Water Quality Modelling for Recreational Use in the Kallang River Basin, Singapore

by

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ABSTRACT

Singapore's Active, Beautiful, and Clean Waters Programme (ABC) aims to provide functional use of its water bodies to the public. The Kallang River Basin, being part of the ABC Programme, will be used for recreational purposes such as dragon boating and other water sports. In order to provide safe recreational use for the public, the water quality of the Kallang River Basin needed to be determined and modeled. The water quality indicator chosen to be analyzed was *Escherichia coli (E. coli)* bacteria. A heuristic study was performed in order to determine the water quality and as well determine if water quality modeling was feasible for the Kallang River Basin. The study employed the United States Environmental Protection Agency WASP (Water Quality Analysis Simulation Program) model. Through WASP model simulations, it was found that certain parts of the Kallang River Basin were not suitable for recreational purposes and others parts were deemed suitable. *E. coli* concentrations predicted by the model were within the range of actual field data but diurnal variations were not captured by the model for lack of data with which to specify diurnally varying inputs. The WASP model created by this study suggests that water quality modeling for the Kallang River Basin is feasible but there are modifications that need to be made to accurately capture diurnal variations experienced by the Kallang River Basin. Future investigation into the diurnal variations would contribute to creating a more complete and accurate model for the Kallang River Basin.

Thesis Supervisor: Dr. Peter Shanahan
Title: Senior Lecturer of Civil and Environmental Engineering

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Chapter 1: Background of the Study

1.1 Background of Singapore

The Republic of Singapore (Figure 1.1), consisting of several islands, is located in Southeast Asia and at the southern tip of the Malay Peninsula. Its geographic coordinates are 1°22 N, 103°48 E (Rosenburg, 2005).

Figure 1.1: Map of Singapore (Maps of The World)

Singapore was founded in 1819 by Sir Stamford Raffles of the British East India Company (EIC). Singapore was used as a free port because of its strategic location along the Straits of Malacca and Singapore's main trade artery was the Singapore River (Tortajada *et al.*, 2013). Singapore had become one of the world's most important and busiest ports by the late eighteenth century. Rapid development and a lack of long-term planning resulted in overcrowding in the central area. Vacant and marginal lands were occupied and people lived in combustible huts without sanitation, water, or any basic public health service whatsoever (PUB, 1985; Tan, 1972; as cited by Tortajada *et al.*, 2013). The government met a multitude of public health challenges and their central goal was to improve the population's quality of life. Nation-building and the economy were of utmost importance but there were also pressing issues related to the reorganization of governmental administrative organs (Toh, 1959, as cited by Tortajada *et al.*, 2013). After decades of restructuring Singapore's governmental organs and addressing several of the country's issues, the Public Utilities Board (PUB), established in 1963, started developing Singapore's water supply system. In order to answer the needs as well as anticipate the challenges of a growing country, Singapore's water resources planning, development, management, and governance strategy have been developed into one of the best systems in the world. Table 1.1 shows some key statistics describing how Singapore has been transformed over the last four decades, mostly from the water resources perspective (Tortajada *et al.*, 2013).

Table 1.1: Key Statistics on Singapore, 1965 and 2011 (Tortajada et al., 2013)

	1965	**2011**	**Change**
Land Area (km^2)	580 km^2	714 km^2	134 km^2
Population	1,887,000	5,184,000	3,297,000
GDP per capita[a]	\$1,580	\$63,050	\$61,470
Total water consumption	70 Mgal/day	380 Mgal/day	310 Mgal/day
No. of reservoirs	3	17	14
Land area as water catchment	11%	67%	56%
Water Availability	24 hours/day	24 hours/day	

Notes:
[a] In Singapore dollars at 2011 market prices.

Singapore being in Southeast Asia has three different monsoon seasons: the southwestern monsoon (June – September), the northeastern monsoon (December – March), and the inter-monsoon period (heavy thunderstorms in the afternoon). Singapore's annual rainfall average is about 2360 mm (Meteorological Service Singapore, 2014), which is above the global average of 1050 mm per year. However, due to limited catchment area for gathering rainwater plus high evaporation rates, Singapore is classified as a water scarce country (Zhang, 2011). Singapore ranks 170 out of 190 on the United Nations' list of fresh water availability by country (Tan *et al.*, 2009).

1.2 Managing Singapore's Water

This section of the thesis was written in collaboration with Riana Kernan, Tina Liu, and Allison Park.

1.2.1 Water Issue

Due to limited natural water resources, Singapore's Public Utilities Board (PUB) must creatively manage water supplies and encourage conservation in order to provide the needed 400 million gallons a day (MGD) to its 5.4 million residents (PUB, 2013a). To address the growing demand, Singapore has been increasing supply by tripling water reclamation and increasing desalination capacity tenfold. The development of these supply processes will help meet up to 80% of the water demand in 2060.

1.2.2 Water Management

Singapore has four water sources: local catchment water, imported water, desalination, and reclaimed NEWater.

Local Catchment Water

Two-thirds of Singapore's land area is utilized as water catchment (light blue colors in Figure 1.2). Surface water is collected and stored in 17 reservoirs (dark blue colors in Figure 1.2) located throughout the island (Figure .1). Singapore is one of only a few cities around the world that applies urban stormwater harvesting on such a large scale. The extensive use of urban runoff necessitates the reduction of non-point source pollution and careful management of surface water quality. This is one of the goals of PUB's Active, Beautiful, and Clean Waters (ABC Waters) Programme which seeks to transform the city's concrete channels, drains, and reservoirs into more natural looking and sustainably-managed waterways so that Singapore becomes a "City of Gardens and Water" (PUB, 2013a). Another aspect of the ABC Waters Programme is to open up reservoirs for recreational use, in part to increase public appreciation and understanding of Singapore's water resources. PUB hopes that these efforts will help increase water conservation and reduce pollution in Singapore's waterways creating a vitalized community.

Imported Water

Malaysia's Johor State Government and Singapore signed a water agreement in 1961, but it expired on August 31, 2011. Under a second water agreement in 1962, Singapore is still allowed to draw up to 250 MGD from the Johor River until 2061 (PUB, 2013a). Due to the uncertainty of the future of this agreement and the desire to be water independent, PUB hopes to provide all of its water internally by the expiration of this agreement in 2061.

Desalination

Singapore's first desalination plant, built and operated since 2005, supplies about 30 MGD. The plant was designed to supply water to PUB for a period of 20 years. With growing demand for water, a second and larger desalination plant, the Tuaspring Desalination Plant, was officially opened on September 18, 2013 and will supply an additional 70 MGD to Singapore's water supply.

NEWater

Since its introduction in 2003, NEWater provides extremely clean reclaimed water (PUB, 2013a). The process of NEWater uses advanced membrane technologies such as microfiltration, reverse osmosis, and ultraviolet disinfection (PUB, 2013a). NEWater produces high quality reclaimed water that has passed World Health Organization (WHO) and United States Environmental Protection Agency (U.S. EPA) standards. The largest NEWater plant, located in Changi, supplies about 50 MGD of water. NEWater meets 30% of Singapore's current total water demand and is expecting to expand to meet up to 55% of demand in the long run.

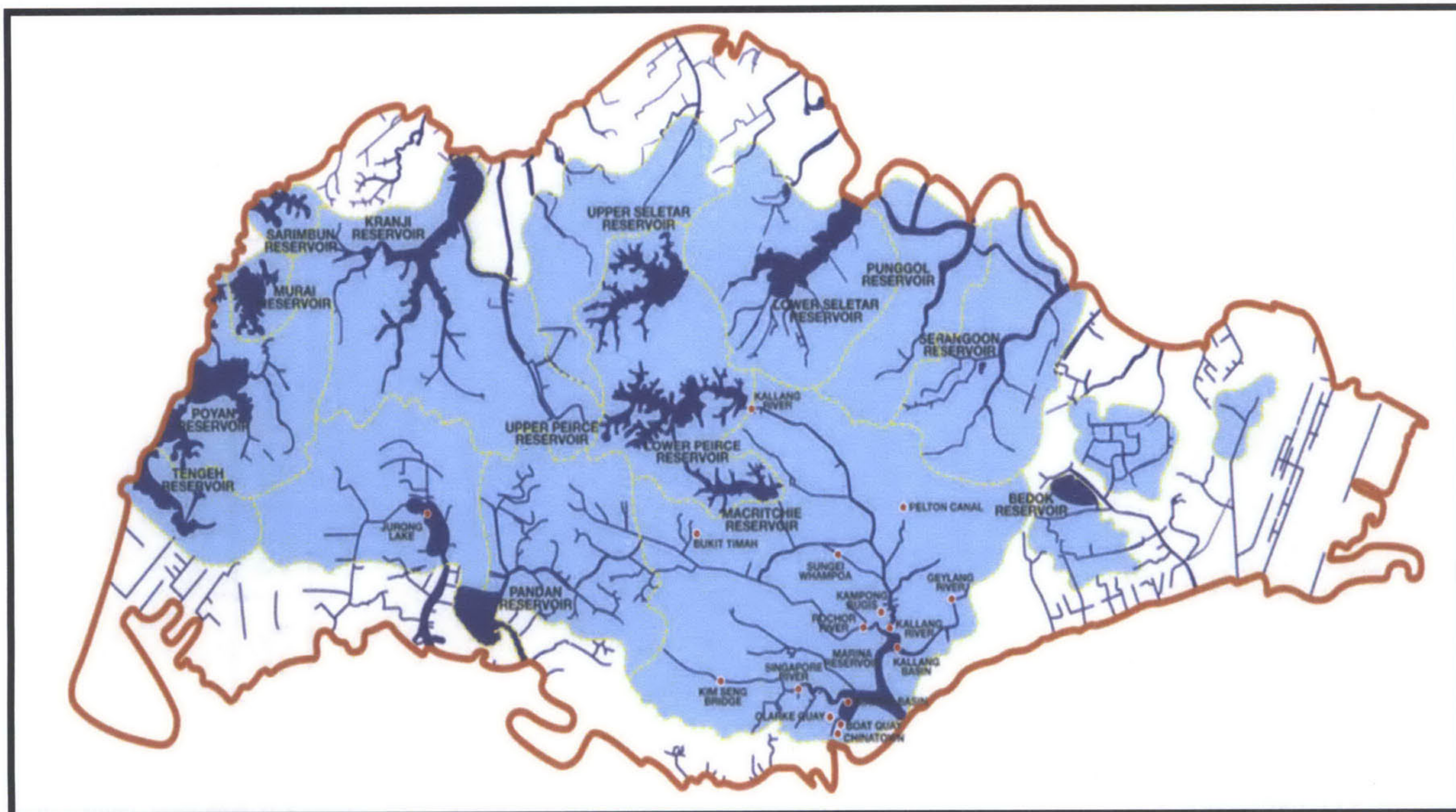

Figure 1.2: Catchment Areas (light blue) and Reservoirs (dark blue) in Singapore (Joshi et al. 2012)

1.2.3 Active, Beautiful, Clean Waters Programme (ABC Waters Programme)

Singapore has progressively developed a vast network of about 8,000 km of waterways and 17 reservoirs for water supply because it aims to turn Singapore into a "City of Gardens and Water" in the hopes of attaining a vision of magnificent rivers with landscaped banks, dragon boaters and kayakers rowing through clear waterways flowing into picturesque lakes. Part of the ABC Waters Programme is to provide a functional use of the water bodies serving as public attractions, to develop and manage water bodies as public spaces but still upholding water quality standards, and to build a community centered on water conservation (PUB, 2013a).

Connecting drains, canals, and reservoirs with the community in a holistic way is a strategic initiative to improve the quality of water and life by developing the full potential of different water bodies. The ABC Waters Programme's goal is to provide community spaces consisting of streams, rivers and lakes that are clean and beautiful.

