Faculty of Resource Science and Technology

HYDROLOGY MODEL OF EXTENSIVE GREEN ROOF

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ABSTRACT

Storm water runoff in urbanised watershed such as roof top is fast flowing and overloading urban drainage system over time, causing flash flood. One of the source controls for this fast run off is installation of extensive green roof to the existing concrete flat roof. Green roof is a close mimic of a natural watershed and has the effect of slowing storm water runoff in comparison with a conventional concrete flat roof. This dissertation relates the green roof runoff response to control system in order to understand the delay response of an extensive green roof in comparison with a conventional concrete flat roof. The averaged time delay for the runoff to reach peak value (99.33 percents) between the conventional concrete roof and the green roof are 244.4 seconds and 252.05 seconds respectively for the 1 to 60 slope configuration and the 1 to 200 slope configuration. The pulse responses for respective controlled volume models were simulated. The simulated results using the estimated time constant were then compared with respective average data acquired from each experimental setup using sum of squared of error. The first order control system response more closely represents the concrete roof than the green roof where the normalised sum of squares of errors (SSE) for the concrete roofs and the green roof are less then 1 and 2 respectively. Finally, this dissertation suggests a theoretical relation the time constant to a hydrology parameter as an example for further possible application of the finding of this dissertation.

ABSTRAK

Pengaliran air hujan di takungan air bandar seperti bumbung adalah cepat dan terlampau memuatkan system pengaliran bandar, megakibatkan banjir kilat. Salah satu pengawalan asal untuk pengaliran cepat ini ialah pemasangan bumbung hijau luas di atas bumbung simen rata. Bumbung hijau meniru takungan air semulajadi dan ia akan menyebabkan penglambatan pengaliran air hujan dibandingkan dengan bumbung simen rata biasa. Laporan ini mengantarakan pengaliran air bumbung hijau dengan sistem kawalan untuk mengahami penglengahan bumbung hijau luas dibandingkan dengan bumbung simen rata biasa. Pembezaan jangka masa pengaliran untuk mencapai kemuncak (99.33 percents) di antara bumbung simen biasa dan bumbung hijau ialah 244.4 saat dan 252.05 saat masing-masing bagi aturan 1: 60 cerunan dan aturan 1:200 cerunan. Keputusan dari simulasi dengan mengunakan pekali masa dibandingkan dengan keputusan purata masing-masing dari setiap aturan kajian dengan mengunakan teknik tambahan kuasa dua bezaan (sum of squared of error). Sifat pengaturan pertama sistem kawalan adalah lebih mengwakili bumbung simen biasa daripada bumbung hijau di mana kelaziman tambahan kuasa dua bezaan untuk bumbung simen biasa dan bumbung hijau adalah kurang daripada 1 dan 2 masing-masing. Ketamatannya, laporan ini juga mengantarakan, secara teori, parameter pekali masa dalam persamaan pengaturan pertama sistem kawan boleh dihubungkan dengan parameter hidrologi sebagai salah satu contoh kemungkinan pengunaan.

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CDF	Cumulative Distribution Function
IDF	Intensity-Duration-Frequency
SSE	Sum of squares of errors

CHAPTER 1

INTRODUCTION

1.1 Introduction

The conversion of natural watersheds to housing and commercial center due to urbanization causes lost of natural rain water retention capability. The lost of the capability results faster runoff of storm water into the urban drainage system.

A fast runoff means wider and deeper drains are required at the down stream to handle the every increase amount of the urban water discharge. This is not feasible in term of land used and economical point of view. More lands are required for the drain system and extension of existing drainage system to overcome overloading and to prevent flash flood.

There are readily available mitigation measures which can be used to slow down the urban storm water discharge, and the more effective way is source control (Anon, N.D.). Green roof is one of the source controls.

Green roof is a type of rooftop garden (Figure 1.0.1). Green roof are further subdivided into two groups, which is the intensive group and the extensive group. The intensive green roof involves plantation of trees, and other heavy structure, while extensive green roof is relatively lighter and planted with lawn grass.

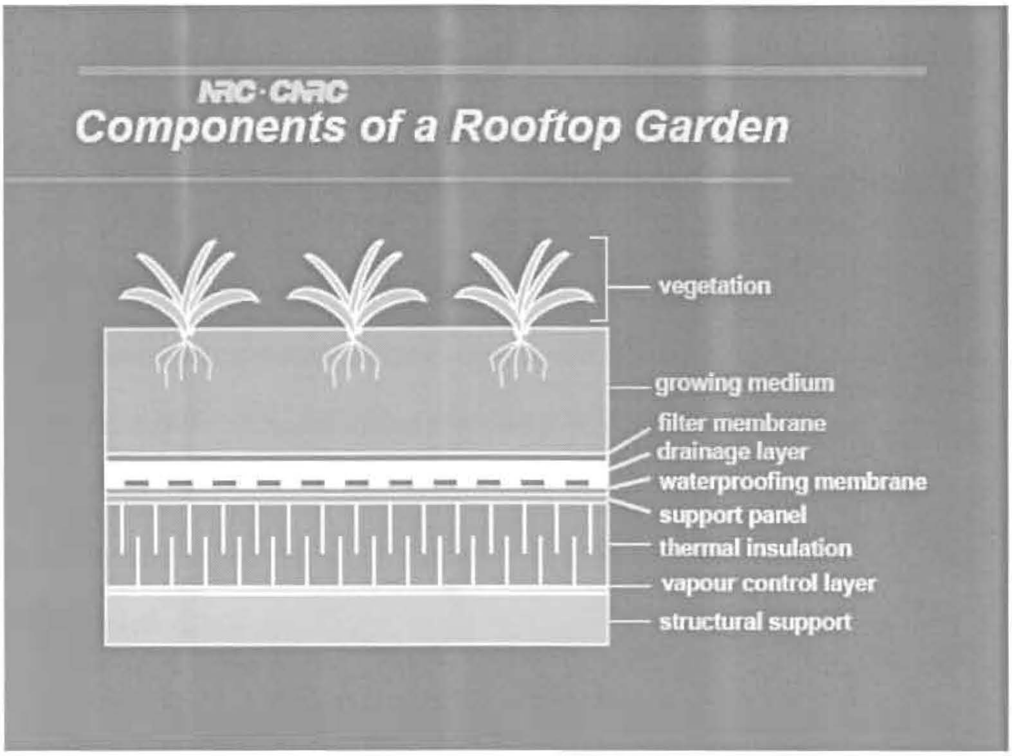


Figure 1.0.1: Structure of green roof after Bass and Baskaran (2003)

Green roof exist more than 25 years in Europe, especially in Germany as well as in Northern America (Office of Water, 2000) and in Japan. Apart from slowing down storm water run off, green roof provides other services such as reduce heat island in urban area, regulate in door temperature and provide habitat for insect, as well as carbon sink within the urban area.

1.2 Study Objectives

The focus of this study was to determine the model for the storm water runoff flow through the extensive green roof in comparison with a concrete flat roof slab. The Laplace Transform and control system theories were applied.

Grass species was identified for suitability to the extensive green roof application in this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Green Roof

Green roof is conventional structural roof top covered with plants and growth mediums or vegetated roof cover (Anon, 2000). These vegetated roof cover were installed apart from the initial aesthetic value, to the microclimate improvement and recently to reduce the rainwater input to the sewage system during rainfalls and cut the peak load to prevent drainage system overload and lead to possible flooding (Kohler et al., 2002).

Sedum species, a native species in temperate countries, are commonly used as vegetation for extensive green roof in North America (Bass and Baskaran, 2003; Office of Water, 2000; Wark and Wark , 2003). However, Wark and Wark (2003) suggested that the plant can be any kind but limited to climate, structural design and maintenance budgets. Plant selection for the application in Kuching area should be a local native species or a common gardening species. Pearl grass[1] was selected for this dissertation due to its availability in this area and it is type of slow growth plant, hence lower maintenance cost. Mat grass (*Axonopus affinis Chase*), cow grass (*Axonopus compressus*) and water couch grass (*Paspalum distichum L.*) are possible species under consideration as well. These species however grow faster and taller than the pearl grass.

[1] The pearl grass which is commonly known in Indonesia, Malaysia and Singapore; and used in the experiment is not the *Hemianthus micranthemoides* nor *Phyllanthus* sp.. The pearl grass that was used in the experiment has similar physical properties with cow grass (*Axonopus compressus*) but with no or short sheath and internode.

