-A	KC3	12:00	TNTC	180	90				5400	TNTC	65	2				650		no		no	1.391	103.731	
1/7/2009	23.4-43.8-B	KC3	12:00	TNTC	TNTC	TNTC				TNTC	TNTC	38	7				380		no		no	1.391	103.731	
1/7/2009	23.4-43.8-C	KC3	12:05	TNTC	TNTC	error				TNTC	TNTC	96	error				960		no		no	1.391	103.731	
1/7/2009	22.6-44.0	KC1	13:00	TNTC	TNTC	49				4900	87	7	0				87		no		no	1.377	103.735	auto-sampler
1/7/2009	25.2-42.9	KC5	13:00	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	31				3100		no		no	1.420	103.716	
1/7/2009	23.6-45.1	KC7	13:30	TNTC	TNTC	184				18400	TNTC	70	5				700		no		no	1.395	103.753	auto-sampler
1/7/2009	24.1-42.0	KC6	15:00	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	107				10700		no		no	1.403	103.701	auto-sampler
1/7/2009	22.9-44.3-A	KC2	16:19	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	43				4300		no		no	1.383	103.739	auto-sampler
1/7/2009	22.9-44.3-D	KC2	16:20	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	TNTC				TNTC		no		no	1.383	103.739	average estimated; lower value
1/7/2009	22.9-44.3-B	KC2	16:20	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	43				4300		no		no	1.383	103.739	
1/7/2009	22.9-44.3-C	KC2	16:20	TNTC	TNTC	TNTC				TNTC	TNTC	TNTC	28				2800		no		no	1.383	103.739	
1/7/2009	22.9-44.3-E	KC2	16:20	TNTC	TNTC	TNTC				TNTC	TNTC	72	13				1010		no		no	1.383	103.739	
1/9/2009	22.9-44.3-A	KC2	10:15			TNTC	TNTC	TNTC		TNTC			29	7	1		2900		no		no	1.383	103.739	auto-sampler
1/9/2009	22.9-44.3-B	KC2	10:25			TNTC	101	7		101000			88	9	1		8800		no		no	1.383	103.739	
1/9/2009	22.9-44.3-C	KC2	10:27			TNTC	190	2		190000			90	3	0		9000		no		no	1.383	103.739	
1/9/2009	22.9-44.3-D	KC2	10:30			TNTC	TNTC	TNTC		TNTC			34	21	1		12200		no		no	1.383	103.739	
1/9/2009	22.9-44.3-D	KC2	10:30			TNTC	TNTC	14		140000			47	0	1		4700		no		no	1.383	103.739	duplicate
1/9/2009	22.9-44.3-E	KC2	10:32			TNTC	3	4		uncertain			2	0	0		uncertain		no		no	1.383	103.739	average estimated; lower value
1/9/2009	23.0-44.7-A	KC2	11:03			34	5	0		3400			0	0	0		uncertain		no		no	1.385	103.747	average estimated; lower value
1/9/2009	23.0-44.7-B	KC2	11:10			TNTC	183	29		236500			4	0	0		uncertain		no		no	1.385	103.746	average estimated; lower value
1/9/2009	23.0-44.6	KC2	11:56			175	85	30		134167			3	0	0		uncertain		no		no	1.384	103.744	average estimated; lower value
1/9/2009	23.0-44.5	KC2	12:06			error	error	error		error			error	error	error		error		no		no	1.384	103.743	
1/9/2009	22.9-44.5	KC2	12:16			1	0	3		uncertain			0	0	0		uncertain		no		no	1.383	103.743	average estimated; lower value
1/9/2009	22.9-44.6	KC2	12:32			69	1	3		6900			0	0	1		uncertain		no		no	1.382	103.743	average estimated; lower value
1/9/2009	22.8-44.7	KC2	12:50			TNTC	TNTC	50		500000			90	8	0		9000		no		no	1.380	103.745	
1/12/2009	23.0-44.7-C	KC2	10:50			TNTC	TNTC	74		740000			6	7	0		uncertain		no		no	1.385	103.747	average estimated; lower value
1/12/2009	23.0-44.7-A	KC2	10:50			84	63	3		35700			3	1	0		uncertain	41	no		no	1.385	103.747	average estimated; lower value
1/12/2009	22.7-44.8-A	KC2	11:30			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	52		520000		no		no	1.379	103.747	very oily
1/12/2009	22.7-44.8-B	KC2	11:34			TNTC	TNTC	147		1470000			79	43	7		25450		no		no	1.379	103.747	
1/12/2009	Blank	KC2	11:38	0						0	0						0							
1/12/2009	22.7-44.9-A	KC2	11:50			error	error	error		error			error	error	error		error		no		no	1.379	103.749	
1/12/2009	22.7-44.9-B	KC2	11:50			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	158		1580000		no		no	1.379	103.749	
1/12/2009	22.7-44.9-B	KC2	11:50			TNTC	TNTC	40		400000			TNTC	17	3		17000		no		no	1.379	103.749	duplicate
1/12/2009	22.6-44.9-B	KC2	12:13			39	5	1		3900			1	0	0		uncertain		no		no	1.378	103.749	average estimated; lower value
1/12/2009	22.6-44.9-A	KC2	12:13			130	60	18		84333			50	15	3		10000		no		no	1.378	103.749	
1/12/2009	22.7-44.9-C	KC2	12:35			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	76		760000		no		no	1.379	103.749	black water - oily
1/12/2009	Blank	KC2	12:55	0						0	0						0							
1/13/2009	22.9-44.4-B	KC2	13:38			TNTC	TNTC	204		2040000			74	12	2		9700		no		no	1.383	103.741	
1/13/2009	22.9-44.4-C	KC2	13:39			TNTC	TNTC	158		1580000			137	49	6		31350		no		no	1.383	103.741	