1.2.4 Kallang River Basin for Recreational Use

In line with the ABC Waters Programme initiative, the Kallang River Basin (Figure 1.3) will be used for recreational purposes such as dragon boat racing, water sports, fishing, and picnicking. However, the PUB has concerns that the bacteriological levels in the waters may pose health and safety risks for people coming in contact with it. Because of its intended use for recreational activities, there is a need to extensively evaluate the water quality of this basin in order to reduce the risk associated with exposure to people participating in recreational activities. Continuous monitoring of runoff and bacterial concentrations from the basin should be established to evaluate the microbial diversity and determine the risks associated.

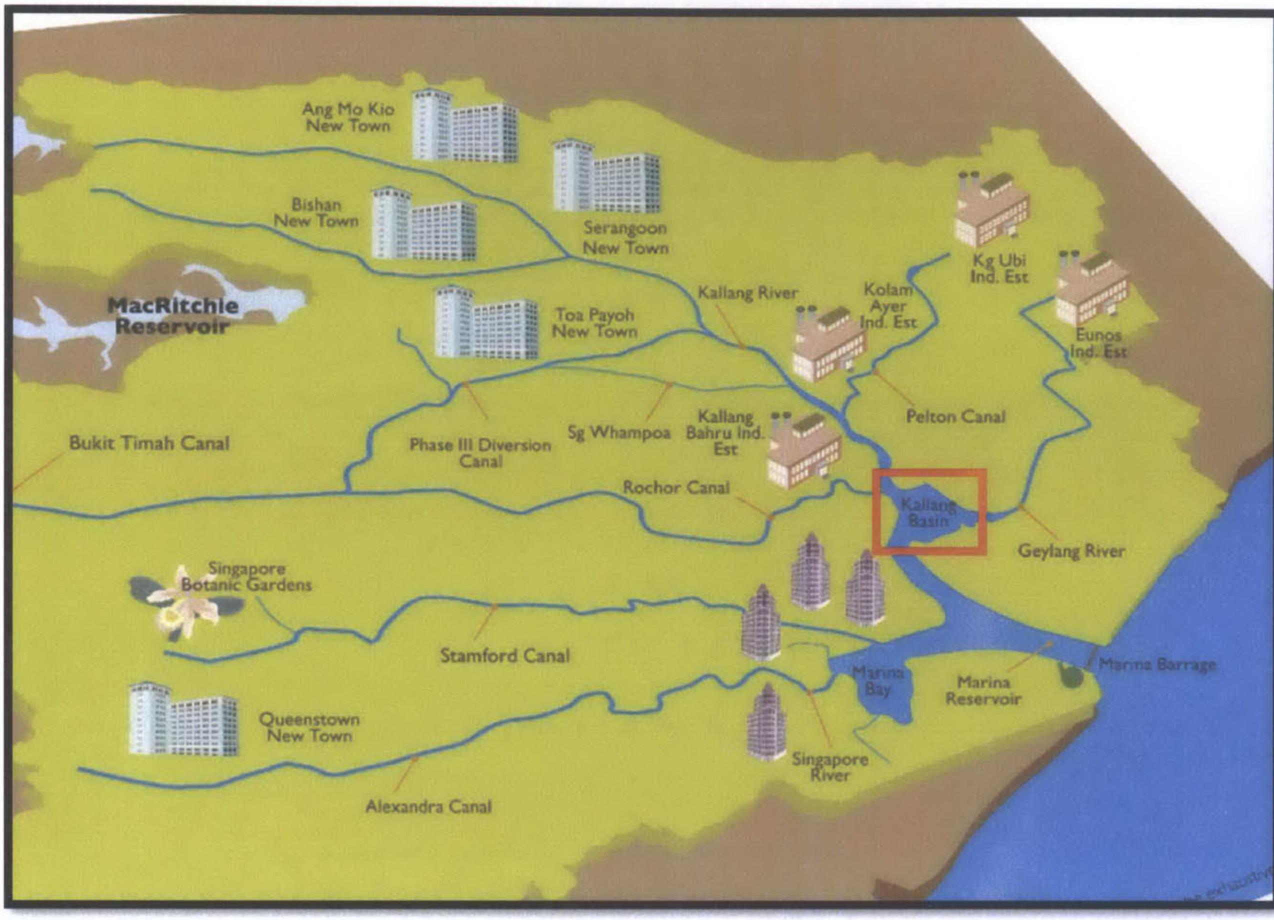

Figure 1.3: Map of Center Catchment of Singapore with a detailed view of the Kallang Basin (PUB, 2013a)

Chapter 2: Water Quality Indicators and Water Quality Modeling

2.1 Water Quality Indicators

2.1.1 *E. coli* Bacteria

Pathogenic and non-pathogenic microorganisms are usually present in recreational waters. The sources of these microorganisms include sewage discharge, people present in the water (defecation or self-shedding), industrial processes, agricultural processes, and livestock (WHO, 2003). In order to determine if there is fecal contamination or a possible presence of pathogenic bacteria, indicator bacteria or indicator organisms (not necessarily pathogenic) are normally analyzed and quantified for a given water body. Presently, the commonly used indicator bacterium for characterizing the water quality is *Escherichia coli* (*E. coli*) (Figure 2.1).

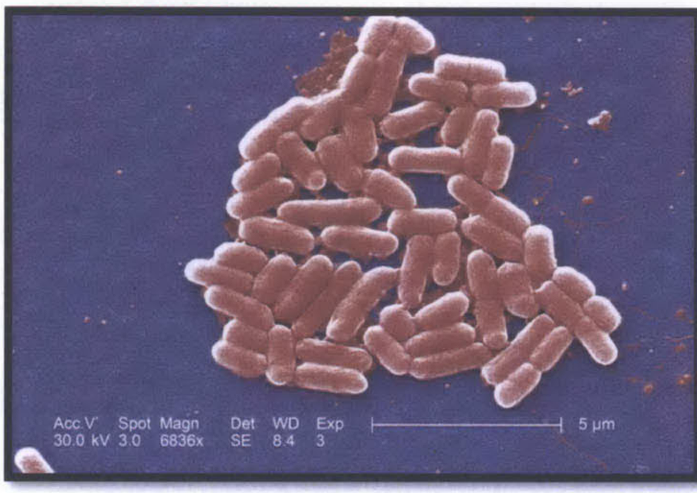

Figure 2.1: *Escherichia coli* (*E. coli*) of the strain O157:H7 (CDC, 2014)

Escherichia coli is normally present within the digestive tracts of humans and warm-blooded animals. The need to monitor the presence of this organism in recreational waters is of the utmost importance because there have been several diarrhea-associated pathotypes of *E. coli* (disease causing) (Nataro and Kaper, 1998 as cited by Mitchell and Gu, 2010). The pathoypes with their associated diseases are (Mitchell and Gu, 2010):

- "Enterohemorrhagic *E. coli* (EHEC): bloody diarrhea, hemorrhagic colitis, and hemolytic–uremic syndrome
- Enteropathogenic *E. coli* (EPEC): diarrhea in children and animals
- Enterotoxigenic *E. coli* (ETEC): traveler's diarrhea, porcine and bovine diarrhea
- Enteroaggregative *E. coli* (EAEC): persistent diarrhea in humans
- Enteroinvasive *E. coli* (EIEC): watery diarrhea and dysentery"

The maximum level of *E. coli* concentration in recreational waters is based on United States Environmental Protection Agency (U.S EPA) standards. Based on U.S. EPA criteria for bathing (full-body contact) in recreational water, the limit for *E. coli* concentrations is 126 colony forming units (CFU) per 100 mL of water (U.S. EPA, 2012).

Some studies (Lopez-Torres et al., 1987; Hazen, 1988) have examined *E. coli* in tropical climates and questioned its applicability as a water quality indicator. However, Dufour (1977) state that because of the broad general characteristics of coliforms, this group has been regarded as the most useful of bacterial indicators. Edberg *et al.*, (2000) indicated that *E. coli* was found in natural waters, natural soils, and sewage treated effluent. *E. coli* was also abundant and specific to human or animal fecal contamination (Dufour, 1977). Edberg et al. (2000) state that approximately 10^9 *E. coli* bacteria are present in a single gram of human or animal feces. In line with this, the presence of *E. coli* has always been regarded as a public health threat (Edberg *et al.,* 2000). Also, Sobsey (2007) highlights the advantages and disadvantages of *E. coli* as indicator bacteria (Table 2.1).

Table 2.1: Advantages and disadvantages of *E. coli* as an indicator bacteria (Sobsey, 2007)

Indicator	Advantages	Disadvantages
E. coli	• A fresh water human health indicator • Indicator of recent fecal contamination • Used to track sources of fecal contamination • Rapid identification if based on beta-Glucuronidasc activity	• Sometimes not suitable for tropical and some other waters due to growth in soils and waters • Poor survival in sea water; low concentrations may give poor predictability of health risks

In support of how *E. coli* is an applicable indicator bacteria for Singapore, recent studies by Massachusetts Institute of Technology (MIT) teams Dixon et al., (2009), Kerigan and Yeager (2009), Granger (2010), Nshimyimana (2010), and Zhang (2011) have verified the applicability of *E. coli* as a good indicator bacteria for Singapore. Therefore, I used *E. coli* as the water quality indicator for the Kallang River Basin.

2.2 Water Quality Modeling

2.2.1 Water Quality Modeling Background

In order to address the need for water pollution control planning, mathematical computer models analyzing water quality have been developed. How do mathematical models help water pollution control planning? One, mathematical models help characterize water quality by describing the physical, biological, and chemical processes affecting water quality. A mathematical model increases the understanding of the behavior of these processes and because of this, control methods could be suggested. Two, mathematical models can be predictive models that forecast future water quality. Because of predictive models, several possible control strategies can be simulated and tested before actual implementation (Shanahan and Harleman, 1984).

With regard to mathematical models trying to predict the behavior of fecal coliform bacteria, Eleria et al. (2005) utilized logistic regression models and ordinary least square (OLS) models to predict fecal coliform bacteria concentrations in the Charles River Basin in Massachusetts, USA. The Eleria et al. (2005) models, which take into account meteorological conditions and streamflow, also predicted if fecal coliform bacteria concentrations would exceed the Massachusetts secondary contact recreation standard.

Other types of lake water quality models that have arisen are finite-difference models (continuum approach) and multiple-box models (discrete approach). An example of a multiple-box model was that developed by Canale et al. (1993). The Canale et al. (1993) model was a two-layer mass balance multiple-box model that simulates spatial and temporal variability of fecal coliform bacteria concentrations in Onondaga Lake, Syracuse, N.Y. Advection, dispersion, kinetic losses, and other mass transport processes in the lake were correlated with fecal coliform bacteria concentrations.

Given that previous mathematical-water quality models specifically the multiple-box model is applicable in predicting the fate and transport of fecal coliform bacteria, I modeled the Kallang River Basin as a multiple-box system that also integrates the time-varying mass transport processes.

2.2.2 U.S. EPA – Water Quality Analysis Simulation Program (WASP)

The WASP model is a "dynamic compartment-modeling" program for water bodies or aquatic environments (1-, 2-, or 3-dimensional systems) that analyzes and predicts water quality responses to naturally occurring events and human source pollution. The WASP model's analysis considers time-varying processes such as advection, point and diffuse mass loading, dispersion, and boundary exchange (Wool et al., 1995).

The WASP model has been used to analyze several different pollutant types in different water bodies all over the world (U.S. EPA, 2014). WASP has the ability to provide analysis over numerous years and running these analyses through various environmental and meteorological conditions. Because of its capabilities, the WASP model has been used for eutrophication analysis in Tampa Bay, FL, Neuse River Estuary, NC, and the Coosa River and Reservoirs, AL;

for phosphorus loading to Lake Okeechobee, FL; for PCB pollution analysis of the Great Lakes; for kepone pollution of the James River Estuary; and other places around the world.