2.2 Hydrology Model

Chow et al. (1988) and Beven (2001) referring a storage in a control volume as a balance of the inflow and the outflow to the said volume. Chow et al. (1988) compare the analogue relationship between the linear function in response to a unit pulse input and the unit hydrograph to a centimeter excess rainfall with the following assumptions:

- Direct runoff hydrograph starts from zero. All previous rainfall is absorbed by the watershed (initial abstraction or loss, or zero initial condition)
- Direct runoff hydrograph is calculated using principles of proportionality and superposition
- Watershed response is time invariant, not changing from one storm to another
- Total depths of excess rainfall (Q) and direct runoff (P) are equal
  - $\sum_{n} Q_n = \sum_{m} P_m$

The watershed response is only considered as time invariant for situation where there is no major topography or vegetables' cover change such as bush fire, land clearing, urbanization and restoration of green cover.

Chow et al. (1988) using a first order system to represent the storage transfer function. A general first order system with response to a unit step input is shown in Figure 2.0.1. The output will reaches 63.21 percent of the unit step input after one time constant, τ and reach 99.33 percent of the unit step input after five times τ. Time constant is an important parameter to determine the response behavior of the system. The unit step response of the system is:

$$y(t) = 1 - e^{-t/\tau} \qquad [2.1]$$

or, in Laplace Transform (Appendix C) form as:

$$Y(s) = 1/(\tau s + 1) \qquad [2.2]$$

and the unit step input in Laplace Transform form is:

$$U(s) = 1/s \qquad [2.3]$$

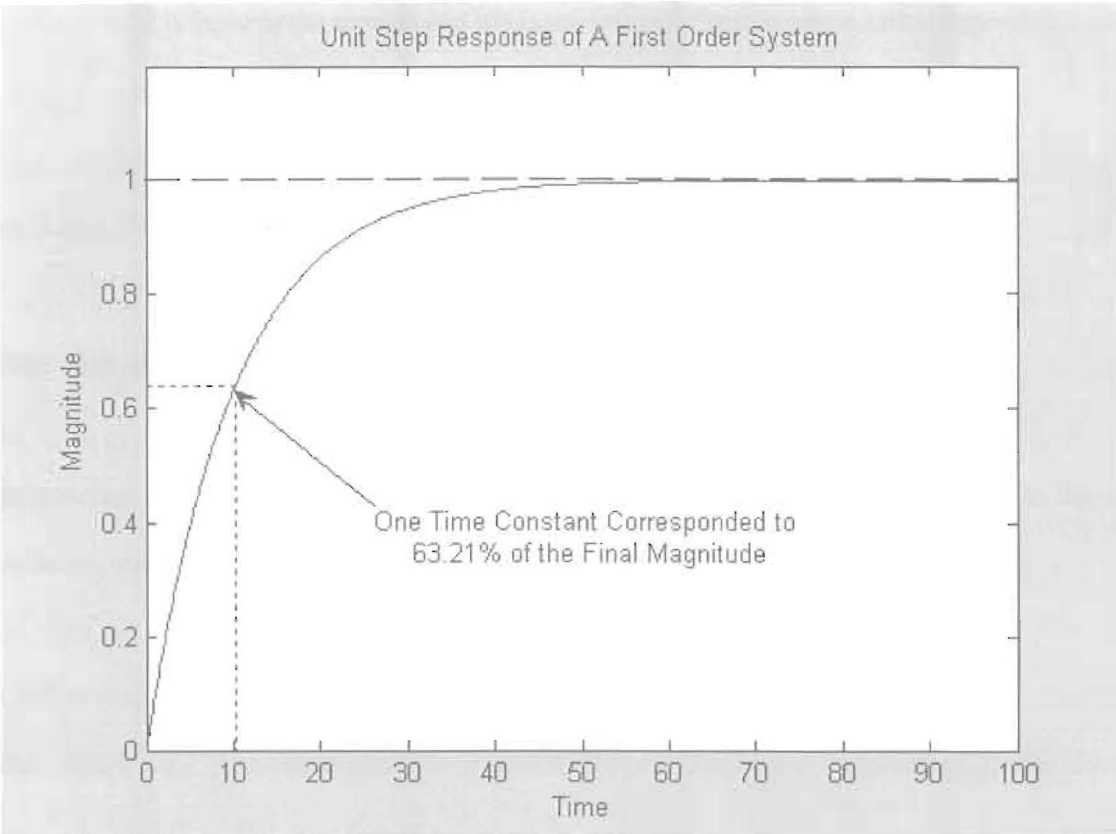


Figure 2.0.1: A unit step response of a first order system

When a step input of gain, K_g is applied to the Y(s) function, the final steady state will be K_g or the linear system principle of proportionality (Chow et al. 1988) as:

$$K_g \cdot U(s) \cdot Y(s) = [K_g/s] \cdot [1/(\tau s + 1)] \qquad [2.4]$$

2.3 Hydrology and First Order System

A small concrete flat roof (area of approximately one meter square) can be represented by a controlled volume storage with an opened end. Change in the storage, ΔS with reference to time in the controlled volume can be related to the inflow into the storage and the outflow flows from the storage according to Chow et al. (1988) as:

$$dS/dt = I(t) - Q(t) \qquad [2.1]$$

where: S is storage function

Q is output from the storage and Q(t) is the outflow dependence on time

I is input to the storage and I(t) is the inflow/effective precipitation dependence on time

t is time.

Chow et al. (1988) further replace S by kQ and rearrange equation 2.1 to get:

$$k(dQ/dt) + Q(t) = I(t) \qquad [2.2]$$

and rearrange to get the ratio of Q(t)/I(t) or f(t):

$$f(t) = Q(t)/I(t) = 1/(1 + kD) \qquad [2.3]$$

where constant k is the function of time invariant parameters, or the parameters change in relatively much longer than the time of interest. D is the differential operator d/dt.

The differential operator in differential equation can be transformed into an algebraic equation in another variable s. The transformation is called Laplace Transform (Appendix C), and then the solution of the differential equation is achieved by simple algebraic manipulations in the s domain (Raven, 1995).

Take equation 2.3 into a Laplace transform, assuming zero initial condition yields:

$$\mathscr{L}[f(t)] = \int_0^\infty f(t)\, e^{-st}\, dt = f(s) = Q(s)/I(s) = 1/(1 + ks) \qquad [2.4]$$

which is a first order transform function of a linear system.

The unit step is then applied to the system which is equivalent to a sudden heavy rainfall falls on a dry impermeable concrete flat roof or a saturated green roof. Take the inverse Laplace Transform gives

$$U(t) \cdot Q(t)/I(t) = 1 - e^{-t/k} \qquad [2.5]$$

Equation 2.5 is plotted and compared with the Cumulative Distribution Function (CDF) of an unit hydrograph as shown in Figure 2.0.1. The CDF of the unit hydrography is approximated as a first order system. The more accurate representation can be a second order function with time delay but is beyond the discussion here.

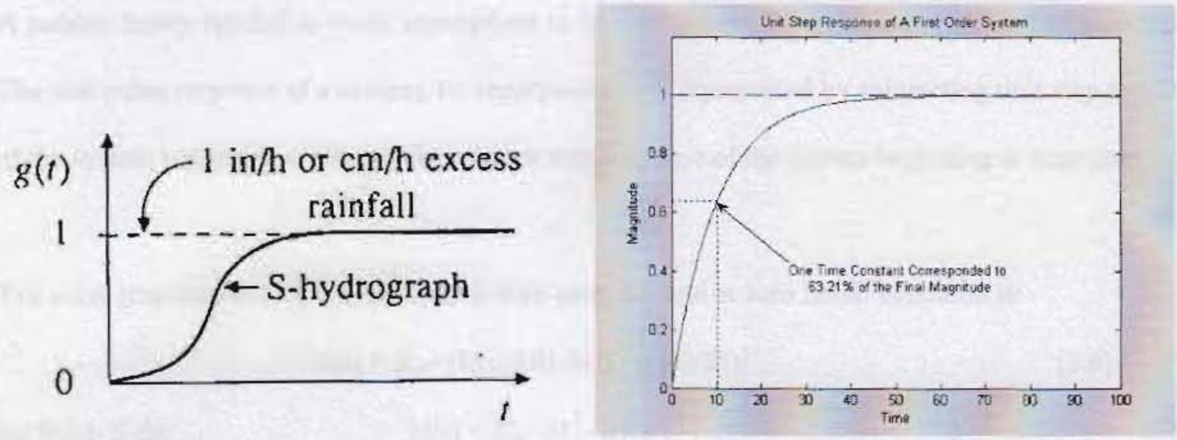


Figure 2.0.2: CDF of unit hydrograph after Table 7.3.1, Third Unit Hydrograph in Chow et al. (1988) and the approximation representation by a first order unit step response (Figure 2.0.1)

The constant k of the system, Q(t)/I(t), can be estimate from the plot by taking the response time to reach 99.33 percents of the maximum input magnitude and divide by 5 or more directly the time when the output reach 63.21 percents of the final value (Appendix D).