1/13/2009	22.6-44.3	KC2	14:20			TNTC	151	18		165500			22	5	0		2200		no		no	1.378	103.740	trash burning residue on grates nearby
1/13/2009	22.6-44.4-E	KC2	14:25			4	0	0		uncertain			0	0	0		uncertain		no		no	1.378	103.741	average estimated; lower value
1/13/2009	22.6-44.4-D	KC2	14:25			18	0	0		1800			0	0	0		uncertain		no		no	1.378	103.741	average estimated; lower value
1/13/2009	22.6-44.4-B	KC2	14:25			45	10	0		4500			10	0	0		uncertain		no		no	1.378	103.741	average estimated; lower value
1/13/2009	22.6-44.4-A	KC2	14:25			TNTC	132	7		132000			11	2	2		uncertain		no		no	1.378	103.741	average estimated; lower value
1/13/2009	22.6-44.4-C	KC2	14:25			TNTC	76	24		158000			18	1	1		1800		no		no	1.378	103.741	
1/13/2009	22.6-44.4-A	KC2	14:25			TNTC	178	21		194000			18	5	0		1800		no		no	1.378	103.741	duplicate
1/13/2009	Blank	KC2	14:30	0						0	0						0							
1/14/2009	22.6-44.9-A	KC2	10:01			136	29	14		60867			11	0	0		uncertain		yes		no	1.378	103.749	average estimated; lower value
1/14/2009	22.7-44.9-C	KC2	10:11			TNTC	TNTC	TNTC		TNTC			79	10	0		7900		yes		no	1.378	103.749	black sewage water
1/14/2009	22.7-44.9-A	KC2	10:30			TNTC	TNTC	79		790000			9	13	2		13000		no		no	1.379	103.748	
1/14/2009	22.7-44.9-B	KC2	10:35			TNTC	TNTC	TNTC		TNTC			10	1	0		uncertain		no		no	1.379	103.748	average estimated; lower value; duplicate
1/14/2009	22.7-44.9-B	KC2	10:35			TNTC	TNTC	TNTC		TNTC			7	0	0		uncertain		no		no	1.379	103.748	average estimated; lower value
1/14/2009	22.7-44.9-D	KC2	10:45			56	6	3		5600			2	0	0		uncertain		no		no	1.379	103.749	average estimated; lower value
1/14/2009	Blank	KC2	11:08	0						0	0						0							
1/14/2009	23.0-44.7-A	KC2	11:10			TNTC	5	0		uncertain			49	0	0		4900		yes		no	1.385	103.747	
1/14/2009	23.0-44.5	KC2	11:30			TNTC	144	47		307000			5	1	0		uncertain		no		no	1.384	103.743	average estimated; lower value
1/14/2009	23.9-43.8		12:03			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	TNTC		TNTC		no		no	1.399	103.730	chicken farm runoff; average estimated; lower value
1/14/2009	23.0-43.8-A		12:25			TNTC	TNTC	30		300000			TNTC	49	2		49000		no		no	1.383	103.731	
1/14/2009	23.0-43.8-B		12:27			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	TNTC		TNTC		no		no	1.383	103.731	average estimated; lower value; duplicate
1/14/2009	23.0-43.8-B		12:27			TNTC	TNTC	TNTC		TNTC			TNTC	TNTC	TNTC		TNTC		no		no	1.383	103.731	slight sewage smell; average estimated; lower value
1/14/2009	Blank		12:30	0						0	0						0							
1/14/2009	25.2-42.9	KC5	15:35		TNTC	198	38	7		28900		86	9	1	0		860		no		no	1.420	103.716	
1/14/2009	25.4-43.2		16:10		TNTC	TNTC	68	5		68000		39	10	0	0		390		no		no	1.424	103.721	
1/14/2009	25.0-42.9		16:27			TNTC	130	31		220000			125	7	2		12500		no		no	1.417	103.715	
1/15/2009	22.5-44.1-B	KC1	10:55			TNTC	48	13		89000			2	0	0		uncertain		no		no	1.376	103.736	average estimated; lower value
1/15/2009	22.5-44.1-A	KC1	10:55			TNTC	50	11		50000			3	0	0		uncertain		no		no	1.376	103.736	average estimated; lower value
1/15/2009	22.5-44.1-C	KC1	10:55			error	error	error		error			error	error	error		error		no		no	1.376	103.736	
1/15/2009	21.7-44.5	KC1	11:50			TNTC	98	1		98000			37	4	0		3700		no		no	1.362	103.743	
1/15/2009	21.7-44.5	KC1	11:50			TNTC	199	24		219500			30	8	0		3000		no		no	1.362	103.743	duplicate
1/15/2009	Blank	KC1	11:50	0						0	0						0							
1/15/2009	24.1-42.0	KC6	14:24			TNTC	TNTC	60		600000			10	0	1		uncertain		no		no	1.403	103.701	auto-sampler; average estimated; lower value
1/15/2009	24.0-42.0-A	KC6	14:45			28		0	0	2800			0		0	0	uncertain		no		no	1.402	103.701	average estimated; lower value
1/15/2009	24.0-42.0-B	KC6	14:50			20		1	0	2000			1		0	0	uncertain		no		no	1.402	103.701	average estimated; lower value
1/15/2009	24.0-42.0-D	KC6	14:55			111		24	2	125550			6		4	0	uncertain		no		no	1.401	103.701	average estimated; lower value; duplicate
1/15/2009	24.0-42.0-D	KC6	14:55			11		0	2	uncertain			0		0	0	uncertain		no		no	1.401	103.701	average estimated; lower value
1/15/2009	24.0-42.0-C	KC6	14:55			125		9	0	12500			0		0	0	uncertain		no		no	1.401	103.701	average estimated; lower value
1/15/2009	24.0-42.0-E	KC6	15:00			19		1	0	1900			0		0	0	uncertain		no		no	1.401	103.700	average estimated; lower value