The WASP model has also been used in Singapore for the Kranji Reservoir. A WASP model was created by Kerigan and Yeager (2009) to determine the fate and transport of *E. coli* bacteria concentrations in the Kranji Reservoir and also to locate possible sources of *E. coli* contamination. Another model was created by Zhang (2011) for the Kranji Reservoir as an update to the 2009 model. Zhang's model incorporates more information and real conditions to calibrate the 2009 model. Zhang's model was validated by comparing the model's simulated *E. coli* concentrations with the collected water samples' *E. coli* concentration. The simulation results of the 2011 model coincide with the actual collected water samples (presented in Figure 2.2). The consistency of the simulation and actual water sample results validate that WASP is applicable to model *E. coli* concentrations in the Kranji Reservoir (Zhang, 2011). Given WASP's applicability to a Singapore water body, for this research, I used the Water Quality Analysis Simulation Program (WASP) model for the analysis of *E. coli* concentrations in the Kallang River Basin.

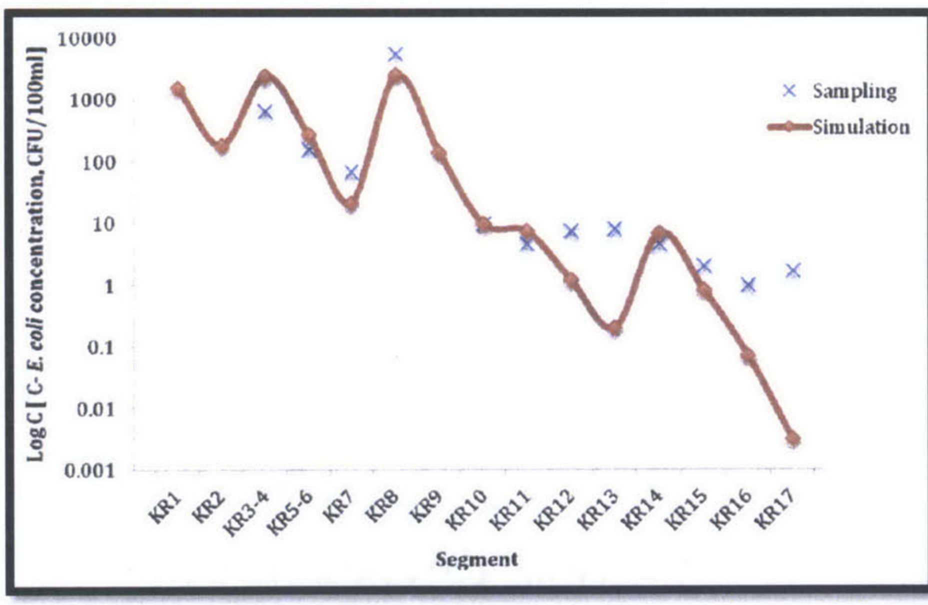

Figure 2.2: 2011 WASP model simulation results vs sampling concentrations of *E. coli* (Zhang, 2011)

Chapter 3: Water Sampling and Analysis Methodology

3.1 Field Sampling Procedure

Field sampling in the Kallang River Basin was conducted over a span of two days (48 hours). Water samples were collected at four-hour intervals starting at 11:00 am on January 5, 2014 and ending at 7:00 am on January 7, 2014. During the day, the weather conditions were sunny with clear skies. During the night, the weather condition was also clear skies but there were very brief and very light rain showers. The points of sampling were located on Jalan Benaan Kepal (Station 2), Kallang Riverside Park (Station 3), Upper Boon Keng Road (Station 4), and Crawford Street (Station 5) (Figure 3.1).

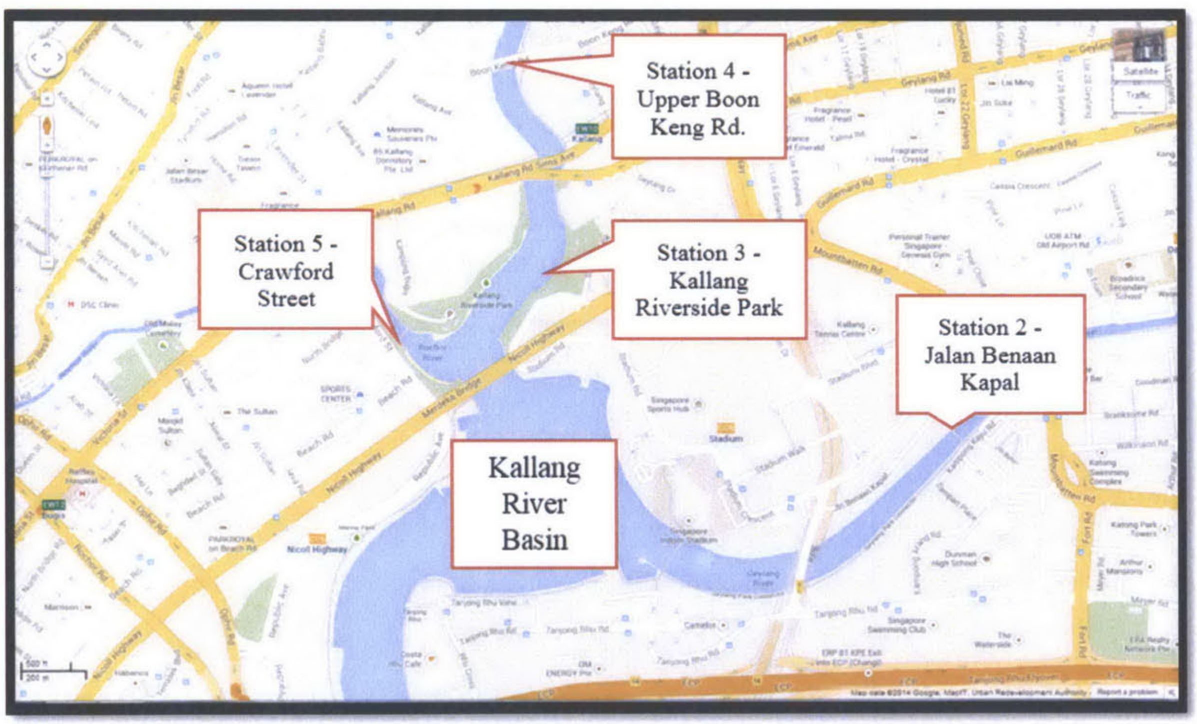

Figure 3.1: Location of Sampling Stations (Google Maps)

The procedure for collecting the river water was to throw a bucket into the river, collect surface water, and then transfer the water into plastic bottles (Figure 3.2). Each sample collected would be the equivalent of about 4 bucketfuls or 20 liters of river water. After all stations in a sampling round were collected, the water samples were immediately brought to the T-Lab of National University of Singapore (NUS) for processing.

Figure 3.2: Kallang River Basin Water Sample Collection and Delivery

3.2 Laboratory Analysis Procedure

3.2.1 Laboratory Test Method

The laboratory analysis implemented was the IDEXX Colilert most-probable-number method using Quanti-Tray/2000 testing trays (IDEXX Laboratories, Inc., Westbrook, Maine, USA). Colilert detects both total coliforms and *E. coli* in water (IDEXX, 2013c). Colilert's nutrient-indicator, ONPG (ortho-Nitrophenyl-β-galactoside) is metabolized by coliform bacteria turning the sample yellow (Figure 3.3a). When *E. coli* metabolizes Colilert's nutrient-indicator, MUG (4-Methylumbelliferyl-beta-D-glucuronide), the sample fluoresces. Colilert detects these bacteria at 1 CFU/100 mL within 24 hours (detection happens after incubating the sample for 24 hours). IDEXX Quanti-Tray/2000 provides quantitated bacterial counts of 100 mL samples (IDEXX, 2013a). The IDEXX Colilert method was also used in previous studies by Granger (2010), Nshimyimana (2010), and Zhang (2011) for the Kranji Reservoir in Singapore to determine the concentration of *E. coli* and total coliform.

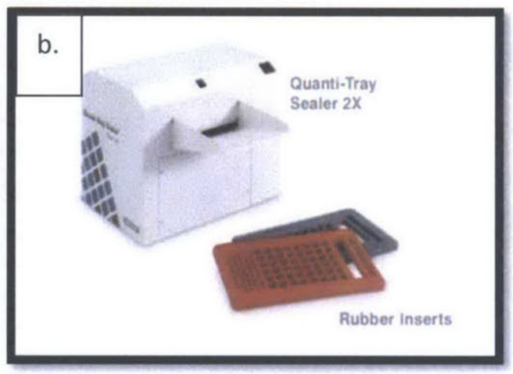

Figure 3.3: a. Quanti-Tray®/2000 and b. Quanti-Tray Sealer (IDEXX, 2013a; b)

3.2.2 Laboratory Procedure

The 20-liter samples were brought to the NUS T-Lab laboratory. A volume of 100 milliliters (mL) of water were collected from each sample in order to carry out the Colilert test. All the samples were diluted to a ratio of 1:10 except for the samples from station 2 which had a dilution of 1:5. In the case of the 1:10 ratio (procedure also carried out for the 1:5 ratio but with different proportions), 10 mL of the sample was pipetted using an Eppendorf Research Pipette® and mixed with 90 mL of deionized (DI) water into a Nasco Sterile Whirl-Pak® bag. After the dilutions were completed, the reagent from the Colilert test kit was added to the mixture (agitated until the reagent fully mixed with DI water and water sample). The whole solution was then poured into a Quanti-Tray/2000, sealed with a Quanti-Tray Sealer (Figure 3.3b) and incubated for 24 hours. After 24 hours, the samples were taken out and analyzed for *E. coli* concentrations. In order to determine the number of fluorescent wells (which indicates the MPN count for *E. coli* concentrations), a 365-nm ultraviolet light was used to make the sample fluoresce. The results were recorded and tabulated (refer to Table A.1 in Appendix A).

Chapter 4: *E. coli* Attenuation Model

4.1 Coliform and *E. coli* reaction kinetics

The coliform or *E. coli* attenuation rate normally follows a first-order kinetics mechanism (Hydroscience, 1971; Bowie et al., 1985).

$$\frac{dC}{dt} = -kC \tag{4.1}$$

or

$$C_t = C_o e^{-kt}$$

Where:
C = concentration of coliform or *E. coli* at time t, MPN/100ml;
C_o = initial concentration of coliform or *E. coli*, MPN/100ml;
k = attenuation rate constant, day^{-1} or hr^{-1};
t = time of exposure, days or hrs.

4.2. *E. coli* attenuation rate

There are three main categories that affect the disappearance rates of *E. coli*. The three main categories are physical, physicochemical, and biochemical-biological. Physical factors include: photo-oxidation, adsorption, sedimentation, and temperature. Physicochemical factors include: pH, osmotic effects, redox potential, and salinity. Biochemical-biological factors include: nutrient levels, algae, presence of fecal matter, and bacteriophages (Bowie et al., 1985). The factors which are most likely to affect *E. coli* population in the Kallang River Basin are photo-oxidation, temperature, salinity and sedimentation.