2.4 First Order System Response Simulation

Figure 2.0.2 shows block diagram representation of a first order linear system with a unit step input. Time of concentration is represented by a delay block and the precipitation is represented by a gain block.

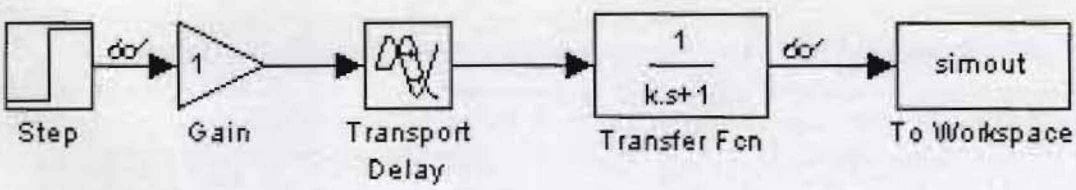


Figure 2.0.3: A block diagram representation of system

Noise can be represented by an addition block to the outflow. However, it is ignored for simplicity and hence it is not shown.

A sudden heavy rainfall is more appropriate to be represented by pulse input instead of step input. The unit pulse response of a system, by superposition, is represented by subtracting unit step response of the system beginning at time Δt from a unit step response of the system beginning at time zero.

The pulse response of a first order system with gain, K_g, and at zero initial condition is:

$$H(s) = K_g \cdot [U(t)-U(t-\Delta t)] \cdot [Q(t)/I(t)] \qquad [2.6]$$

for $0 \le t \le \Delta t$, $$H(s) = K_g \cdot (1 - e^{-t/k})$$

for $t > \Delta t$, $$H(s) = K_g \cdot e^{-t/k} (e^{\Delta t/k} - 1)$$

where Δt is the pulse width and K_g is the pulse height.

2.5 Fitness between Collected Data and Simulation Data

Sum of squares of errors was used to verify that the simulation was representing the actual collected data. Normalisation of the result by power of 2 of the input magnitude enabled the comparison of the SSE between different input magnitudes.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental Materials and Methods

The green roof structured shown by Bass and Baskaran (2003) (Figure 1.0.1) is practical model for template countries. In order to use for this dissertation, the structure was simplified to essential components as shown in Figure 3.0.1. The zinc sheet is to create a form of one meter square (1250 mm x 800 mm) and the 5mm thick screed is to mimic a typical concrete roof.

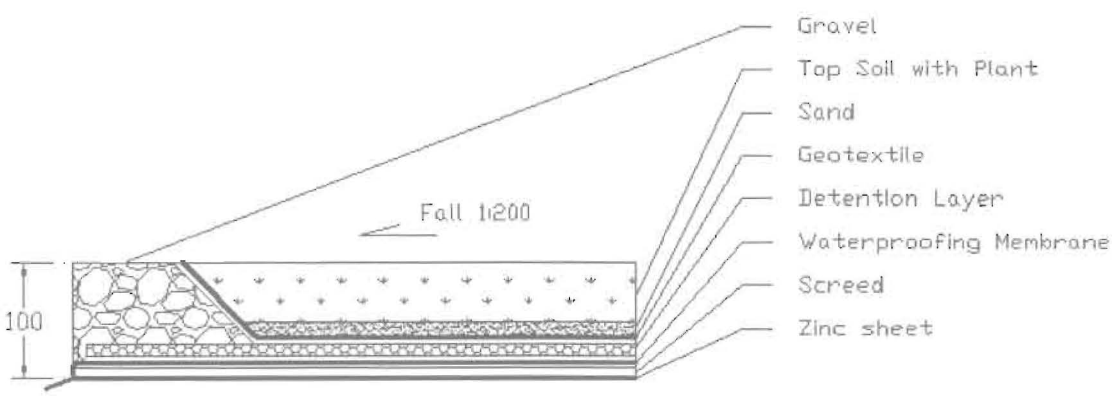


Figure 3.0.1: Cross-section of the experimental green roof

The extensive green roof modules were then laid on top the concrete flat roof. Although the model did not need the waterproofing membrane for preventing water to filter down below layer, the membrane was there to provide the property of the change of the surface roughness which affecting the water flow characteristic such as the runoff coefficient of the Rational Formula. The detention layer was there to create base water channels while detent small amount of water by surface tension. The geotextile permits water to flow through while securing the plant and soil on top in place, and reduce soil runoff. The goetextile however does not filter out silt into the runoff water. The 10 mm thick of sand layer (particle size approximately 0.5 mm diameter) was used to improve grass soil holding, and water drainage to the bottom, and prevent heavy soil erosion before the underlying geotextile.

The top layer is pearl grass with approximately 40 mm soil. Pearl grass is selected for the model for the following reasons:

a) Common landscaping species used in Kuching city.

b) Readily available from landscaping trading company.

c) Low growth species – hence low maintenance (less pruning) and organic waste.

Mat grass (*Axonopus affinis Chase*), cow grass (*Axonopus compressus*) and water couch grass (*Paspalum distichum L.*) are other possible species to be used.

Figure 3.0.2: A snapshot of pearl grass used in the experiment

The required flow for the experiment was based on the Rainfall Intensity-Duration-Frequency Curve for Kuching Airport station in between period of 1952 and 2000 (DID, 2000) (Appendix A) . The minimum available return duration is 15 minute. A 100 years return period is corresponding to 200 mm/hour maximum average rainfall intensity per hour for 15 minutes duration. An area of one meter square will then received 200 mm/hour x 1 m^2 = 0.002 m^3/hour or 3.33 l/min over 15 minutes period. A 10 minutes rainfall for 100 year return period will be approximately 215 mm/hours or 3.58 l/min. The experiment however was run with 20 l/min and 6 l/min. Twenty litres per minute simulated fall was used to fully drive the system into saturation and 6 l/min simulated rain will amplified the response curve for better graphical reading in order to estimate the time constant from the plot.

The H313 Hydrology Apparatus (TecQuipment Limited) was used to simulate the rainfall and to measure the run off. The apparatus has the ability to simulate up to 22 l/min rainfall with all eight sprinklers in operation. The experiment setup is shown in Figure 3.0.3.