Date	Sample Name	Sub-Catchment	Time	Coliform Dilutions						Total Coliform	E Coli Dilutions						Total E Coli (CFU/100	Entero	DNA	Temperature (degrees C)	STP	Latitude	Longitude	Notes
				1	10	100	1000	10000	1000000		1	10	100	1000	10000	1000000								
1/15/2009	23.9-42.0-A	KC6	15:35			TNTC		2	0	uncertain			2		0	0	uncertain		no		no	1.399	103.701	average estimated; lower value
1/15/2009	23.9-42.0-B	KC6	15:40			39		0	1	3900			0		0	1	uncertain		no		no	1.399	103.701	average estimated; lower value
1/16/2009	23.9-43.8		10:45			TNTC		TNTC	TNTC	TNTC			TNTC		TNTC	TNTC	TNTC		yes		no	1.398	103.730	chicken farm runoff; average estimated; lower value
1/16/2009	23.4-43.8	KC3	11:00			TNTC		22	0	220000			7		2	0	uncertain		no		no	1.391	103.731	average estimated; lower value
1/16/2009	23.0-43.8-B		11:15			TNTC		TNTC	33	33000000			TNTC		TNTC	4	uncertain		yes		no	1.383	103.731	average estimated; lower value
1/16/2009	23.0-43.8-A		11:15			TNTC		72	1	720000			TNTC		10	0	uncertain		yes		no	1.383	103.731	average estimated; lower value
1/16/2009	22.9-43.8-B		11:23			TNTC		TNTC	167	167000000			TNTC		TNTC	21	21000000		no		no	1.383	103.731	fish farm runoff
1/16/2009	22.9-43.8-D		11:23			TNTC		TNTC	38	38000000			TNTC		145	7	1450000		no		no	1.383	103.731	fish farm runoff
1/16/2009	22.9-43.8-C		11:23			TNTC		149	0	1490000			141		4	0	14100		no		no	1.383	103.731	fish farm runoff
1/16/2009	22.9-43.8-A		11:23			TNTC		60	9	600000			125		1	1	12500		no		no	1.383	103.731	fish farm runoff
1/16/2009	Blank		12:43	0						0	0						0							
1/16/2009	22.8-44.4-A	KC2	12:45			TNTC		15	0	150000			10		1	0	uncertain		no		no	1.378	103.741	average estimated; lower value
1/16/2009	22.8-44.4-A	KC2	12:45			TNTC		15	0	150000			21		0	0	2100		yes		no	1.378	103.741	duplicate
1/16/2009	25.2-42.9	KC5	14:17			TNTC		41	1	410000			35		1	0	3500		no		no	1.420	103.716	
1/16/2009	23.0-43.8-B		11:15			TNTC		TNTC	83	83000000			TNTC		TNTC	29	29000000		no		no	1.383	103.731	duplicate
1/19/2009	25.2-42.9	KC5	9:45			TNTC		146	1	1460000			TNTC		29	0	290000		yes		no	1.420	103.716	
1/19/2009	25.0-42.9	KC5	10:12			TNTC		9	0	uncertain			5		0	0	uncertain		no	24	no	1.417	103.715	backflow avoided; average estimated; lower value
1/19/2009	22.5-44.1-B	KC1	13:10			1		0	1	uncertain			0		0	0	uncertain		yes	32	no	1.376	103.736	chicken farm; average estimated; lower value
1/19/2009	22.5-44.1-A	KC1	13:10			0		1	0	uncertain			0		0	0	uncertain		yes	32	no	1.376	103.736	average estimated; lower value
1/19/2009	24.0-42.0-B	KC6	14:15			52		4	0	5200			0		0	0	uncertain		yes	30	no	1.411	103.700	average estimated; lower value
1/19/2009	24.0-42.0-A	KC6	14:15			1		0	0	uncertain			0		0	0	uncertain		yes	32	no	1.411	103.700	average estimated; lower value
1/19/2009	24.0-42.0-C	KC6	14:35			2		1	0	uncertain			0		0	0	uncertain		yes	32	no	1.411	103.700	average estimated; lower value
1/20/2009	25.0-43.1	KC5	15:10			TNTC		TNTC	20	20000000			37		4	0	3700		yes	32	yes	1.417	103.719	chicken farm sedimentation tank effluent
1/20/2009	23.8-43.4-B	KC5	16:00			200		14	3	20000			0		0	0	uncertain		no	28	yes	1.414	103.724	chicken farm sedimentation tank effluent; average estimated; lower value
1/20/2009	23.8-43.4-A	KC5	16:00			TNTC		TNTC	119	119000000			TNTC		83	0	830000		no	28	yes	1.414	103.724	chicken farm sedimentation tank influent
1/20/2009	23.2-43.3		17:15			TNTC		16	2	160000			15		1	0	1500		yes		yes	1.386	103.721	fish farm sedimentation tank effluent
1/20/2009	23.0-43.6		17:55			TNTC		TNTC	TNTC	TNTC			TNTC		TNTC	TNTC	TNTC		no		yes	1.383	103.726	farmart sedimentation tank effluent; average estimated; lower value
1/21/2009	22.9-44.3-13	KC2	13:00			TNTC		TNTC	142	142000000			90		4	1	9000		no		no	1.383	103.739	auto-sampler
1/21/2009	22.9-44.3-14	KC2	14:00			TNTC		TNTC	TNTC	TNTC			28		6	3	2800		no		no	1.383	103.739	auto-sampler
1/21/2009	22.9-44.3-15	KC2	15:00			TNTC		TNTC	TNTC	TNTC			35		6	1	3500		no		no	1.383	103.739	auto-sampler
1/21/2009	22.9-44.3-16	KC2	16:00			TNTC		26	0	260000			20		0	0	2000		no		no	1.383	103.739	auto-sampler
1/21/2009	22.8-45.5-C	KC7	16:30			TNTC		TNTC	40	40000000			10		1	1	uncertain		yes		no	1.381	103.759	average estimated; lower value
1/21/2009	22.8-45.5-B	KC7	16:30			TNTC		30	14	7150000			5		0	0	uncertain		yes		no	1.381	103.759	average estimated; lower value
1/21/2009	22.8-45.5-A	KC7	16:30			TNTC		TNTC	108	108000000			70		21	5	108500		no		no	1.381	103.759	
1/21/2009	22.8-45.5-A	KC7	16:30			TNTC		TNTC	TNTC	TNTC			21		7	4	2100		yes		no	1.381	103.759	duplicate
1/21/2009	22.9-44.3-17	KC2	17:00			TNTC		80	5	800000			5		2	0	uncertain		no		no	1.383	103.739	auto-sampler; average estimated; lower value
1/21/2009	23.4-43.8	KC3	17:37			TNTC		8	1	uncertain			2		0	0	uncertain		yes		no	1.381	103.759	average estimated; lower value
1/21/2009	22.9-44.3-18	KC2	18:00			TNTC		53	14	7285000			23		1	0	2300		no		no	1.383	103.739	auto-sampler
1/22/2009	22.9-44.3-0	KC2	0:00			TNTC		37	7	370000			TNTC		6	0	uncertain		no		no	1.383	103.739	auto-sampler; average estimated; lower value
1/22/2009	22.9-44.3-1	KC2	1:00			TNTC		TNTC	10	uncertain			TNTC		15	0	150000		no		no	1.383	103.739	
1/22/2009	22.9-44.3-2	KC2	2:00			TNTC		25	13	6625000			54		3	0	5400		no		no	1.383	103.739	
1/22/2009	22.9-44.3-3	KC2	3:00			TNTC		112	0	1120000			TNTC		1	0	uncertain		no		no	1.383	103.739	average estimated; lower value
1/22/2009	22.9-44.3-4	KC2	4:00			TNTC		58	0	580000			26		0	0	2600		no		no	1.383	103.739	
1/22/2009	22.9-44.3-5	KC2	5:00			TNTC		54	0	540000			TNTC		6	0	uncertain		no		no	1.383	103.739	average estimated; lower value
1/22/2009	22.9-44.3-6	KC2	6:00			TNTC		14	0	140000			78		2	0	7800		no		no	1.383	103.739	
1/22/2009	22.9-44.3-7	KC2	7:00			TNTC		63	0	630000			TNTC		10	0	uncertain		no		no	1.383	103.739	average estimated; lower value
1/22/2009	22.9-44.3-8	KC2	8:00			TNTC		error	0	error			57		error	0	5700		no		no	1.383	103.739	
1/22/2009	22.9-44.3-9	KC2	9:00			TNTC		3	0	uncertain			13		0	0	1300		no		no	1.383	103.739	
1/22/2009	22.9-44.3-10	KC2	10:00			TNTC		104	0	1040000			16		0	0	1600		no		no	1.383	103.739	
1/22/2009	22.1-42.7-B	KC4	13:45			8		0	0	uncertain			1		0	0	uncertain		yes		no	1.369	103.712	average estimated; lower value
1/22/2009	22.1-42.7-A	KC4	13:45			TNTC		0	0	uncertain			0		0	0	uncertain		yes		no	1.369	103.712	average estimated; lower value
1/22/2009	22.9-44.3-19	KC2	19:00			TNTC		86	1	860000			10		1	0	uncertain		no		no	1.383	103.739	average estimated; lower value
1/22/2009	22.9-44.3-20	KC2	20:00			TNTC		68	0	680000			TNTC		1	0	10000		no		no	1.383	103.739	average estimated; lower value
1/22/2009	22.9-44.3-21	KC2	21:00			TNTC		45	2	450000			43		1	0	4300		no		no	1.383	103.739	
1/22/2009	22.9-44.3-22	KC2	22:00			TNTC		TNTC	2	uncertain			107		2	0	10700		no		no	1.383	103.739	
1/22/2009	22.9-44.3-23	KC2	23:00			TNTC		100	17	9000000			74		4	0	7400	10000	no		no	1.383	103.739	auto-sampler