For this study, the effective attenuation rate constant (k_E) for modeling *E. coli* is composed of a photo-oxidation rate (k_P), a sedimentation rate (k_S) and a natural mortality rate (k_M). A coefficient of 0.5 (12 hrs / 24 hrs per day) is applied to the k_P value to incorporate the 12-hour effective time of sunlight.

$$k_E = 0.5k_P + k_S + k_M \tag{4.2}$$

Where:
k_E = effective attenuation rate of *E. coli*, day^{-1};
k_P = attenuation rate for photo-oxidation day^{-1};
k_S = attenuation rate for sedimentation, day^{-1};
k_M = attenuation rate for natural mortality, day^{-1};

4.2.1 *E. coli* photo-oxidation attenuation rate

According to Chamberlin and Mitchell (1978), photo-oxidation is one of the most important factors because there is a significant relationship between light intensity and coliform disappearance rates. Chamberlin and Mitchell (1978) stated that there are several light mechanisms increasing coliform disappearance rates. One example of a mechanism is when light quanta drive some exogenous or endogenous chromophore to an electronically excited state. These light mechanisms induced mortality.

Given that photo-oxidation affects *E. coli* disappearance rates, Chamberlin and Mitchell (1978) together with Mancini (1978) defined a light-dependent disappearance rate coefficient. An assumption made for this equation is that bacterial cell concentrations are uniform over depth.

$$k_P = k_l \, I_o \frac{1 - e^{-\alpha H}}{\alpha H} \tag{4.3}$$

Where:
k_P = attenuation rate for photo-oxidation day^{-1};
k_l = proportionality constant for the specific organism, cm^2/cal;
I_o = incident light energy at the surface, cal/cm^2-day;
α = light attenuation coefficient per meter depth;
H = depth of reservoir.

Gameson and Gould (1975) have established a k_l value of 0.362 cm^2/cal based on four field studies. The value of I_o (based on average daily amount of light energy received at the surface water) is derived by multiplying the average solar irradiance at the earth's surface (5.9 x 10^{-3} cal/cm^2 min, based on Singapore being in the 0 – 2.5 degree north category per Hanson, 1976) and the number of minutes of sunlight in a day (assumed 12 hours = 720 minutes of sunlight in a day). The resulting I_o is 260 cal/cm^2 for Singapore. During the water sampling program, TSS was not included in the analysis, however the related parameter turbidity was measured. In order to determine the TSS, a study by Xiang et al. (2011) approximated that TSS = 0.8*NTU (turbidity). The light attenuation coefficient α was approximated based on the total suspended solids concentration (TSS, mg/L) as α = TSS*0.55 (Di Toro et al., 1981, as cited by Chapra, 1997).

4.2.2 *E. coli* sedimentation attenuation rate

Sedimentation is the settling of bacterial particles due to adsorption to sediment particles. Sedimentation is important with regard to water column coliform levels (Bowie et al., 1985). Sedimentation has been regarded as a predominant mechanism of removal by Gannon et al. (1983) as documented in a field study of fecal coliform bacteria accumulating at the sediment surface of Ford Lake (Michigan). The field study showed that sedimentation greatly influences the disappearance of fecal coliform bacteria in the water column.

Zhang (2011) derived an expression for the sedimentation attenuation rate combining Chapra's (1997) equation and Sadat-Helbar's study (2009):

$$k_S = F_p \frac{V_s}{H} \tag{4.4}$$

Where:
F_P = fraction of *E. coli* attaching to particles;
V_s = settling velocity of particles;
H = depth of water body.

Using parameter values from Sadat-Helbar (2009), Equation 4.4 becomes:

$$k_S = 0.871 \text{ x } \frac{0.4}{H} = \frac{0.3484}{H} \tag{4.5}$$

4.2.2 *E. coli* natural mortality attenuation rate

The natural mortality rate of *E. coli* based on Mancini (1978) is a function of temperature and the salinity of the water.

$$k_M = (0.8+0.006 \text{ x } (\%\text{seawater})) \text{ x } 1.07^{(T-20)} \tag{4.6}$$

Where:
%seawater = percentage of seawater in the water;
T = temperature of the water, °C.

The percentage of seawater for each of the segments differed based on water quality data collected. The temperature of the water in the segments ranged from 27 – 28 degrees Celsius.

Chapter 5: Kallang River Basin WASP Model Development

5.1 Model Type

The fate and transport of *E. coli* is affected by four factors. These four factors are hydraulic transport, photo-oxidation, sedimentation and natural mortality of *E. coli*. In order to model all these factors related to *E. coli*, the model type chosen to characterize *E. coli* in the Kallang River Basin was "simple toxicant." *E. coli* is not really a simple toxicant but WASP's "simple toxicant" algorithms can be adapted to model *E.* coli. Since *E. coli* follows a first-order kinetics mechanism and a simple user-specified transformation rate can be inputted, WASP can become a first-order water pollutant model to simulate *E. coli* die-off and other fate and transport processes (Wool et al., 1995).

5.2 Model Segmentation

The WASP model follows a "box model" approach. WASP requires that the water body be divided into segments or boxes and each of these boxes is then treated as a fully-mixed tank. These segments can be modeled following the basic principle of the conservation of mass. A series of mass balance equations are employed in order to track and account for water volumes and water-quality constituent masses over time.

The segmentation of the Kallang River Basin was created by using the bathymetry of the Marina Reservoir (Figure 5.1). There are three tributaries that flow into the Kallang River Basin: the Geylang River (1), the Kallang River (2) and the Sungei Rochor Canal (3). Figure 5.2 and Figure 5.3 show zoomed-in views of how the Kallang River Basin was segmented.

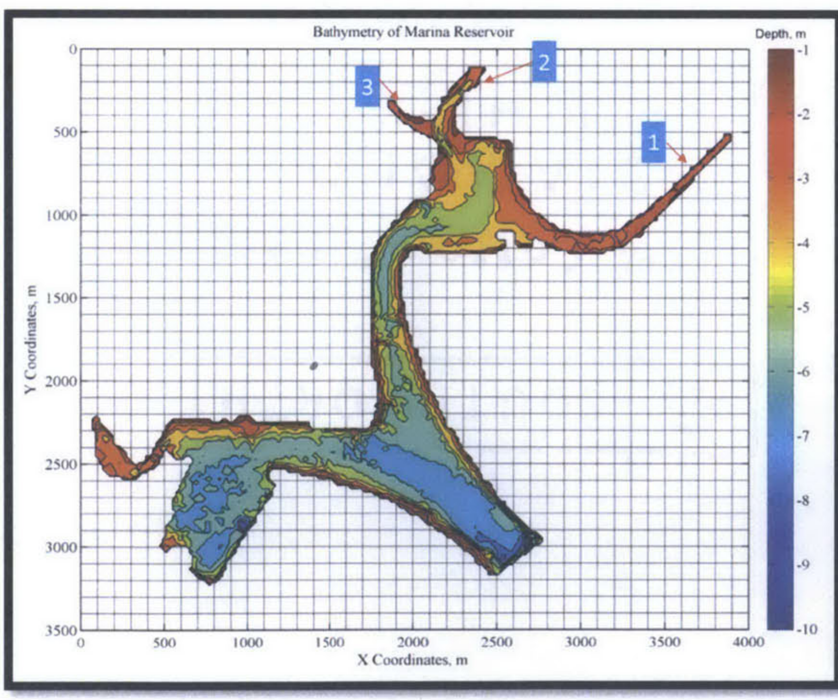

Figure 5.1: Bathymetry of Marina Reservoir (provided by PUB)

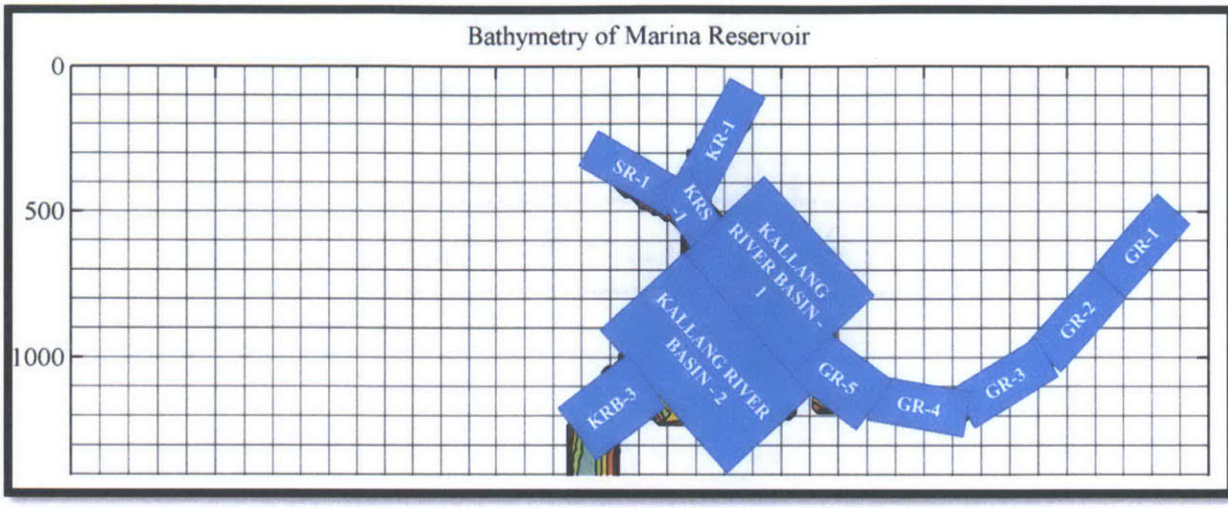

Figure 5.2: Segmentation of Kallang River Basin

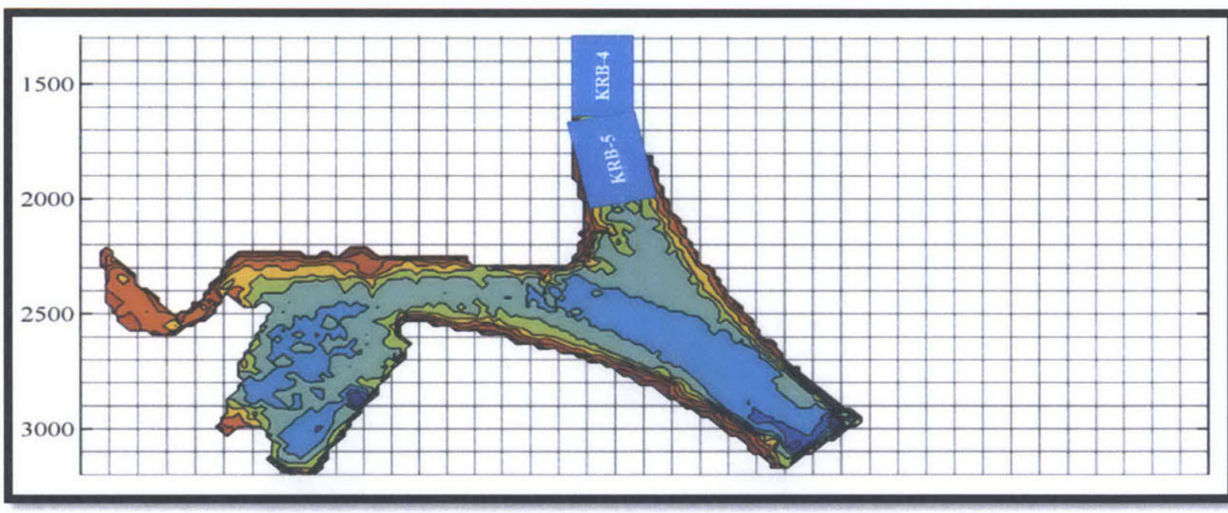

Figure 5.3: Segmentation of Kallang River Basin

The Peclet number (Pe) may be used to determine a reasonable number of segments (Shanahan and Harleman, 1984). In support of Shanahan and Harleman (1984), Levenspiel and Bischoff (1963), as cited by Shanahan and Harleman, 1984, related the analytical expression of dispersion with the variance of discharge concentration with time, which lead to the conclusion that the Peclet number is approximately related to the number of fully-mixed tanks (n) (Equation 5.2)

$$\mathrm{Pe} = \frac{QL}{AD} \tag{5.1}$$

$$\frac{1}{n} = \frac{2}{\mathrm{Pe}^2}\left(\mathrm{Pe} - 1 + e^{-\mathrm{Pe}}\right) \tag{5.2}$$

Where:
Q = flow rate through the reactor, m^3/s;
L = total length between the two closed ends of the reactor, m;
A = cross-sectional area of the reactor, m^2;
D = one-dimensional dispersion coefficient, m^2/s;
n = number of fully-mixed tanks.