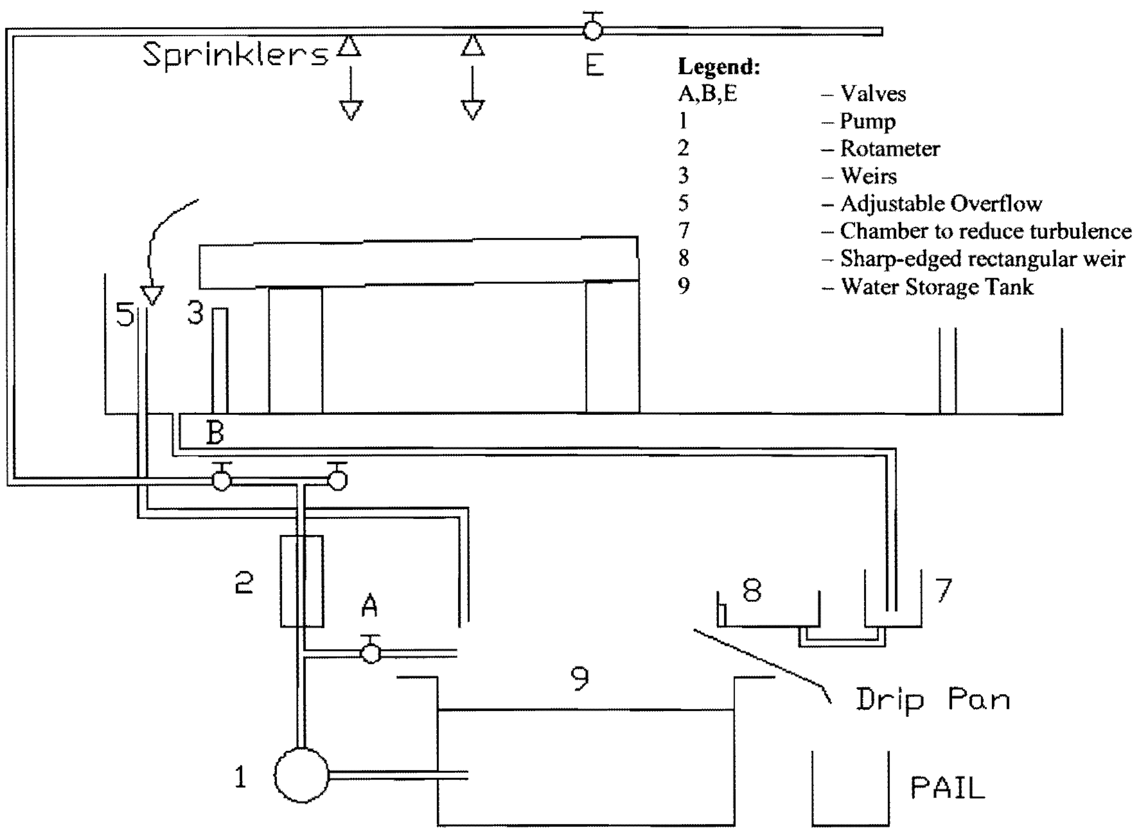


Figure 3.0.3: Experimental setup of H313 hydrology apparatus

The left-hand side four sprinklers were sufficient to create water shower over the one meter square (800 mm x 1250 mm) model roof. Hence, the right hand side sprinkler set was not used and the model roof was positioned at the left hand side. Water runoff from the model flowed into the gutter and to the damping tank number 7. The experiment used a flexible hose with an internal diameter of 20 mm to flow the water from the gutter to the damping tank (7). This caused oscillation to the out flow and detailed under Chapter 4.

The runoff measurement was done over a sharp weir (8). The measurement however was not in litre per minute but in weir head in millimetre. Prior to the experiment, the weir was calibrated according to the equipment's operator manual to acquire the correlation between the weir head and the water volume. By using the Microsoft Excel worksheet Trendline function, the parameters, was related by Equation 3.1 with the R-squared value equal to 0.9994. R-squared value equal to one means the actual data falls on the estimated values of the equation.

$$y = 0.0828x^{1.3634} \qquad [3.1]$$

Equation 3.1 is the power function where y is flow in litre per minute and x is the weir head in millimetre. The plot is shown in Appendix B.

The 20 l/min flow can only be achieved with two out of the four sprinklers nozzle removed to reduce the pressure head. The 6 l/min flow was achievable with all four sprinklers nozzle attached.

The experimental duration was taken using two digital stopwatches with accuracy down to 100^{th} of a second. One stopwatch was used together with its 10 memory storage to record rising water level during initial precipitation and falling water level after precipitation stopped. The second stopwatch was used to record the water level when the water level reached the set level till the precipitation stopped at a minute interval.

Data were collected for both concrete flat roof and the extensive green roof for roof gradient set at 1 to 60 and 1 to 200; 6 l/min and 20 l/min flow. All simulations with 20 l/min flow were done 5 times. Simulations with 6 l/min were done 3 times. Artificial rain run for 10 minutes after the outflow reaches the set value for all the configurations.

Thermal and vapour insulations were omitted for simplicity.

3.2 Data Processing

Data processing were done using Microsoft Excel and Matlab with Simulink. Each individual run was plotted on the graph. Matlab's curve fitting algorithm "Interpolate - Shape conservation" was used to create a common time step data set in order to average the data set. Time step of 10 second was used to create smooth line over the time period of up to 1200 seconds or 20 minutes. The data were then exported to Microsoft Excel worksheet to do the averaging between tries for the same configuration.

The average data set were then plotted for each configuration. The time constants for each configuration were found using graphical method. On the plotted graph, the final magnitude was determined approximately equal to the input magnitude. In this case were 6 l/min and 20 l/min respectively. The values for each respective time constant are the time when the outflow reached 63.21 percent of the final magnitude. Time constants from the same roof slope were averaged for the concrete roof and the green roof respectively and the different of them are the average delay benefited from the green roof. Hence,

$$\text{Avg Delay}_{\text{slope}} = (\text{Avg Time Constant}_{\text{Green, Slope}}) - (\text{Avg Time Constant}_{\text{Concrete, Slope}}) \qquad [3.2]$$

The time to reach 63.21 percents of the final value is one time constant and according to the first order system step response (Appendix D), the output will reach 99.33 percents of the final value or peak value for the hydrological point of view after five time constants. That means:

$$\text{Time}_{\text{peak value}} = 5 \times \text{Time Constant} \qquad [3.3]$$

and relating equation 3.2 and 3.3, the Average Delay between peak values of the roofs is:

$$\text{Avg Delay}_{\text{peak value, Slope}} = 5 \times \text{Avg Delay}_{\text{Slope}} \qquad [3.4]$$

The time constants acquired from the graphical method were used to generate pulse response using Simulink block diagram (Figure 2.0.3) with same time interval and duration as for the collected data. In order to determine the fit of the pulse response data over the collected data, the pulse response data were import to a Microsoft Excel spreadsheet to calculate the sum of squares of errors using the SUMXMY2 worksheet function which is equaled to

$$SSE = \sum (x-y)^2 \qquad [3.5]$$

where x is the averaged of the collected data set and y is the simulated data set.

In order to determine the fit of both 6 l/min and 20 l/min group, the SSE of these groups were normalised by dividing the SSE value by the square of the input magnitude.

$$\text{Normalised SSE}_{\text{input magnitude}} = \text{SSE} / (\text{input magnitude})^2 \qquad [3.6]$$

CHAPTER 4

RESULTS AND ANALYSIS

Figure 4.0.1 shows the average outflow patterns for each configuration in response to a pulse input of duration of 10 minutes. Outflow at the weir that is less than one mm but higher than zero mm are approximated to 0.5 mm water head which is equivalent to 0.03 l/min flow.

The fluctuation is mainly due to the air pocket in the transport pipe from the gutter (5) to the damping tank (7) of the hydrology apparatus. Both the magnitude and frequency of this noise is related to the input (which was outflow from the roof) pattern into the gutter (5) as well as pressure head at the end tip of the transport pipe which was submerging in the damping tank (7). The fluctuation is not same for both type of the roof due to the different outflow from these two types of roof will cause different output characteristic from the damping tank (7) though they were passed through from the same pipe. The green roof outflow is the sum of infiltration base flow and surface overflow where the concrete roof outflow is direct or just a base flow. The used of waterproofing membrane and the detention layer in the green roof also change the characteristic of the base and hence the base flow.

Time constant, where the time take to rise from zero to 63.21 percents of the final value, (Appendix D), for each pulse response curve were estimated from the plots shown in the Figure 4.0.1 (Section 2.3). The result is shown in Table 4.0.1.