Appendix B
Select Data Sheets

Date: 16/5/09

Sample Name: 23.9-43.8

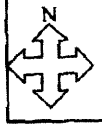
Latitude: _____

Longitude: _____

Sub-Catchment: NA

Notes: Chicken Farm. DNA

Location Sketch



Sampling	
Time Sampled	10:45pm
Sample Volume	Bag + 1 Liter
Sampled By	SP.
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/11 JY
Dilution	10^6	10^4	10^2	DNA
Volume Analyzed	100	100	100	Volume pumped
Incubator Time	1:41 p	1:41	1:41	139mL
Read Date	17/1	—	—	Date 16/11/09 Pumped 3:58PM
Read Time	2:15p	—	—	
Read By	KK	—	—	
# TC	TNTC	TNTC	TNTC	
# EC	TNTC (over 200)	TNTC	TNTC	

Much higher % e. coli than regular coliform

Date: 16/01/09

Sample Name: 23.4-43.8

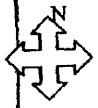
Latitude: 01023.4131

Longitude: 103043.8889

Sub-Catchment: KC3

Notes: _____

Location Sketch



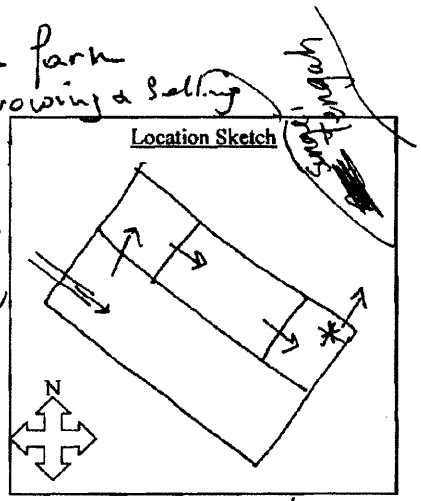
Sampling	
Time Sampled	11:00 pm
Sample Volume	Bag
Sampled By	SP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/1 JY
Dilution	10^6	10^4	10^2	
Volume Analyzed	100	100	100	
Incubator Time	1:55 p	1:55	1:55	
Read Date	17/1	—	—	
Read Time	2:25p	2:25p	—	
Read By	KK	—	—	
# TC	0	22	TNTC	
# EC	0	2	7	

Date: 20/1/09

fish farm
Growing & Selling

Location Sketch



Sample Name: 23.2-43.3

Latitude: ~~103°43~~ 01°23.177'

Longitude: 103°43.285'

Sub-Catchment:

Notes: Septic tank drains directly to Sungei Tengah

Sampling	
Time Sampled	5:15p
Sample Volume	100ml bag bottle for DNA
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

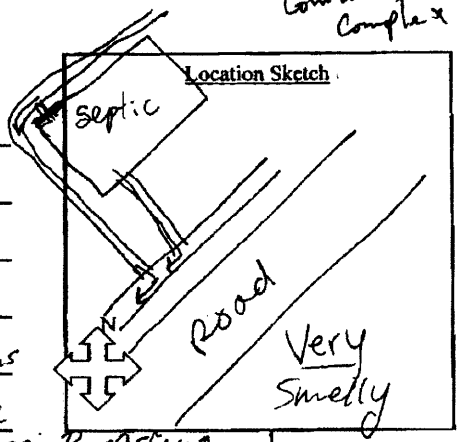
Analysis				
Dilution	10^6	10^4	10^2	DNA
Volume Analyzed	100	→	→	186ml/bottle
Incubator Time	11:50a	→	→	20/01/09 5:15PM
Read Date	22/01/09	22/01/09	22/01/09	21/01/09
Read Time	12:15AM	12:15AM	12:15AM	9:30AM
Read By	JP	JP	JP	
# TC	2	16	TNTC	
# EC	0	1	15	

21/1 JY

Date: 20/1/09

P.Dc Fishing & Restaurant Commercial Complex

Location Sketch



Sample Name: 23.0-43.6

Latitude: 01°23.005'

Longitude: 103°43.569'

Sub-Catchment:

Notes: Farm A septic drains directly through concrete drain on side of st. to Sungei Pengsiang

Sampling	
Time Sampled	5:55p
Sample Volume	100ml bag bottle DNA
Sampled By	JP
Temp	31/26
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	10^6	10^4	10^2	DNA
Volume Analyzed	100ml	→	→	7oml NSL
Incubator Time	12:00A	12:00A	12:00A	21/01/09
Read Date	22/01/09	22/01/09	22/01/09	9:45AM
Read Time	12:10AM	12:10AM	12:10AM	
Read By	JP	JP	JP	
# TC	TNTC	TNTC	TNTC	
# EC	TNTC	TNTC	TNTC	