The one-dimensional dispersion coefficient was assumed to be the same as the longitudinal dispersion coefficient for rivers and was calculated using Fischer's empirical equation (Fischer, 1975, as cited by Shanahan and Gaudet, 2000).

$$E_L = 0.011 \frac{U^2 \overline{W}^2}{du^*} \tag{5.3}$$

Where:
E_L = longitudinal dispersion coefficient
U = mean stream velocity, m/s;
$\overline{W}$ = total length between the two closed ends of the reactor, m;
d = mean depth level, m; and
u^* = shear velocity, m/s.

$$u^* = \sqrt{\frac{f}{8} U^2} \tag{5.4}$$

Where:
U = cross-sectionally averaged stream velocity, m/s; and
f = dimensionless friction factor approximately equal to 0.02 for natural fully turbulent flow.

These equations can be used to specify an appropriate number of model segments in each reach. For example, the Sungei-Rochor canal tributary has an approximate flow rate of 0.35 m^3/s, a length of 320 m, a cross-sectional area of 150 m^2, and a dispersion coefficient of 1.06 m^2/s. The resulting Peclet number is 0.7 or approximately 1. This value agreed with the one segment I used for the Sungei-Rochor canal (SR-1, refer to Table 5.1 for Peclet numbers).

Table 5.1: Peclet number of each part of the Kallang River Basin Model

Kallang River Basin Model Reach	Length (m)	Average Depth (m)	Peclet Number	Number of Segments Applied
Geylang River	1,700	2.4	1.3	5
Kallang River	350	2.5	0.4	1
Sungei-Rochor Canal	320	2.2	0.7	1
Kallang River Basin	2,000	4.2	0.4	5

For the Geylang River, the resulting Peclet number was approximately 1 which did not seem appropriately applicable for the segmentation of the Geylang River because unlike the Sungei-Rochor canal, the Geylang River has a longer reach (refer to table 5.1) with varying depths (the depths shown in the table are averaged). Because of this, I opted to segment the Geylang River into five box segments (this rationale was also applied to the Kallang River Basin). Other parts of the model were segmented as well with respect to the Peclet number but also taking into consideration its appropriate applicability to the water body.

5.3 Segment Definition

WASP requires the user to define parameters such as the length, width, depth, volume, and velocity of each model segment. The geometric parameters of each of the segments were determined by using a planimeter. The velocity and flow going through each of the segments were calculated based on flow data provided by NUS. For the Geylang River and Kallang River, the flow data provided were for October 2013 and January 2014, and these flows were averaged. For the Sungei-Rochor canal, the flow data provided was for October 2013 and was averaged as well. A summary of all the required parameters is presented in Table A.2 to Table A.6 of Appendix A.

5.4 Simulation Date and Time Step

The simulation start date for the model was set to August 9, 2013 because the initial concentrations for the segments were calculated based on August 2013 data (Table A.2 of Appendix A) provided by NUS. The simulation end date was on January 9, 2014 because that was the end date of the sampling period for the Kallang River Basin as previously mentioned in Chapter 3.

For the simulation time step, WASP already specifies a minimum time step of 0.0001 day. This minimum time step is the default because it provides the model with a wide enough range to calculate a suitable time step (which the program calculates by itself) (Wool et al., 1995). For the maximum time step (maximum time step was also used as the print interval and actual time step), I used a value of 0.1 day which is about every 2 hours in a day. I used that time step because as previously mentioned, samples were collected every 4 hours for 2 days and I wanted to simulate the data to correspond to the 4-hour interval and to determine *E. coli* behavior in between those intervals.

5.5 Dispersion

Two mechanisms are most responsible for the mixing of a mass of material or pollutant in a river. The first mechanism is due to flow velocity varying throughout the river causing the mass to be dispersed (advective dispersion). The second mechanism, which is turbulent diffusion, moves the mass of the material among zones of varying velocity in order to ensure that none of the material stays indefinitely in one zone. The combination of these two mechanisms is called longitudinal dispersion (Shanahan and Gaudet, 2000). In the WASP model, longitudinal dispersion is modeled through exchange flow between adjacent segments which is represented in the model by "surface-water exchange." The value for the dispersion through the segments was assumed to be the same as the longitudinal dispersion coefficient calculated in section 5.2.

$$\frac{\partial M_{ik}}{\partial t} = \frac{E_{ij}(t) * A_{ij}}{L_{cij}} (C_{jk}-C_{ik}) \tag{5.5}$$

Where:
M_{ik} = mass of chemical "k" in segment "i," g;
Cik, Cjk = concentration of chemical "k" in segments "i" and "j," g/m^3;
$Eij(t)$ = dispersion coefficient time function for exchange "ij", m^2/day;
$Lcij$ = characteristic mixing length between segments "i" and "j," m;
Aij = interfacial area shared by segments "i" and "j," m^2.

5.6 Flows

As mentioned earlier, the Kallang River Basin receives water from three tributaries: the Geylang River, the Kallang River, and the Sungei Rochor Canal (Figure 5.4). For the Geylang River (0.53 m^3/s), Kallang River (3.63 m^3/s), and Sungei-Rochor canal (0.35 m^3/s) the flow data was averaged. Further dissecting the flow, Figure 5.5 presents how the flow is routed through the segments.

Figure 5.4: Flow values

Figure 5.5: WASP Model Flow Sequence

WASP models the flow through the segments by "fraction of flow" which is the percentage of the total flow going through the segment. As presented in Figure 5.4, the total flow for the system is 4.61 m^3/s and this will be divided through the system. Table 5.1 presents the fraction of flow of each segment.

Table 5.2: Fraction of flow through each segment

From	To	Fraction of Flow
Boundary	SR-1	0.07
Boundary	KR-1	0.79
Boundary	GR-1	0.14
KR-1	KS-1	0.79
SR-1	KS-1	0.07
GR-1	GR-2	0.14
GR-2	GR-3	0.14
GR-3	GR-4	0.14
GR-4	GR-5	0.14
GR-5	KRB-1	0.14
KS-1	KRB-1	0.86
KRB-1	KRB-2	1
KRB-2	KRB-3	1
KRB-3	KRB-4	1
KRB-4	KRB-5	1
KRB-5	Boundary	1

5.7 Boundaries and Loadings

"Boundary segments" in WASP represent water and pollutant exchanges with sources outside of the network. Boundary segments of *E. coli* loading may vary with time depending on the loading characteristics of the sour. Boundary loadings were specified based on the initial concentrations calculated from the data provided by NUS (Table A.10 in Appendix A). Boundary loadings are represented in WASP as:

$$S_{Bi} * V_i = Q_{i0} * C_{Bi} + L_i \tag{5.7}$$

Where:
S_{Bi}= boundary loading rate response of *E. coli* in boundary segment *i*, MPN/m^3;
V_i= volume of boundary segment *i*, m^3;
Q_{i0}= inflow from outside the network, m^3/day;
C_{Bi}= concentration *of E. coli* in the inflow water, MPN/m^3; and
L_i= point source and non-point source loading rate, MPN/day.

Other than boundary loadings, loadings contributed by point and non-point sources (e.g. farms and industrial discharge) may be included in the model (Wool *et al.*, 1995). Loadings due to the point and non-point sources were not included in this model due to the lack of information for the Kallang River Basin.

5.8 *E. coli* decay rate

For this model, a total lumped first-order decay rate was used for each of the segments. Recalling the attenuation model for *E. coli* from Chapter 4, the photo-oxidation decay rate, the sedimentation rate, and the natural mortality rate compose the total lumped first-order decay rate (effective attenuation rate). Table 5.2 presents the resulting attenuation rates for each of the segments.

$$k_E = 0.5k_P + k_S + k_M \tag{5.9}$$

Where:
k_E = effective attenuation rate of *E. coli*, day^{-1};
k_P = attenuation rate for photo-oxidation, day^{-1};
k_S = attenuation rate for sedimentation, day^{-1};
k_M = attenuation rate for natural mortality, day^{-1}..

Table 5.3: Decay rate coefficients for the segments

Segment	Depth (m)	k_p (day^{-1})	k_s (day^{-1})	k_m (day^{-1})	k_E (day^{-1})
GR-1	2.0	5.5	0.2	1.3	4.2
GR-2	2.1	5.4	0.2	1.3	4.2
GR-3	2.6	4.3	0.1	1.3	3.6
GR-4	2.4	4.6	0.1	1.3	3.7
GR-5	3.0	3.7	0.1	1.3	3.3
KR-1	2.5	4.9	0.1	1.4	3.9
SR-1	2.2	5.6	0.2	1.4	4.3
KRB-1	4.1	2.9	0.1	1.3	2.8
KRB-2	4.1	2.9	0.1	1.3	2.8
KRB-3	4.3	2.8	0.1	1.3	2.8
KRB-4	4.4	2.7	0.1	1.3	2.7
KRB-5	4.1	2.9	0.1	1.3	2.8
KS-1	3.3	3.7	0.1	1.3	3.3

Chapter 6: Model Simulation Results and Accuracy Evaluation

6.1 Model Simulation Results

For the first WASP simulation, which is represented by Figure 6.1, the goal was to determine how *E. coli* concentrations would vary over time for each of the segments and whether concentrations were getting better (decrease in concentrations) or worse (increase in concentrations in the segments). The first simulation predicts *E. coli* concentrations over a time period from August 9, 2013 (based on the initial concentrations calculations) to January 9, 2014 (ending of the sampling period). The first simulation was also used to determine if segments were complying with EPA standards. As previously mentioned in Chapter 2, Section 2.1.1, the maximum level of *E. coli* concentration in recreational waters should be less than 126 MPN/ 100ml.