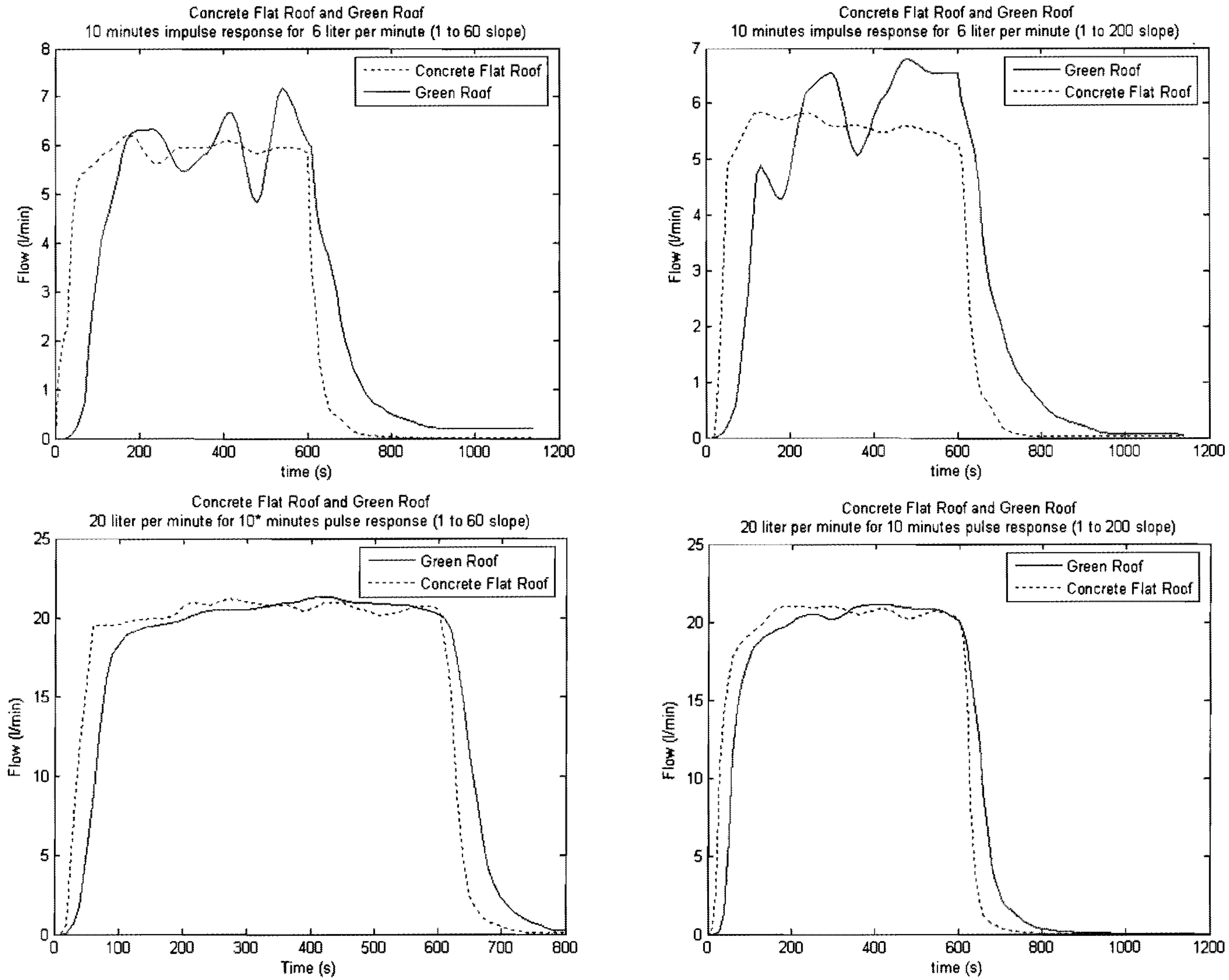
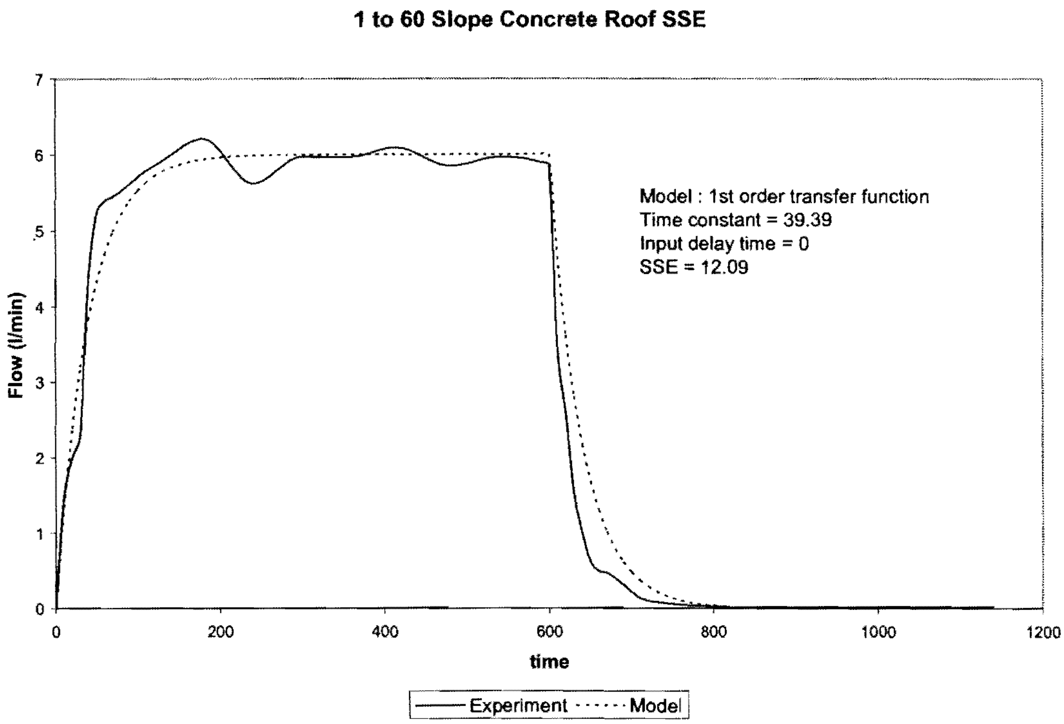


Figure 4.0.1: Delay in time to pulse responses for each experimental setup

Table 4.0.1: Time constant for each experimental setup

Flow (l/min)		Time Constant			
	Roof Slope	1 to 60		1 to 200	
	Roof Type	Concrete	Green	Concrete	Green
6		37.31	106.10	44.76	111.70
20		41.47	70.53	49.65	90.84
	Average time constant	39.39	88.27	44.86	101.27

The time constants for both 6 l/min and 20 l/min of each configuration were used in the model. The results were plotted overlaying with the average response of each configuration (Figure 4.0.2 to Figure 4.0.5). SSE was calculated for each data set to determine the fit of the model to the actual collected data (Section 3.2). SSE shown in all graphs are prior to normalisation which was done using equation 3.6.