Date: 16/01/10

Sample Name: 23·0·43.8-A

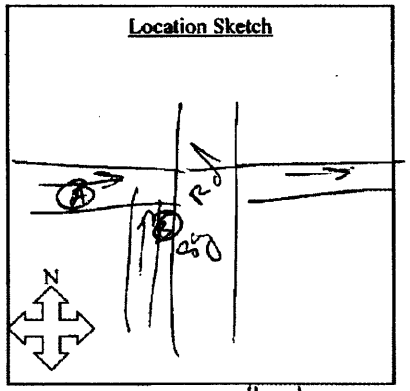
Latitude: 01°23.007

Longitude: 103° 43.876

Sub-Catchment: —

Notes: Upstream
D NA

Location Sketch



Date: 16/01/10

Sample Name: 23.0-43.8-B

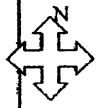
Latitude: 01°23.007

Longitude: 103°43.876

Sub-Catchment: —

Notes:
D-NA

Location Sketch



Sampling	
Time Sampled	11:15 am
Sample Volume	Bag + 1 Liter
Sampled By	SP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/1 JV
Dilution	10^6	10^4	10^2	NA
Volume Analyzed	100	→	→	Stored Volume pumped
Incubator Time	2:15 p	→	→	16/1/10
Read Date	17/1	→	→	11:15AM Sample 4:20PM Pumped
Read Time	2:20p	→	→	
Read By	KK	→	→	
# TC	1	72	TNTC	
# EC	0	10	TNTC	

Sampling	
Time Sampled	11:17am
Sample Volume	Bag + 1 Liter
Sampled By	JP.
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/1 JV
Dilution	10^6	10^4	10^2	NA
Volume Analyzed	100	→	→	Pumped Volume
Incubator Time	2:28 p	→	→	170mL
Read Date	17/1	—	—	11:17AM Sample
Read Time	2:35p	→	→	4:38 PM Pu
Read By	KK	→	→	
# TC	83	TNTC	TNTC	
# EC	29	TNTC (n=23)	TNTC	

Date: 16/01/09

Sample Name: 229-43.8-C

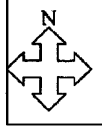
Latitude: 61°22.996'

Longitude: 103°43.870

Sub-Catchment: —

Notes: 2nd Drain from fish farm.

Location Sketch



Sampling	
Time Sampled	11:29 am
Sample Volume	Bag
Sampled By	SD
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				1/16 JY
Dilution	10^6	10^4	10^2	
Volume Analyzed	100	→	→	
Incubator Time	2:53p	→	→	
Read Date	17/1	→	→	
Read Time	2:45p	→	→	
Read By	KK	→	→	
# TC	0	149	TNTC	
# EC	0	4	141	

Date: 16/01/09

Sample Name: 229-43.8-B

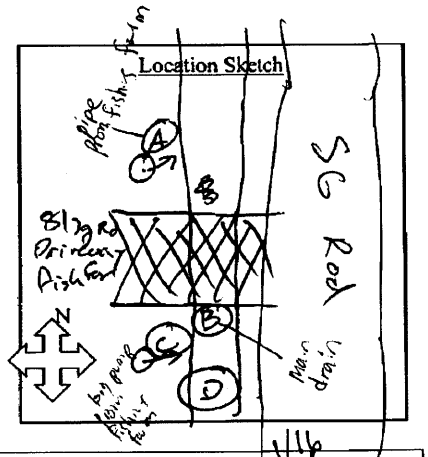
Latitude: 61°22.956'

Longitude: 103°43.870

Sub-Catchment: —

Notes: Upstream of fish farm drainage

Location Sketch



Sampling	
Time Sampled	11:30 am
Sample Volume	Bag
Sampled By	SP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				1/16 JY
Dilution	10^6	10^4	10^2	
Volume Analyzed	100	→	→	
Incubator Time	3:10p	→	→	
Read Date	17/1	→	→	
Read Time	2:50p	→	→	
Read By	KK	→	→	
# TC	167	TNTC	TNTC	
# EC	21	TNTC	TNTC	

L

Date: 14/01/09

Sample Name: 23.0-44.5

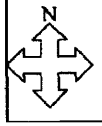
Latitude: 01°23.021'

Longitude: 103°44.573'

Sub-Catchment: KC2

Notes:

Location Sketch



Sampling	
Time Sampled	11:30am
Sample Volume	Bag
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	10000	1000	100	
Volume Analyzed	100	100	100	
Incubator Time	4:05p	4:05p	4:03p	
Read Date	15/1/09	15/1/09	15/1/09	
Read Time	3:06p	3:06	3:06	
Read By	JP	KK	KK	
# TC	47	144	TNTC	
# EC	0	1	5	

Date: 14/1/09

Sample Name: 23.9-43.8

Latitude: 01°23.966'

Longitude: 103°43.876'

Sub-Catchment: ~~[illegible]~~ -NA

Notes: ~~Do not leave this~~ chicken farm

~~Sheet filled out check on 15/1/09~~ JP

Location Sketch

Sampling	
Time Sampled	12:03pm
Sample Volume	bag
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:10000	1:1000	1:100	
Volume Analyzed	100	100	100	
Incubator Time	4:54p	4:54p	4:54p	
Read Date	15/01/09	15/01/09	15/01/09	
Read Time	4:47PM	4:47PM	4:47PM	
Read By	JP	JP	JP	
# TC	TNTC	TNTC	TNTC	
# EC	TNTC	TNTC	TNTC	

(*) Need another sample for chicken farm

Date: 14/01/09

Sample Name: 23.0-43.8 - A

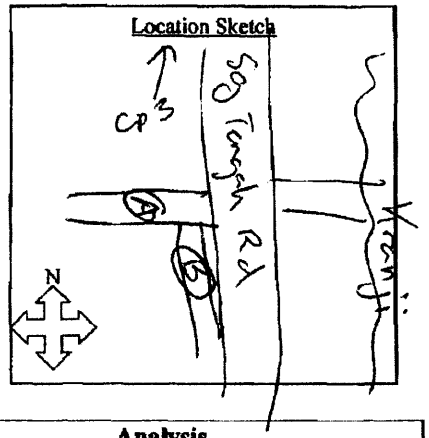
Latitude: 01° 23.007'

Longitude: 103° 43.876

Sub-Catchment: —

Notes: _____

Location Sketch



Sampling	
Time Sampled	12:25 pm
Sample Volume	Bag
Sampled By	SP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:10000	1:1000	1:100	
Volume Analyzed	100	100	100	
Incubator Time	2:58 pm	2:58	2:58	
Read Date	15/1/09	15/1/09	15/1/09	
Read Time	1:57 pm	1:57 pm	1:57	
Read By	JY	JY	JY	
# TC	30	TMTC	TMTC	
# EC	2	49	TMTC	

Date: 14/01/09

Sample Name: 23.0-43.8-B

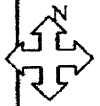
Latitude: 01° 23.007'