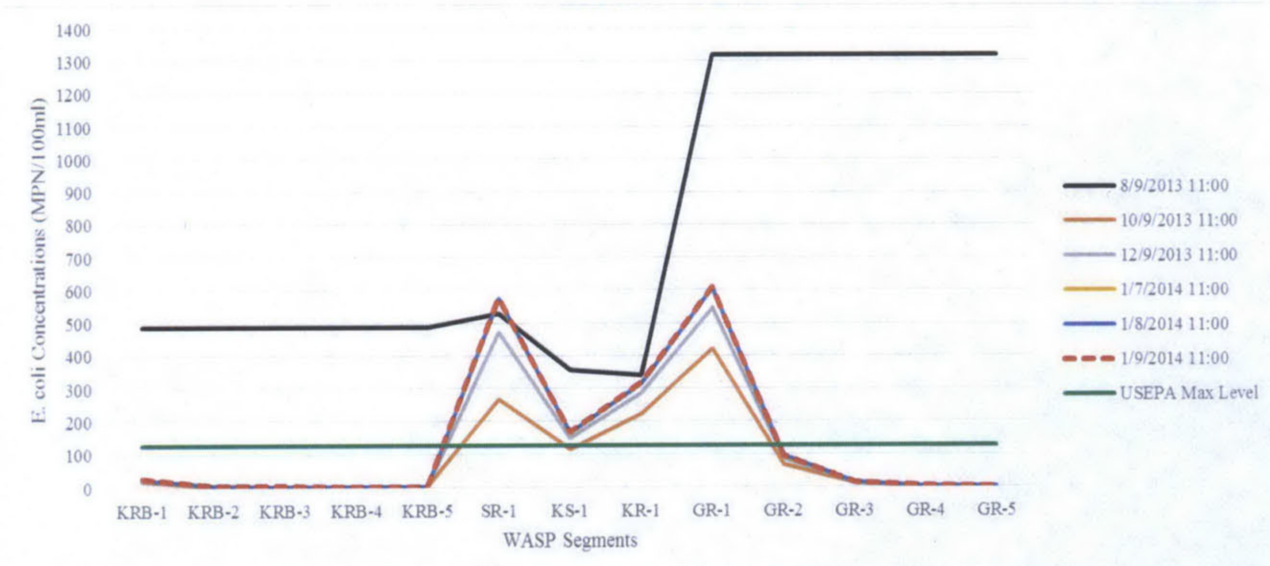

Figure 6.1: *E. coli* concentrations of the different segments over time

Analyzing the results from the first simulation, *E. coli* concentrations in segments SR-1, KR-1, GR-1, and KS-1 are seen to be increasing over time. Referring to Table 6.1a (SR-1), there was an increase of 200 MPN/100ml from 10/9/2013 to 12/9/2013 (from 270 to 470 MPN/100ml). For KR-1 (Table 6.1b), there was also an increase of 60 MPN/100ml in the same time two-month span and for the other two segments as well (GR-1, KS-1 in Table 6.1c and 6.1d). The increase of *E. coli* concentrations suggests that given an increasing steady amount of *E. coli* concentration being introduced into the water body from the boundary loadings, decay due to photolysis, sedimentation, and natural mortality are insufficient to decrease *E. coli* concentrations within tolerable levels (EPA recreational standard). Recalling the maximum level of 126 MPN/ 100ml for *E. coli* concentrations (represented by the green line on Figure 6.1), the Kallang River (KR-1), the Sungei-Rochor Canal (SR-1), the Kallang-Sungei intersection (KS-1) and part of the Geylang River (GR-1) are over the maximum level of *E. coli* concentrations. The KR-1, SR-1, KS-1, and GR-1 are then not recommended spots for recreational activities. For the other parts of the Geylang River namely, GR-2, GR-3, GR-4, and GR-5, they are within the 126 MPN/ 100ml level of *E. coli* and may be used for recreational activities but it still is important to note that *E. coli concentrations* in these segments are increasing over time (refer to Table A.8 in Appendix A).

Table 6.1: Predicted *E. coli* concentrations over time for SR-1, KR-1, GR-1, and KS-1

a. Segment SR-1

SR-1	
Date	***E. coli (MPN/100ml)***
10/9/2013	270
12/9/2013	470
1/7/2014	570
1/8/2014	573
1/9/2014	576

b. Segment KR-1

KR-1	
Date	***E. coli (MPN/100ml)***
10/9/2013	220
12/9/2013	280
1/7/2014	313
1/8/2014	314
1/9/2014	315

c. Segment GR-1

GR-1	
Date	***E. coli (MPN/100ml)***
10/9/2013	420
12/9/2013	550
1/7/2014	604
1/8/2014	606
1/9/2014	608

d. Segment KS-1

KS-1	
Date	***E. coli (MPN/100ml)***
10/9/2013	110
12/9/2013	150
1/7/2014	165
1/8/2014	166
1/9/2014	166

Focusing on the Kallang River Basin segments, both segments KRB-1 and KRB-2 (these segments are the main focus of the study) are under the 126 MPN/100 ml standard for recreational waters (refer to Figure 6.2 and Table 6.2a and 6.2b). Similar to the segments analyzed above, *E. coli* concentrations continue to rise as time passes (reasons similar as previously mentioned). At the start of the graph, it is seen that there is an abrupt decrease from an initial concentration of about 500 MPN/100ml to about 20 MPN/100ml. This abrupt decrease is due to the *E. coli* attenuation rate for the KR-1 and KR-2 segment. The decay rate of *E. coli* is greater than the incoming steady concentration of *E. coli*. The *E. coli* concentrations of KRB-3 to KRB-5 can be located in Appendix A (Table A.9).

Table 6.2: Predicted *E. coli* concentrations over time for KRB-1 and KRB-2

a. Segment KRB-1

KRB-1	
Date	***E. coli (MPN/100ml)***
10/9/2013	16.6
12/9/2013	21.9
1/7/2014	24.4
1/8/2014	24.5
1/9/2014	24.6

b. Segment KRB-2

KRB-2	
Date	***E. coli (MPN/100ml)***
10/9/2013	2.34
12/9/2013	3.10
1/7/2014	3.45
1/8/2014	3.47
1/9/2014	3.48

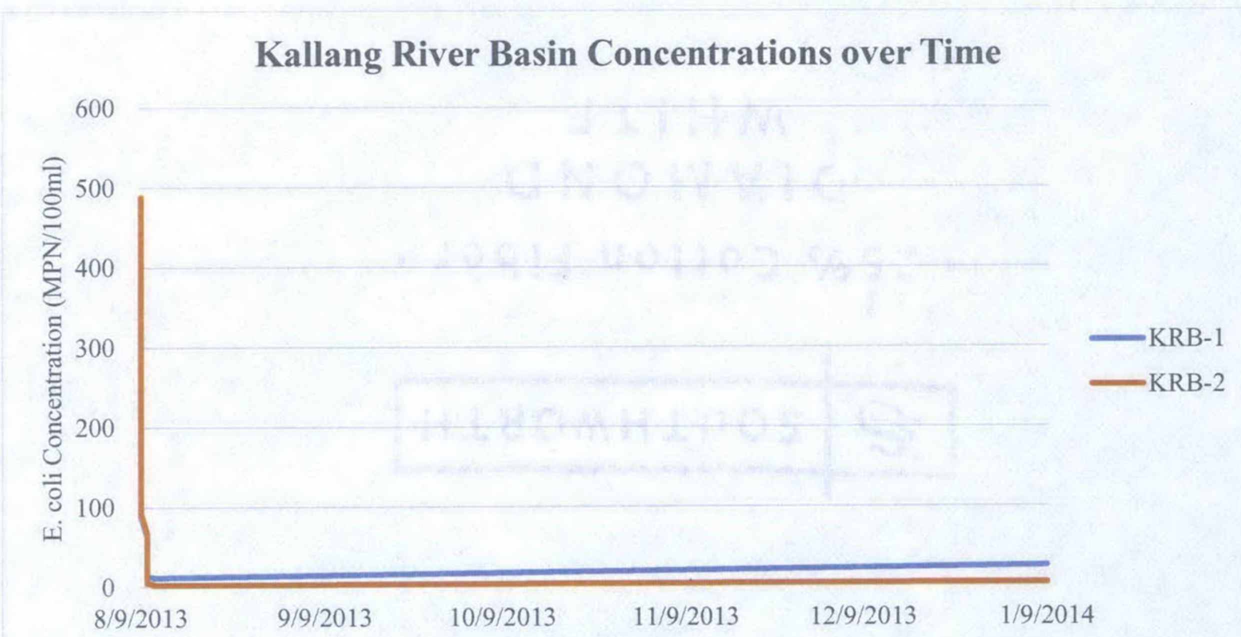

Figure 6.2: *E. coli* concentrations of the Kallang River Basin Segment 1 & 2

6.2 Model Accuracy Evaluation

In order to determine whether the model reasonably predicts *E. coli* concentrations for the Kallang River Basin, I plotted the results from the simulation during the same time period of the sampling event in January (January 7, 2014 11:00 AM to January 9, 2014 7:00 AM). Analyzing the graph (Figure 6.3) for Station 2 – Jalan Benaan Kepal (Station 2 refers to the Geylang River which is within model segment GR-1), the results of the simulation concentrations (orange line) fall within the range of the actual *E. coli* concentrations (blue line) from the sampling period. With respect to diurnal patterns of the station, one reason why the simulation result curve does not follow the pattern of the actual *E. coli* concentration curve is because the model does not include loadings contributed by point and non-point sources. As previously mentioned, point and non-point source loading concentrations vary with time and if these loadings were inputted, it may have resulted in a better fit of the simulation results to the pattern of the actual field results. A second possible explanation of the differences between actual and simulation *E. coli* concentrations is the water sampling depth. The samples were taken from the surface of the water body which may have not been fully mixed with the water from other depths.

The simulation results for the other two sampling stations are shown in Figure 6.4 for Station 3 – Kallang Riverside Park (KR-1 segment) and Figure 6.5 for Station 5 – Crawford Street (SR-1 segment). Model results for these segments also fell within the range of their respective actual concentrations. All the simulation results for the stations were unable to capture the diurnal patterns but they were within the range of actual *E. coli* concentration values.

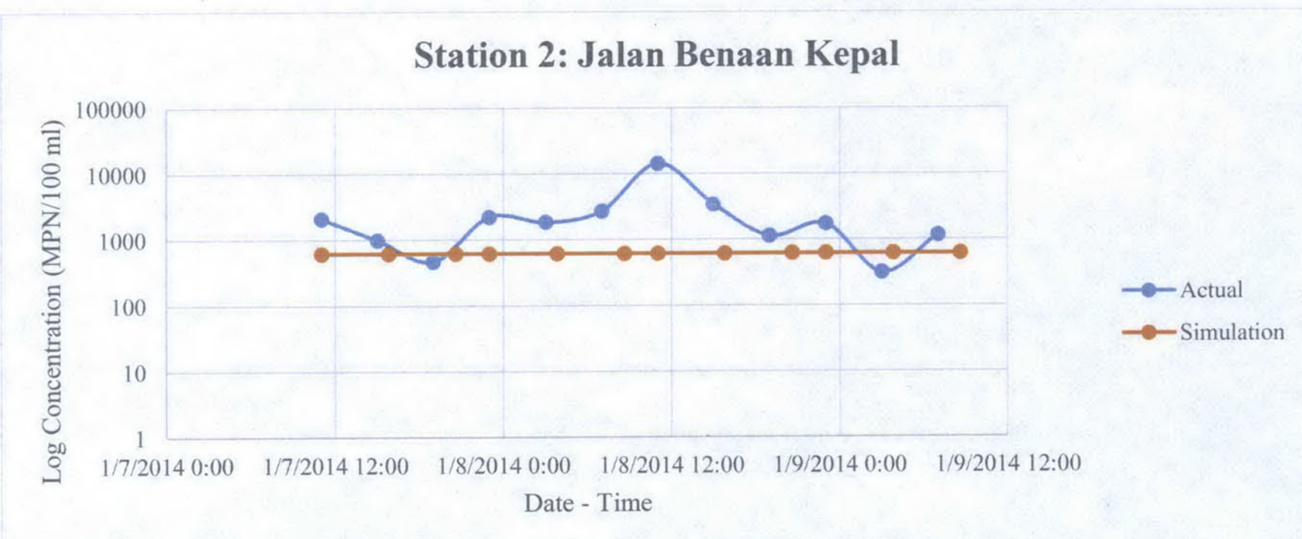

Figure 6.3: Actual *E. coli* concentrations for Station 2 vs Simulation results for Segment GR-1