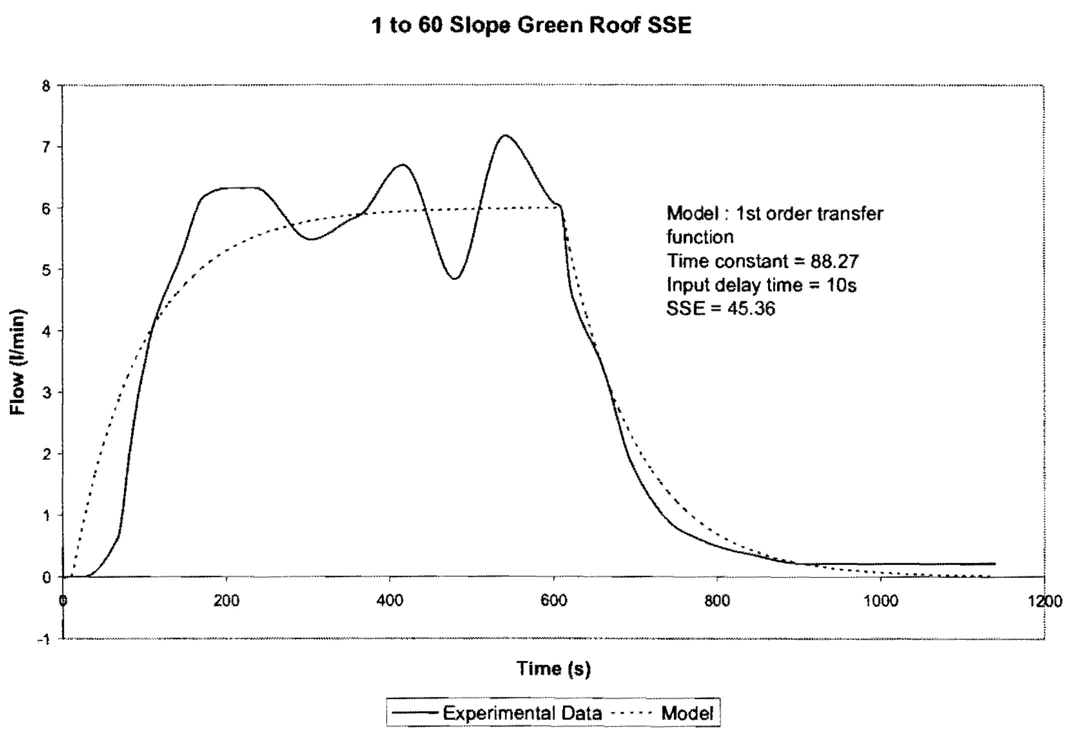
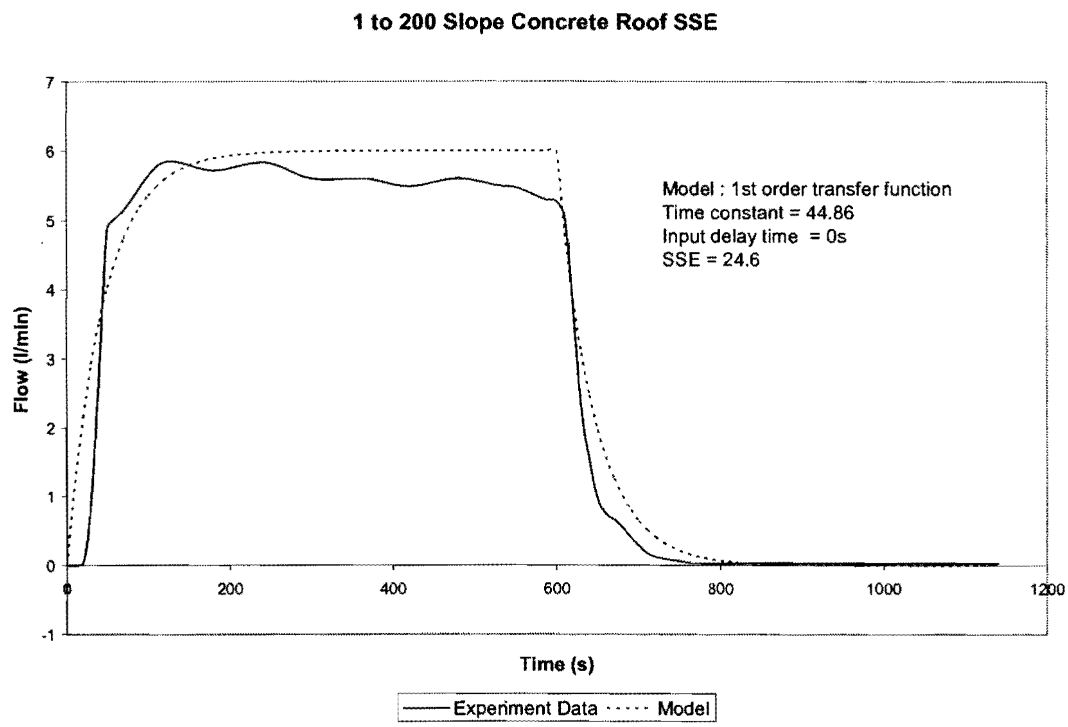


Figure 4.0.2: 1 to 60 slope 6 l/min 10 minutes pulse response



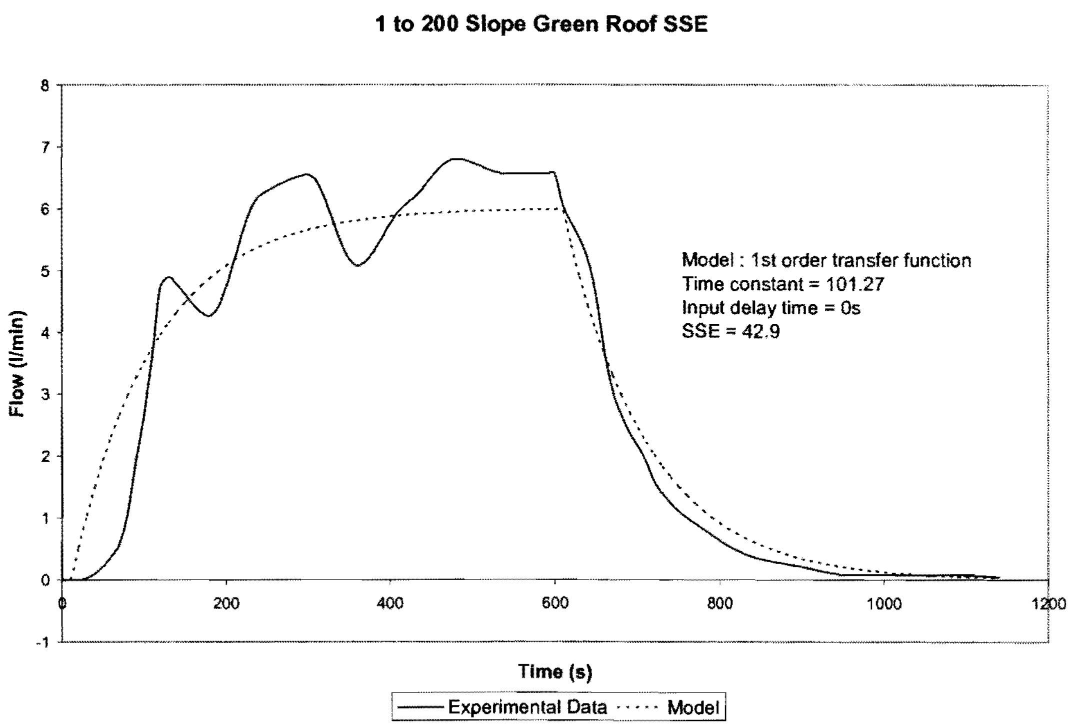
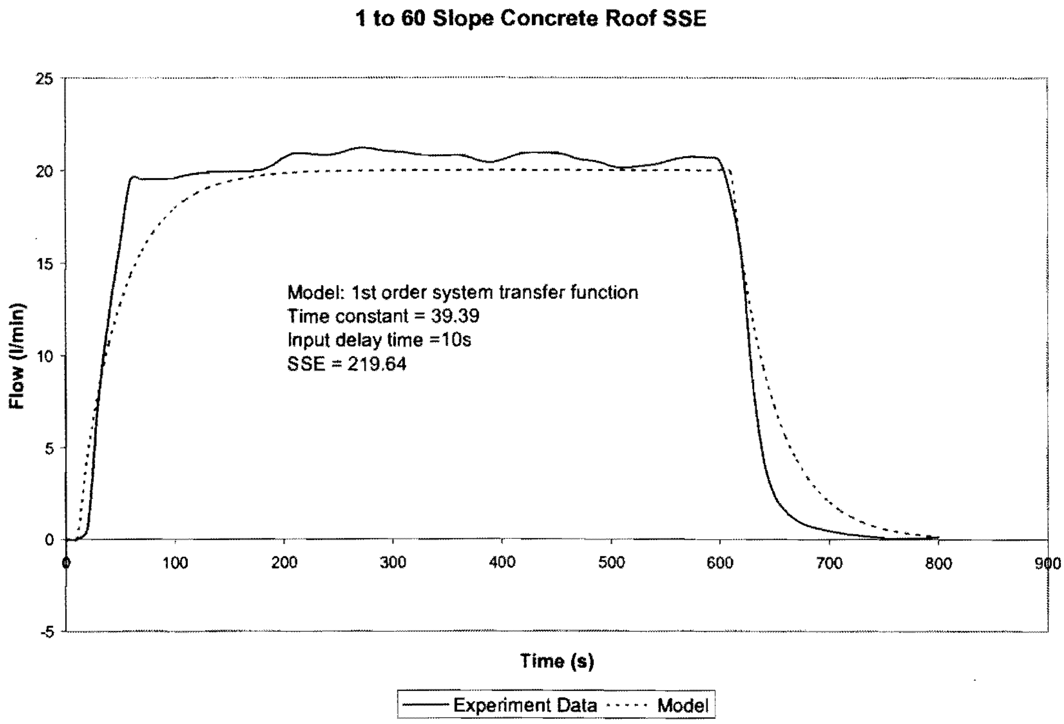