Longitude: 103° 43.876

Sub-Catchment: _____

Notes: Slight sewage smell

Location Sketch



Sampling	
Time Sampled	12:27 pm
Sample Volume	Bag
Sampled By	SP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:10000	1:1000	1:100	
Volume Analyzed	100	100	100	
Incubator Time	3:13 pm	3:13 pm	3:13 pm	
Read Date	15/1/09	15/1/09	15/1/09	
Read Time	2:05 pm	2:05	2:05	
Read By	JY	JY	JY	
# TC	TMTC	TMTC	TMTC	
# EC	TMTC	TMTC	TMTC	

Date: 14/01/09

Sample Name: 23.0-438-B duplicate

Latitude: 01° 23.007

Longitude: 103° 43.876

Sub-Catchment:

Notes:

Location Sketch

N

Date: H 1 09

Sample Name: method Blank

Latitude:

Longitude:

Sub-Catchment:

Notes: 12:30 pm

Location Sketch

N

Sampling	
Time Sampled	12:27 pm
Sample Volume	Bag
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:6000	1:1000	1:100	
Volume Analyzed	100	100	100	
Incubator Time	3:25p	3:25p	3:25p	
Read Date	15/1/09	15/1/09	15/1/09	
Read Time	2:32 pm	2:32	2:32	
Read By	JY	JY	JY	
# TC	TMTC	TMTC	TMTC	
# EC	TMTC	TMTC	TMTC	

14/01/09 Showed no TC or EC Absence

Sampling	
Time Sampled	12:30 pm
Sample Volume	bag
Sampled By	Cameron B.
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:1			
Volume Analyzed	100			
Incubator Time	3:30p			
Read Date	15/1/09			
Read Time	2:35 pm			
Read By	JY			
# TC	0			
# EC	0			

Date: 16/01/09

Sample Name: 23.0-43.8-B

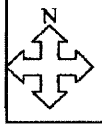
Latitude: _____

Longitude: _____

Sub-Catchment: _____

Notes: Duplicate.

Location Sketch



Date: _____

Sample Name: _____

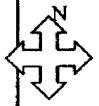
Latitude: _____

Longitude: _____

Sub-Catchment: _____

Notes: _____

Location Sketch



Sampling	
Time Sampled	11:17am
Sample Volume	Bag
Sampled By	SP.
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	10^0	10^4	10^2	
Volume Analyzed	100	→	→	
Incubator Time	2:40 ?	→	→	
Read Date	17/1	→	→	
Read Time	2:35p	→	→	
Read By	LK	→	→	
# TC	~~33~~	TNTC	TNTC	
# EC	~~24~~	TNTC	TNTC	

16/1

Sampling	
Time Sampled	
Sample Volume	
Sampled By	
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution				
Volume Analyzed				
Incubator Time				
Read Date				
Read Time				
Read By				
# TC				
# EC				

Date: 12/01/09

Sample Name: ~~22.7-44.8-C~~ 22.7-44.9-A

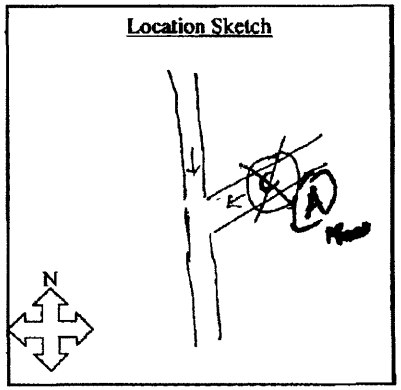
Latitude:

Longitude:

Sub-Catchment: KC2

Notes: ~~KC2~~

Location Sketch



Sampling	
Time Sampled	11:50am
Sample Volume	Bag
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:10000	1:1000	1:100	
Volume Analyzed	100 mL	100 mL	100 mL	
Incubator Time	4:15PM	4:15PM	4:15PM	
Read Date	13/1/09	13/1/09	13/1/09	
Read Time	3:32 PM	3:32 PM	3:32 PM	
Read By	JY	JY	JY	
# TC	error	error	error	
# EC	error	error	error	

all 6-8 EC
all TMTC TC
no error in dilution - labeling

Date: 12/01/09

Sample Name: ~~22.7-44.8-D~~ 22.7-44.9-B

Latitude:

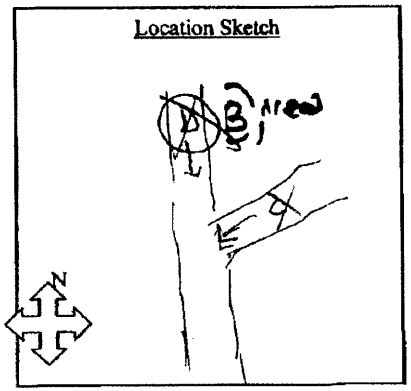
Longitude:

Sub-Catchment: KC2

Notes: ~~KC7~~ B blue

strong sewage smell

Location Sketch



Sampling	
Time Sampled	11:50am
Sample Volume	Bag
Sampled By	JP
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				
Dilution	1:10000	1:1000	1:100	
Volume Analyzed	100 mL	100 mL	100 mL	
Incubator Time	3:45PM	3:45PM	3:45PM	
Read Date	13/1/09	13/1/09	13/1/09	
Read Time	5:25 PM	5:25 PM	5:25 PM	
Read By	JY	JY	JY	
# TC	TMTC	TMTC	TMTC	
# EC	158	TMTC	TMTC	

Date: 16/01/09

Sample Name: 22.9-43.8-A

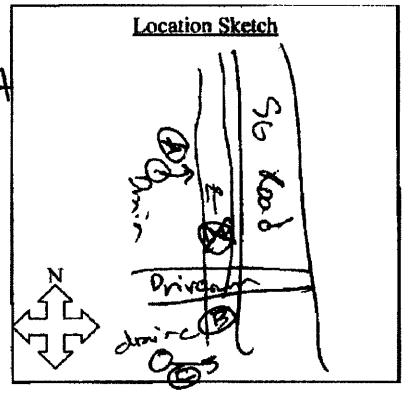
Latitude: 0° 22.967

Longitude: 103° 43.871

Sub-Catchment: —

Notes: From 81 Sg Rd fish farm

Location Sketch



Sampling	
Time Sampled	11:23am
Sample Volume	Bag
Sampled By	JD
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/1 JV
Dilution	10^6	10^4	10^2	
Volume Analyzed	100	→	→	
Incubator Time	3:20 p	→	→	
Read Date	17/1	→	→	
Read Time	3	→	→	
Read By	KK	→	→	
# TC	9	60	TNTC	
# EC	1	1	125	

Date: 16/01/09

Sample Name: 22.9-43.8-B 961

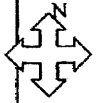
Latitude: 0° 22.~~967~~

Longitude: 103° 43.~~871~~ 870

Sub-Catchment: NA

Notes:

Location Sketch



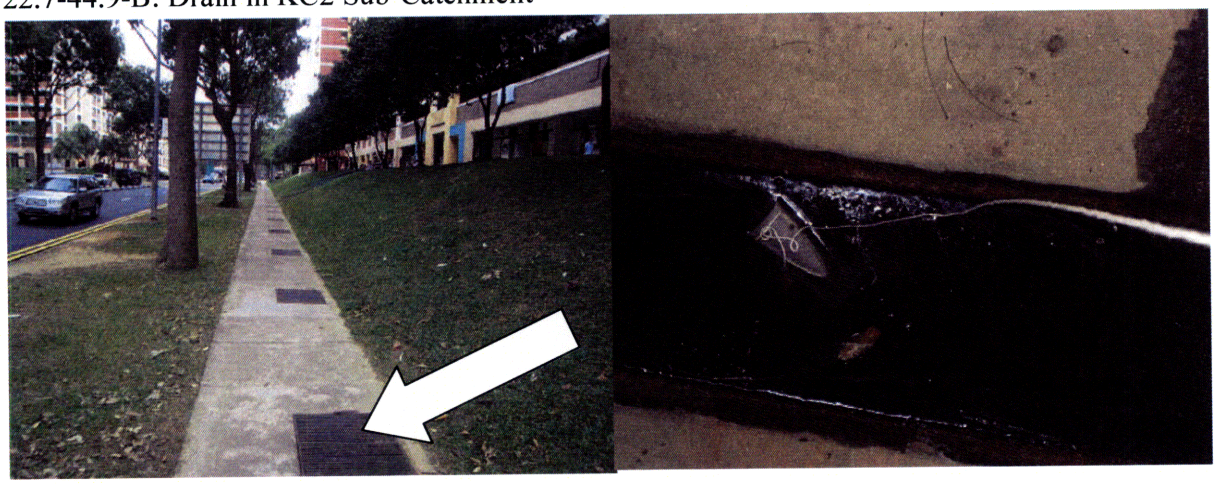
Sampling	
Time Sampled	11:29am
Sample Volume	Bag
Sampled By	
Temp	
pH	
Conduc.	
DO	
Turbidity	

Analysis				16/1 JV
Dilution	10^6	10^4	10^2	
Volume Analyzed	100	→	→	
Incubator Time	3:35 p	→	→	
Read Date	17/1	→	→	
Read Time	3:12	→	→	
Read By	KK	→	→	
# TC	38	TNTC	TNTC	
# EC	7	145	TNTC	

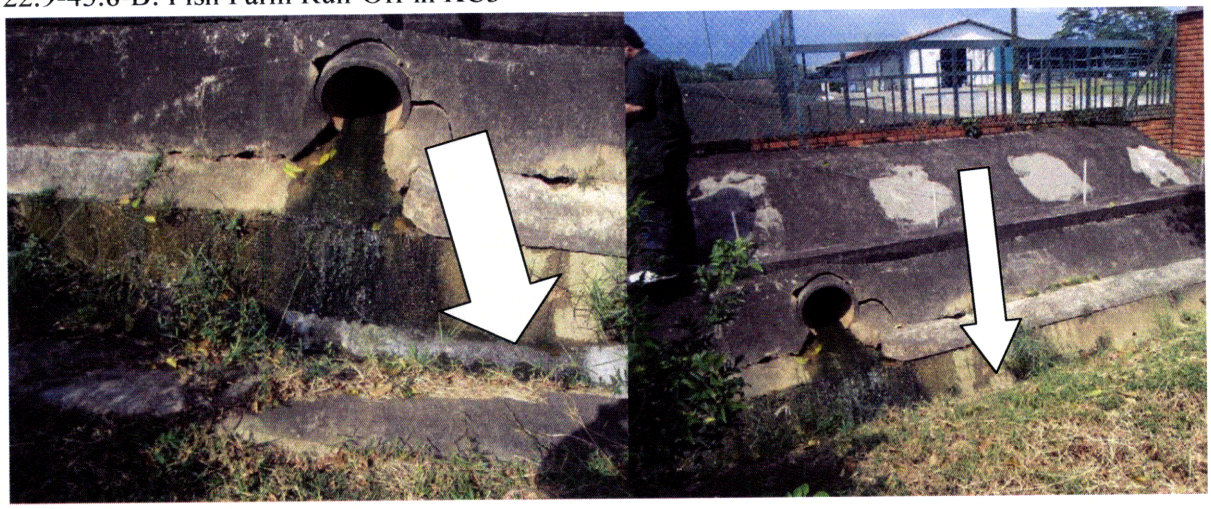
Appendix C
Pictures of the Six Sampling Locations with the Ten Highest Concentrations

Our team has provided pictures of the sampling locations with the ten highest E. coli concentrations with the exact location of sampling indicated with an arrow. The sites are listed in order of sample name.