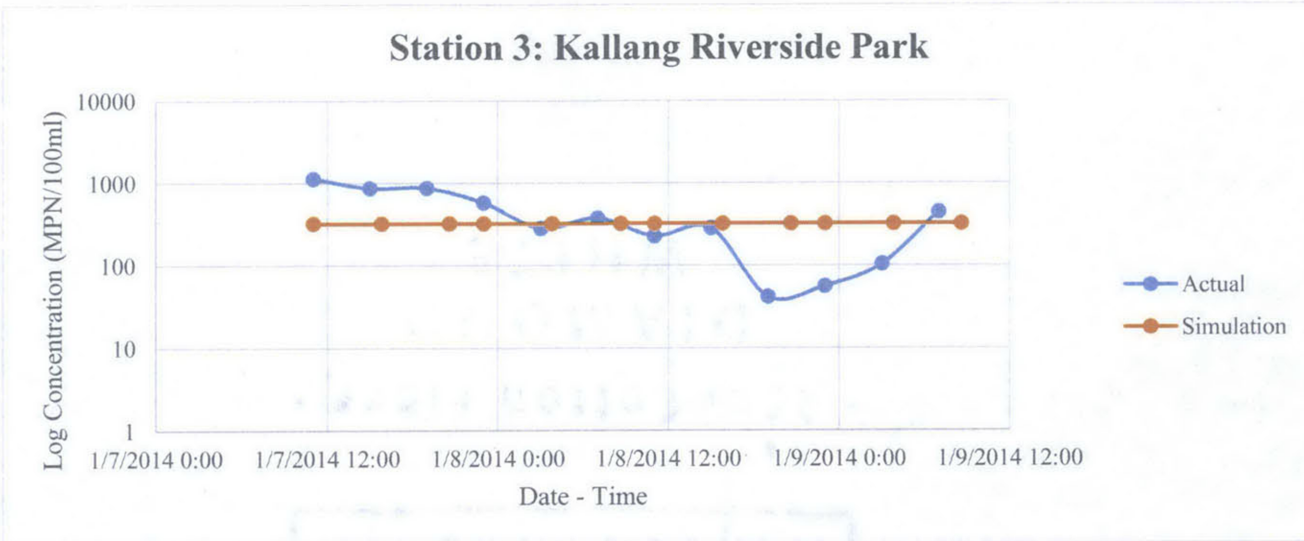

Figure 6.4: Actual *E. coli* concentrations for Station 3 vs Simulation results for Segment KR-1

Figure 6.5: Actual *E. coli* concentrations for Station 5 vs Simulation results for Segment SR-1

Chapter 7: Limitations

7.1. Limitations of the Model

The results of the simulation in Chapter 6 indicate that the model is able to predict *E. coli* concentrations within an order of magnitude of actual field data *E. coli* concentrations; however, the model did not capture the variations over time due to certain limitations which will be discussed in this chapter.

The first limitation of the model is the *E. coli* decay rate. The model uses a total lumped sum *E. coli* decay coefficient comprised of photolysis, sedimentation, and natural mortality (refer to Equation 4.2). Why the total lumped sum decay rate coefficient is a limitation is because there is no distinction between a daytime decay rate of *E. coli* and a possible decay or growth rate of *E. coli* at night. This distinction between the day and night rates could account for some of the diurnal variation that is presented in the field data.

The second limitation of the model is the non-inclusion of point and non-point sources of loading. The *E. coli* loading in the model only comes from the three tributaries (Geylang River, Kallang River, and Sungei-Rochor Canal) flowing into the Kallang River Basin. The Geylang River field data (Table 7.1) shows what seem to be surges of *E. coli* coming into the Geylang River between 19:00 and 23:00 on January 7, between 3:00 and 7:00 on January 8, and between 7:00 and 11:00 on January 8. An interesting point in time in the field data, as seen in Figure 7.1, is at 1/8/2014, 11:00 because of its very high concentration. The value of the *E. coli* concentration at this point (14,316 MPN/ 100ml) is much higher than other values and is an order of magnitude greater than other *E. coli* concentrations. These surges and the occurrence of a very high *E. coli* concentration are likely due to point and non-point sources which need to be identified so that the diurnal variations may be captured.

Table 7.1: Field Sampling Data for Station 2

Station 2	
Date - Time	**MPN / 100ml**
1/7/2014 11:00	2098
1/7/2014 15:00	985
1/7/2014 19:00	465
1/7/2014 23:00	2224
1/8/2014 3:00	1842
1/8/2014 7:00	2723
1/8/2014 11:00	14316
1/8/2014 15:00	3441
1/8/2014 19:00	1133
1/8/2014 23:00	1726
1/9/2014 3:00	314
1/9/2014 7:00	1160

Figure 7.1: Field data results for *E. coli* concentrations in Station 2 (GR-1 segment)

The third limitation of the model is that the boundary loadings from the three tributaries are assumed to be linearly increasing or decreasing with time. The initial concentrations (August 2013 concentrations) and present concentrations (January 2014) used for the loading of the tributaries for the simulation were based on the data provided by NUS. The model does a linear interpolation (be it increasing or decreasing from initial to present concentrations) of the amount of *E. coli* contributed by the boundary loadings. Based on the data of the Geylang River station (Figure 7.1), there is extensive variation of *E. coli* concentration at different points in time (increasing and decreasing) over the 48-hour sampling period. The other stations as well have their own distinct behavior (presented in Figures 7.2 and 7.3). These variations need to be quantified and understood in order to come up with the actual behavior of loading from the different sources.

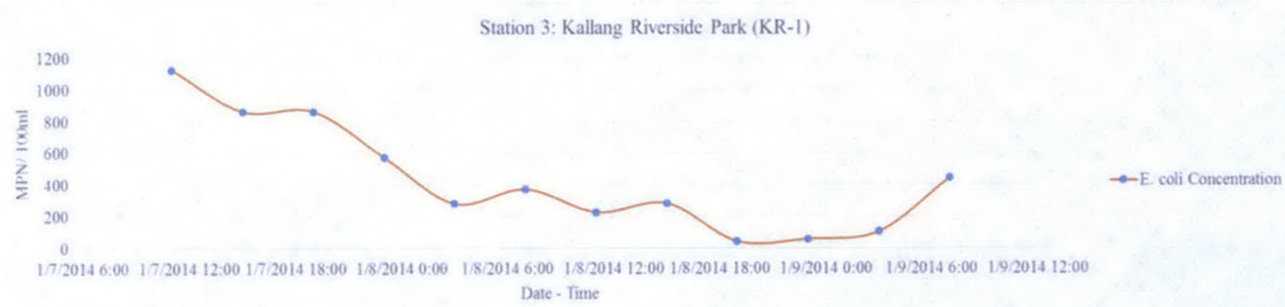

Figure 7.2: Field data results for *E. coli* concentrations in Station 2 (KR-1 segment)

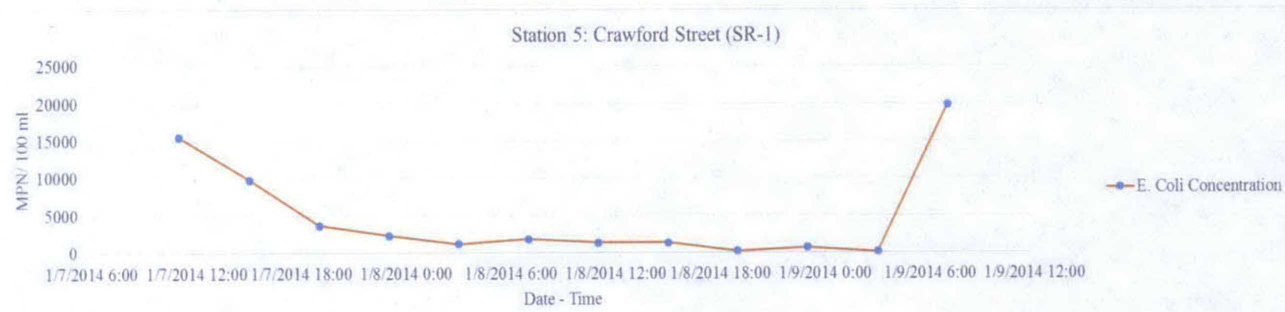

Figure 7.3: Field data results for *E. coli* concentrations in Station 2 (SR-1 segment)

Chapter 8: Simulation Findings, Conclusion and Recommendation

8.1 Kallang River Basin WASP Model Simulation Findings

Given the limitations and conditions discussed in Chapter 6 and 7, the following is a summary of the findings and results of the simulation:

1. With regard to determining whether the Kallang River Basin is safe for recreational activities or not, it was found through the simulation that *E. coli* concentrations in the KRB-1 and KRB-2 segments (representative segments of the Kallang River Basin) are below the 126 MPN/100ml maximum *E. coli* level stipulated by the U.S. EPA for recreational waters. Two of the three tributaries, the Sungei-Rochor canal and Kallang River, are above the 126 MPN/100ml level and recreational activities are not recommended there. For the Geylang River, segment GR-1, which is at field sampling Station 2, is above the maximum level but the other segments GR-2 to GR-5, which are closer to the KRB, could be used for recreational activities (refer to Figure 8.1).

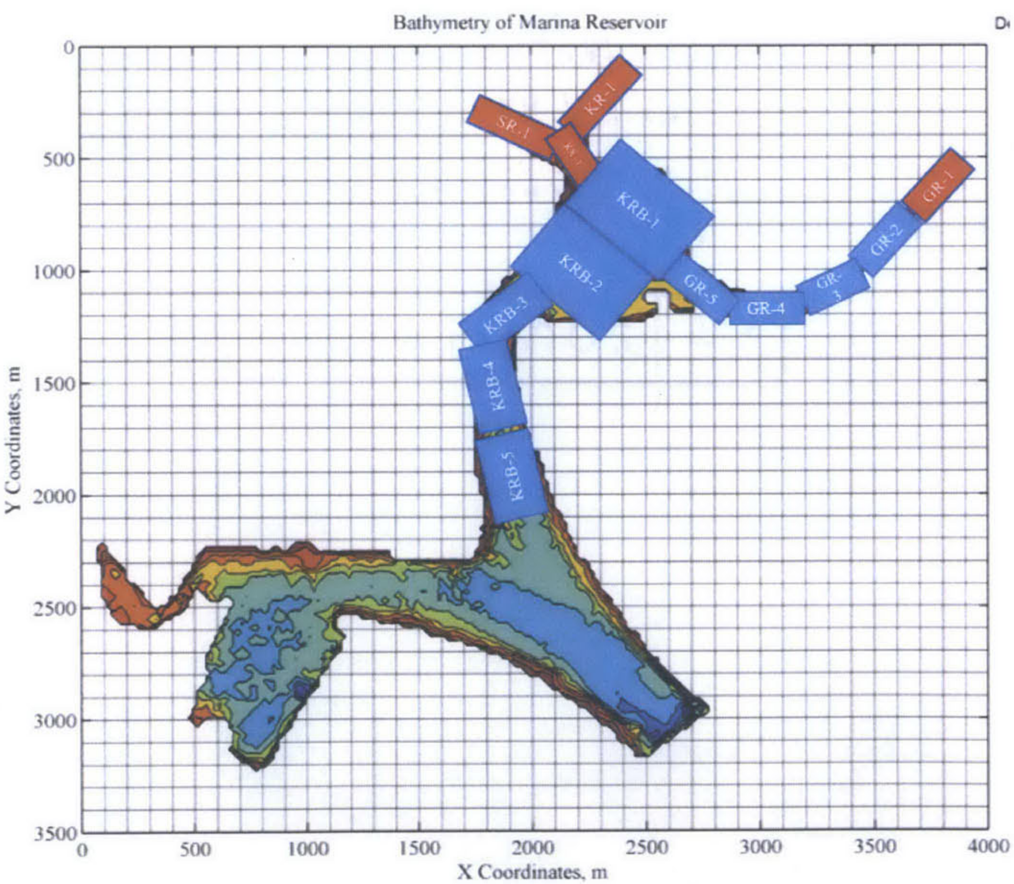

Figure 8.1: Segments with *E. coli* concentrations under 126 MPN/ 100ml (blue boxes) and over 126 MPN/ 100ml (red boxes).