Figure 4.0.3: 1 to 200 slope 6 l/min 10 minutes pulse response



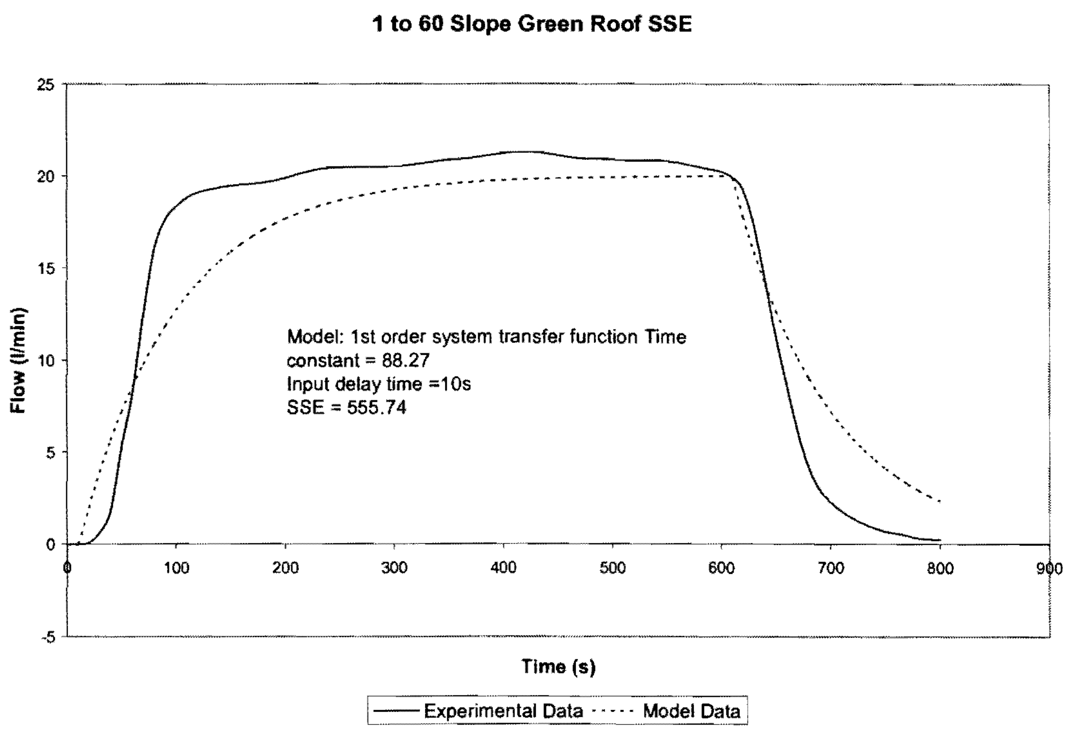
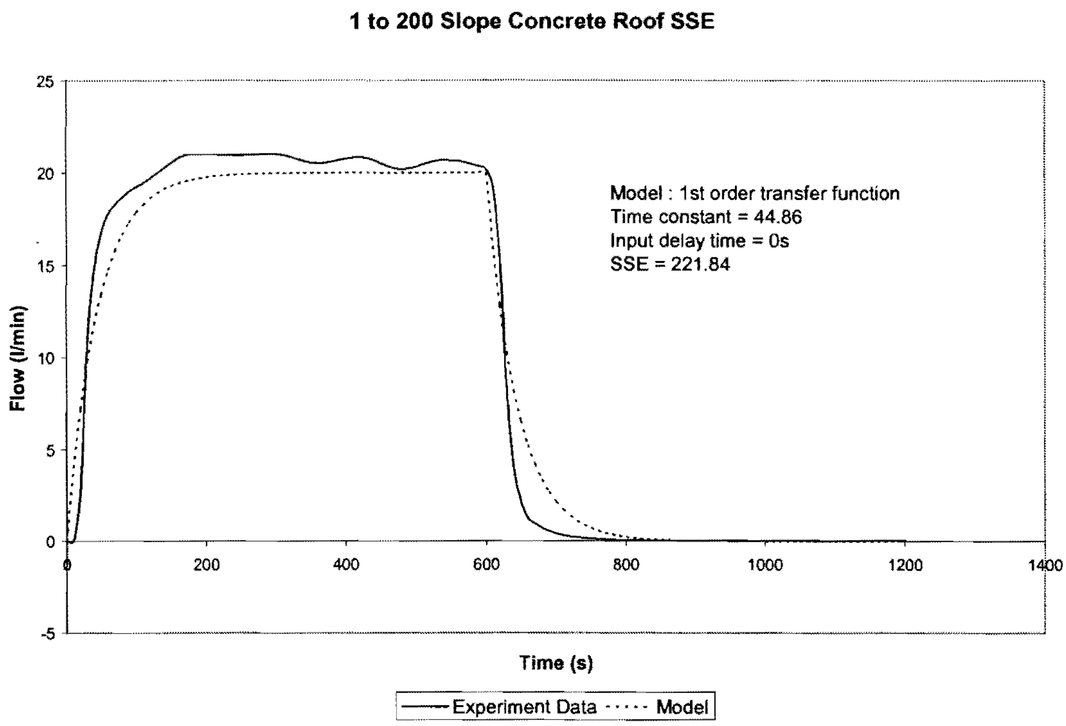


Figure 4.0.4: 1 to 60 slope 20 l/min 10 minutes pulse response



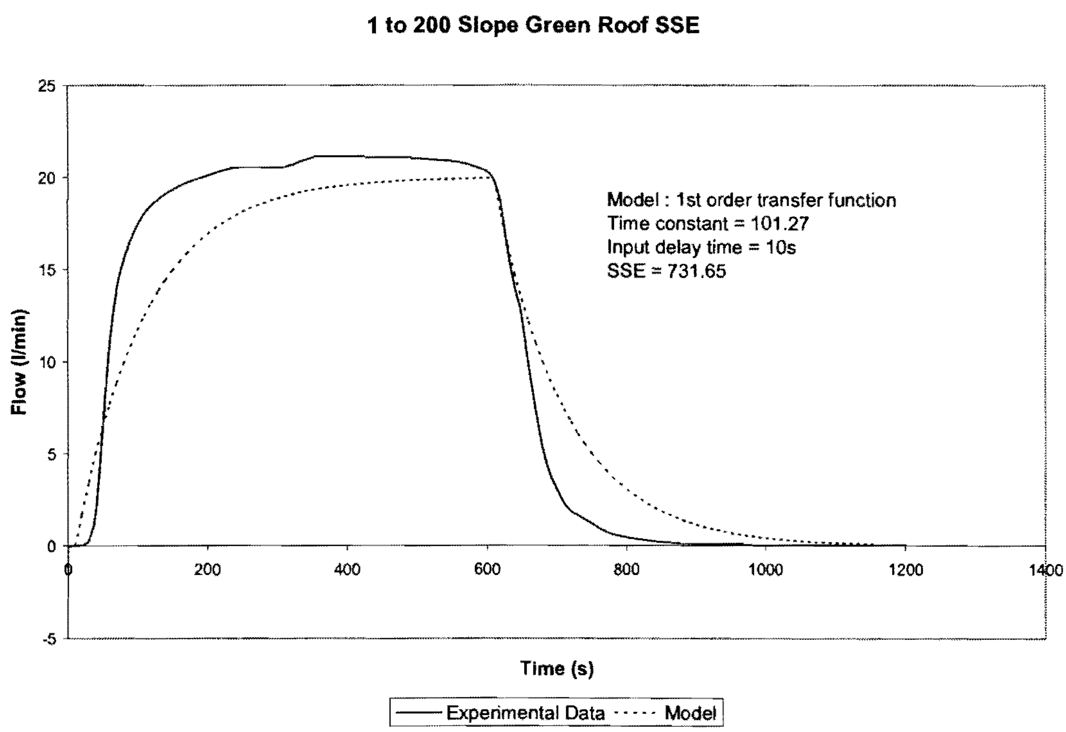


Figure 4.0.5: 1 to 200 slope 20 l/min 10 minutes pulse response

CHAPTER 5

DISCUSSION

Pulse response for the saturated green roof configuration shows delay when compared with the pulse response for the concrete flat roof. The simulated results (Table 4.0.1) show that the one meter square green roof model configuration have slower response to reach the 63.21 percents of the final value when compare to the one meter square conventional concrete roof model. The average delays (equation 3.2) are 48.88 seconds for the 1 to 60 slope configuration and 56.41 seconds for the 1 to 200 slope configuration.

Comparing the time to reach peak value (99.33 percents) between the conventional concrete roof and the green roof are 244.4 seconds and 252.05 seconds (equation 3.4) respectively for the 1 to 60 slope configuration and the 1 to 200 slope configuration. The one meter square green roof will delays storm water by at least four minutes.