22.7-44.9-B: Drain in KC2 Sub-Catchment



22.9-43.8-B: Fish Farm Run-Off in KC3

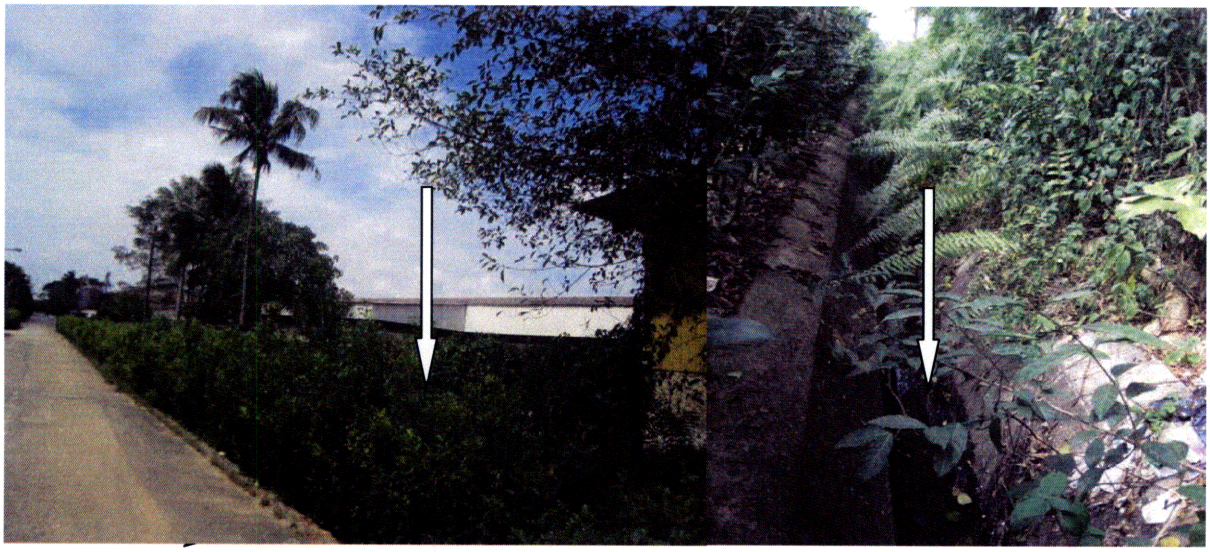


22.9-43.8-D: Fish Farm Run-Off in KC3

23.0-43.6: Farmart Restaurant and Fish Pond

23.0-43.8-B: Fish Farm Run-Off in KC3

23.9-43.8: Chicken Farm Run-Off in KC3



Appendix D
WASP Data

Jan 2005 Flow Q [m^3/d]	Normalized Flow[1] Q [m^3/d]	Flow [m^3/s]	Width [m]	Depth [m]	Veloc [m/s]	Time	Date
49,520	42,092	0.573	300	2	0.0010	12:00	1/1/2009
49,470	42,050	0.573	300	2	0.0010	12:00	1/2/2009
49,440	42,024	0.572	300	2	0.0010	12:00	1/3/2009
42,230	35,896	0.489	300	2	0.0008	12:00	1/4/2009
82,030	69,726	0.949	300	2	0.0016	12:00	1/5/2009
87,200	74,120	1.009	300	2	0.0017	12:00	1/6/2009
71,700	60,945	0.830	300	2	0.0014	12:00	1/7/2009
68,390	58,132	0.792	300	2	0.0013	12:00	1/8/2009
87,270	74,180	1.010	300	2	0.0017	12:00	1/9/2009
86,220	73,287	0.998	300	2	0.0017	12:00	1/10/2009
86,560	73,568	1.002	300	2	0.0017	12:00	1/11/2009
77,520	65,892	0.897	300	2	0.0015	12:00	1/12/2009
50,940	43,299	0.590	300	2	0.0010	12:00	1/13/2009
50,150	42,628	0.580	300	2	0.0010	12:00	1/14/2009
49,950	42,458	0.578	300	2	0.0010	12:00	1/15/2009
50,100	42,585	0.580	300	2	0.0010	12:00	1/16/2009
50,230	42,696	0.581	300	2	0.0010	12:00	1/17/2009
50,360	42,806	0.583	300	2	0.0010	12:00	1/18/2009
50,300	42,755	0.582	300	2	0.0010	12:00	1/19/2009
47,850	40,673	0.554	300	2	0.0009	12:00	1/20/2009
49,990	42,492	0.579	300	2	0.0010	12:00	1/21/2009
51,210	43,529	0.593	300	2	0.0010	12:00	1/22/2009
51,070	43,410	0.591	300	2	0.0010	12:00	1/23/2009
50,790	43,172	0.588	300	2	0.0010	12:00	1/24/2009
67,320	57,222	0.779	300	2	0.0013	12:00	1/25/2009
87,850	74,673	1.017	300	2	0.0017	12:00	1/26/2009
88,030	74,826	1.019	300	2	0.0017	12:00	1/27/2009
87,710	74,554	1.015	300	2	0.0017	12:00	1/28/2009
87,570	74,435	1.014	300	2	0.0017	12:00	1/29/2009
87,680	74,528	1.015	300	2	0.0017	12:00	1/30/2009
87,600	74,460	1.014	300	2	0.0017	12:00	1/31/2009

1 Flow is normalized for lower January 2009 levels, which averaged 85% of January 2005 levels

Segment ID	Segment	Normalized Flow[1] [m^3/d]	Flow [m^3/s]	Width [m]	Depth [m]	Velocity [m/s]	Length [m]	Volume [m^3]	X-sect Area [m^2]	Fraction of Flow
1	KC1KC2	16291.7568	0.189	5.8	0.11	0.295551724	1913.7931	1221.12		0.246000
2	KC3SP	26659.7568	0.309	11	2	0.014025545	1120	24640	22	0.433528
3	KC4	15552	0.180	12	3	0.005	2000	72000	36	0.278292
4	Station Tengah	15552	0.180	300	3	0.0002	750	675000	900	0.278292
5	KC6	3041.28	0.035	0.5	0.32	0.22	1800	288	0.16	0.054422
6	Station Kangkar	3041.28	0.035	400	2	0.000044	650	520000	800	0.054422
7	Station 3 Arm Junction	45253.0368	0.524	400	4	0.000327351	900	1440000	1600	0.766241
8	KC5S1	55883.7568	0.647	700	5	15.96678766	700	2450000	3500	0.999760
9	KC7	10630.72	175.000	250	7	0.1	670	1172500	1750	0.190229
10	Station 3	10000	0.116	550	7	3.00625E-05	1350	5197500	3850	0.178943
11	Station 4	10000	0.116	650	8	2.22578E-05	1000	5200000	5200	0.178943

1 Flow is normalized for lower January 2009 levels, which averaged 85% of January 2005 levels

Sample Date	Segment	Distance to Res [m]	Travel Time [s]	Time [days]	Initial Conc [counts/100 ml]	Downstream Conc [counts/100 ml]
2009	KC1	500	1850.48	0.02141761	219500	177181.7738
2009	KC2	225	1071.43	0.01240079	1580000	1395729.071
2009	KC3	2.5	12.50	0.00014468	960	958.6121153
2009	KC4	1000	200000.00	2.31481481	120	1.06186E-08
2009	KC5	50	250.00	0.00289352	830000	806327.9258
2009	KC6	925	4204.55	0.04866372	10700	6577.182986
2009	KC7	1850	6335.62	0.07332889	108500	52115.43871
2005	Station Tengah	In reservoir	0.00	0	N/A	200
2005	Station Pengsiang	In reservoir	0.00	0	N/A	2400
2005	Station Kangkar	In reservoir	0.00	0	N/A	700
2005	Station 3 Arm Junction	In reservoir	0.00	0	N/A	1800
2005	Station 1	In reservoir	0.00	0	N/A	530
2005	Station 3	In reservoir	0.00	0	N/A	130
2005	Station 4	In reservoir	0.00	0	N/A	140

Location	E. Coli Density [counts/100 ml]				Sample Size
	Minimum	Maximum	Geometric Mean	STDEV	
Reservoir Sampling Locations					
Station 1	1	530	18	150	17
Station 3	1	130	3.4	34	17
Station 4	1	140	3.5	33	14
Station 3 Arm Junction	1	1,800	20	480	17
Station Pengsiang	7.5	2,400	100	840	14
Station Tengah	2	200	17	70	16
Station Kangkar	1	700	14	170	10