2. The *E. coli* concentrations of the segments increase with time as presented in Chapter 6, thus there is a need to control the amount of *E. coli* loading from the tributaries running into the Kallang River Basin.
3. The WASP model predicts *E. coli* concentrations within the range (order of magnitude) of actual sampled *E. coli* concentrations.

8.2 Conclusion

The WASP model created in this study for the Kallang River Basin serves as a heuristic exercise to determine whether modeling is possible or not for the water body. The WASP model predicts *E. coli* concentrations within the range (order of magnitude) of actual concentrations and this suggests that it is feasible to model the Kallang River Basin. The model may be regarded as a preliminary model wherein there are several aspects of the model that need further improvement. Those aspects such as the diurnal variations, the point and non-point source loadings, and others (refer to Chapters 5 and 7) need to be researched and experimented with in order to come up with a more complete and realistic model for the Kallang River Basin.

8.3 Recommendations

With respect to diurnal variations, I recommend that there be further study into the boundary loadings and point and non-point source loadings of the Kallang River Basin. Further study into diurnal concentration loading from the three tributaries should be analyzed in order to improve the accuracy of the model. In order to do this, the sampling period could be increased from 48 hours to a greater period of time. This will better characterize loading of the tributaries and may also show insight into possible external loadings. As previously mentioned, each of the tributaries have their distinct loading patterns and at some points in time, there were *E. coli* concentrations that deviated as much as an order of magnitude (refer to Chapter 7). These sudden and large increases in *E. coli* concentration may be attributed to external sources (point and non-point) such as stormwater, sewer, and industrial discharges.

With respect to the *E. coli* attenuation rate, I recommend that there be further study into the actual *E. coli* decay rates of the tributaries and the Kallang River Basin because the *E. coli* decay rates used for this study were derived from theoretical formulas using water quality parameters. A study should be designed to determine an accurate *E. coli* decay rate. Also, a total lumped sum *E. coli* attenuation rate was used for this study and because of this, I recommend that further investigation should be done to determine if there is a night and day *E. coli* decay rate coefficient or possibly an *E. coli* growth rate coefficient during the night (refer to Chapter 7). This could also be studied by increasing the sampling period duration.

The sampling method for water could also be improved since the water collected was from a shallow water depth (at the surface of the water). The water collected at the surface of the river may not be very representative of the whole river. Water sampling at different depths can give a better view as to how much *E. coli* are present. Also, other indicator bacteria or organisms (e.g. Enterococci), viruses, and pathogens could also be used and analyzed to determine the water quality of the Kallang River Basin.

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APPENDIX

Table A.1 Laboratory results

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
7/1/2014	11:00 AM	2 (Jalan Benaan Kapal)	10	48	14	146	210	301	1,455	2,098	3,011
		3 (Kallang Riverside Park)	5	46	23	170	225	296	848	1,127	1,481
		4 (Upper Boon Keng Road)	10	49	23	261	411	619	2,606	4,106	6,189
		5 (Crawford Street)	10	49	44	1,016	1,553	2,353	10,162	15,531	23,531

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
7/1/2014	3:00 PM	2 (Jalan Benaan Kapal)	10	40	10	72	99	132	722	985	1,321
		3 (Kallang Riverside Park)	5	45	18	126	173	229	632	863	1,143
		4 (Upper Boon Keng Road)	10	43	6	75	105	144	748	1,050	1,439
		5 (Crawford Street)	10	49	38	661	980	1,410	6,606	9,804	14,102

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
7/1/2014	7:00 PM	2 (Jalan Benaan Kapal)	10	27	6	32	47	65	323	465	647
		3 (Kallang Riverside Park)	5	46	15	123	173	236	615	863	1,178
		4 (Upper Boon Keng Road)	10	39	6	60	84	114	596	836	1,138
		5 (Crawford Street)	10	49	21	232	365	556	2,319	3,654	5,555

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
7/1/2014	11:00 PM	2 (Jalan Benaan Kapal)	10	47	19	159	222	303	1,585	2,224	3,033
		3 (Kallang Riverside Park)	5	43	9	82	115	156	408	573	778
		4 (Upper Boon Keng Road)	10	36	6	51	72	98	511	717	975
		5 (Crawford Street)	10	47	20	169	231	316	1,692	2,310	3,155

Table A.1 Laboratory results

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	3:00 AM	2 (Jalan Benaan Kapal)	10	46	17	135	184	251	1,349	1,842	2,514
		3 (Kallang Riverside Park)	5	29	9	40	56	76	200	281	380
		4 (Upper Boon Keng Road)	10	41	5	65	91	124	646	906	1,241
		5 (Crawford Street)	10	44	8	85	119	163	847	1,187	1,627

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	7:00 AM	2 (Jalan Benaan Kapal)	10	48	20	184	272	383	1,835	2,723	3,829
		3 (Kallang Riverside Park)	5	35	9	53	74	99	265	372	494
		4 (Upper Boon Keng Road)	10	42	8	75	105	142	746	1,046	1,421
		5 (Crawford Street)	10	46	17	135	184	251	1,349	1,842	2,514

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	11:00 AM	2 (Jalan Benaan Kapal)	10	49	43	925	1,432	2,102	9,249	14,316	21,016
		3 (Kallang Riverside Park)	5	25	8	31	45	63	157	226	313
		4 (Upper Boon Keng Road)	10	27	3	28	42	60	283	420	597
		5 (Crawford Street)	10	45	10	97	135	184	965	1,354	1,840

Table A.1 Laboratory results

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	3:00 PM	2 (Jalan Benaan Kapal)	10	48	25	245	344	473	2,453	3,441	4,725
		3 (Kallang Riverside Park)	5	31	6	39	56	78	196	282	388
		4 (Upper Boon Keng Road)	10	32	6	42	59	81	421	591	812
		5 (Crawford Street)	10	44	12	95	133	178	951	1,334	1,779

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	7:00 PM	2 (Jalan Benaan Kapal)	10	37	22	87	113	144	874	1,133	1,442
		3 (Kallang Riverside Park)	1	26	4	28	41	59	28	41	59
		4 (Upper Boon Keng Road)	10	18	4	17	27	40	171	269	398
		5 (Crawford Street)	10	11	10	16	24	35	155	237	350

			Colilert			95% Confidence Limit			FINAL MPN COUNT		
Date	Time	Stations	Dilution	Big Wells	Small Wells	MPN LOWER	MPN ACTUAL	MPN UPPER	MPN LOWER	MPN ACTUAL	MPN UPPER
8/1/2014	11:00 PM	2 (Jalan Benaan Kapal)	10	45	18	126	173	229	1,264	1,726	2,285
		3 (Kallang Riverside Park)	1	32	4	39	56	77	39	56	77
		4 (Upper Boon Keng Road)	10	19	0	14	23	36	144	233	361
		5 (Crawford Street)	10	34	8	51	69	94	505	689	938

Table A.2 Initial Concentrations in August 2013

	Sungei-Rochor	Kallang River	Geylang River
E. coli			
Detection Rate (%)	100%	100%	100%
Min (MPN/100ml)	4	13	9
Max (MPN/100ml)	24190	9804	24196
Mean (MPN/100ml)	528	339	1320

Table A.3 Geylang River Segment Properties

GEYLANG RIVER

Segment Code	Segment Name	Length (m)	Width (m)	Surface Area (m^2)	Depth (m)	Volume (m^3)	Velocity (m/s)
GR-1	Geylang River - 1	410	55	23000	2	46000	0.006
GR-2	Geylang River - 2	470	78	36000	2	75000	0.004
GR-3	Geylang River - 3	320	110	35000	3	90000	0.002
GR-4	Geylang River - 4	280	140	38000	3	92000	0.002
GR-5	Geylang River - 5	250	220	54000	3	170000	0.001
	Total Length (m)	1730		**Average Flow**	**0.63**	m^3/s	

Table A.4 Sungei-Rochor Canal Segment Properties

SUNGEI-ROCHOR

Segment Code	Segment Name	Length (m)	Width (m)	Surface Area (m^2)	Depth (m)	Volume (m^3)	Velocity (m/s)
SR-1	Sungei Rochor Canal - 1	320	68	22000	2	48000	0.002
	Total Length (m)	320		**Average Flow**	**0.35**	m^3/s	

Table A.5 Kallang River Segment Properties

KALLANG RIVER

Segment Code	Segment Name	Length (m)	Width (m)	Surface Area (m^2)	Depth (m)	Volume (m^3)	Velocity (m/s)
KR-1	Kallang River - 1	350	100	35000	3	87000	0.014
	Total Length (m)	350		**Average Flow**	**3.63**	m^3/s	

Table A.6 Kallang River + Sungei Rochor Canal Segment Properties

K+S

Segment Code	Segment Name	Length (m)	Width (m)	Surface Area (m^2)	Depth (m)	Volume (m^3)	Velocity (m/s)
KS-1	Kallang Sungei -1	200	170	33000	3	110000	0.007
	Total Length (m)	200		**Average Flow**	**3.98**	**m^3/s**	

Table A.7 Kallang River Basin Segment Properties

KALLANG RIVER BASIN

Segment Code	Segment Name	Length (m)	Width (m)	Surface Area (m^2)	Depth (m)	Volume (m^3)	Velocity (m/s)
KRB-1	Kallang River Basin -1	400	410	170000	4	680000	0.003
KRB-2	Kallang River Basin -2	460	460	210000	4	860000	0.002
KRB-3	Kallang River Basin -3	310	190	57000	4	240000	0.006
KRB-4	Kallang River Basin -4	420	200	84000	5	370000	0.005
KRB-5	Kallang River Basin -5	430	300	130000	4	530000	0.004
	Total Length (m)	**2020**		**Average Flow**	**4.51**	**m^3/s**	

Table A.8 GR-2 to GR-5 *E. coli* concentrations

GR-2	
Date	***E. coli (MPN/100ml)***
10/9/2013	64.2
12/9/2013	83.1
1/7/2014	92.1
1/8/2014	92.4
1/9/2014	92.7

GR-3	
Date	***E. coli (MPN/100ml)***
10/9/2013	9.43
12/9/2013	12.22
1/7/2014	13.54
1/8/2014	13.59
1/9/2014	13.64

GR-4	
Date	***E. coli (MPN/100ml)***
10/9/2013	1.330
12/9/2013	1.723
1/7/2014	1.910
1/8/2014	1.916
1/9/2014	1.923

GR-5	
Date	***E. coli (MPN/100ml)***
10/9/2013	0.1267
12/9/2013	0.1600
1/7/2014	0.1820
1/8/2014	0.1826
1/9/2014	0.1833

Table A.9 KRB-3 to KRB-5 *E. coli* concentrations

KRB-3	
Date	***E. coli (MPN/100ml)***
10/9/2013	0.874
12/9/2013	1.156
1/7/2014	1.290
1/8/2014	1.294
1/9/2014	1.299

KRB-4	
Date	***E. coli (MPN/100ml)***
10/9/2013	0.247
12/9/2013	0.327
1/7/2014	0.365
1/8/2014	0.366
1/9/2014	0.367

KRB-5	
Date	***E. coli (MPN/100ml)***
10/9/2013	0.052
12/9/2013	0.069
1/7/2014	0.077
1/8/2014	0.078
1/9/2014	0.078

Table A.10 Boundary Loading *E. coli* concentrations

Geylang River		
Date	**Time**	***E.coli* Loading (MPN/100ml)**
8/9/2013	11:00	1,300
1/9/2014	11:00	2,700

Sungei-Rochor Canal		
Date	**Time**	***E.coli* Loading (MPN/100ml)**
8/9/2013	11:00	528
1/9/2014	11:00	4,800

Kallang River		
Date	**Time**	***E.coli* Loading (MPN/100ml)**
8/9/2013	11:00	340
1/9/2014	11:00	660