The pulse responses for respective controlled volume models were calculated as detailed in Section 3.2. The results were then compared with respective average data acquired from each experimental setup using sum of squares of error (equation 3.5). The SSE is shown in Table 5.0.2

Table 5.0.2: SSE of the pulse response of the first order system model

Flow (l/min)		SSE			
	Roof Slope	1 to 60		1 to 200	
	Roof Type	Concrete	Green	Concrete	Green
6		12.09	45.36	24.60	42.9
20		219.64	555.77	221.84	731.65

The SSE was normalised using equation 3.6 by dividing 36 (square of 6 l/min) from the 6 l/min group and 400 (square of 20 l/min) from the 20 l/min group to compare these two groups. The normalised SSE is shown in Table 5.0.3

Table 5.0.3: Normalised SSE of the pulse response of first order system

Flow (l/min)		Normalised SSE			
	Roof Slope	1 to 60		1 to 200	
	Roof Type	Concrete	Green	Concrete	Green
6		0.34	1.26	0.68	1.19
20		0.55	1.39	0.55	1.83

The concrete roof models are fit with low SSE (<1) as compare to the green roof models (SSE <2). This means the concrete roof model is better represented by the controlled volume model (Chow et al.,1998 and Beven, 2001) in comparison with the green roof model. The response of the green roof modules are more distorted as compared to the concrete roof module due to the interaction between the simulated rain water and the vegetation, growth media, filter, the detention layer and lastly the concrete roof. By the superposition theorem of the Laplace Transform, the green roof model can be represented by multiple cascaded or parallel controlled volume models or each component of the green roof.

From the control system point of view, the obvious oscillation on both 6 l/min precipitation green roof response suggested that there is at least a feedback loop within those controlled volume module and the hydrology apparatus. This oscillation at magnitude of approximately one liter per minute peak to peak is considered as negligible disturbance for both 20 l/min precipitation green roof response.

In theory, considering Horton's equation:

$$dF/dt = f(t) = f_c + (f_0 - f_c)e^{-kt} \qquad [5.1]$$

where F is the cumulative infiltration from the green roof modules that contribute as input to the conventional concrete roof.

The saturated flow flows from the green roof are then adding up to the infiltration flow to contribute to the total runoff. The saturated flow can be approximated with discharge per unit width equation (Chow et al. 1988):

$$q_0 = (i - f)\, L_0 \cos \theta \qquad [5.2]$$

where, i is rainfall intensity,

f is infiltration and related to Horton equation

L_o is overland wetted length

θ is slope angle of the overland

If equation 5.1 is per unit infiltration, then substitute equation 5.1 to equation 5.2 gives:

$$q_0 = \{i - [f_c + (f_0 - f_c)e^{-kt}]\}\, L_0 \cos \theta \qquad [5.3]$$

which is unit response function of saturated flow of a watershed or the extensive green roof. Then the overall runoff from the green roof is the sum of equation 5.1 and equation 5.3. However equation 5.3 is still in the theory state.

The constant k is then could be related to the time constant of the first order control system transfer function. Hence, in theory, by knowing the time constant of a green roof by relating the time constant to hydrology parameters such as the example above, the green roof could be designed to achieve a desired storm water delay from the building.

Evapotranspiration is not simulated due to the relative short simulation time. Losses of water due to evaportranspiration are low with reference to the inflow volume. The experiment was also done in a laboratory without direct sunlight and breeze, the two importance factors for evapotranspiration. Temperature effect on green roof is also out of the scope of this dissertation.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 Summary and Conclusion

This dissertation relates the green roof runoff response to control system in order to understand the delay response of an extensive green roof in comparison with a conventional concrete flat roof. Sum of squares of errors was used to test the relationship between the first order control system pulse response and the experimental data.

Pearl grass was selected for the vegetation of the green roof. The green roof consists of the vegetation, growth medium, geotextile or filter and detention layers sit on top a conventional concrete roof.

Data were collected for both concrete roof and green roof precipitated with 6 l/min and 20 l/min simulated rainfall; and each module were tilted to 1 to 60 slope as well as 1 to 200 slope for each type of flow of artificial precipitation.

The comparison of the time to reach peak value (99.33 percents) between the conventional concrete roof and the green roof are 244.4 seconds and 252.05 seconds respectively for the 1 to 60 slope configuration and the 1 to 200 slope configuration.

The experiment data were then compared with a first order model based on the controlled volume theorem. The first order control system response is more closely represent the concrete roof than the green roof, where the normalised SSE for the concrete roofs and the green roof are less then 1 and 2 respectively.

6.2 Recommendation

In theory, by knowing the time constant of a green roof and relating the time constant to hydrology parameters, the green roof could be designed to achieve a desired storm water delay from the building. The relation between the time constant and hydrology parameters however required further investigation.

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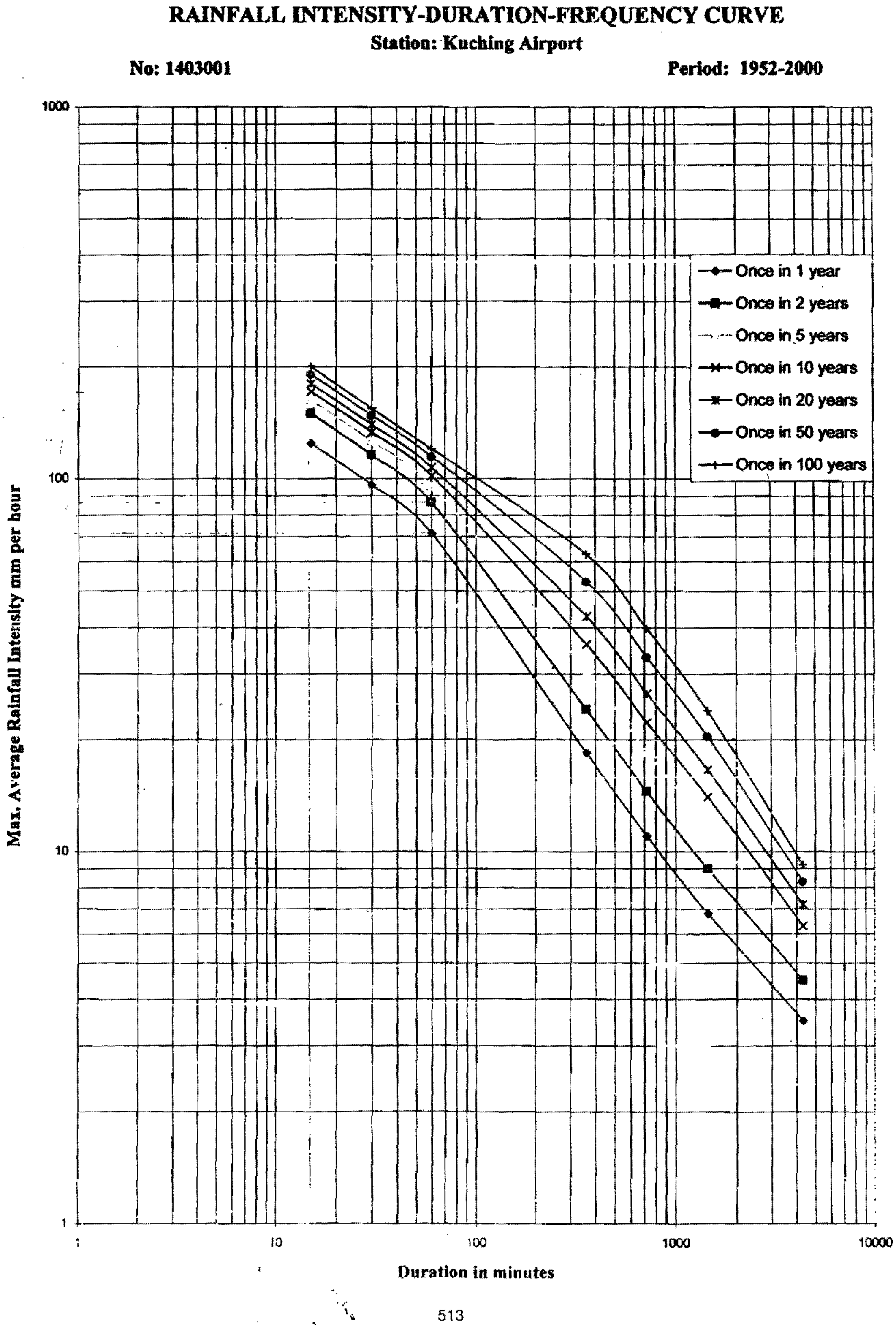
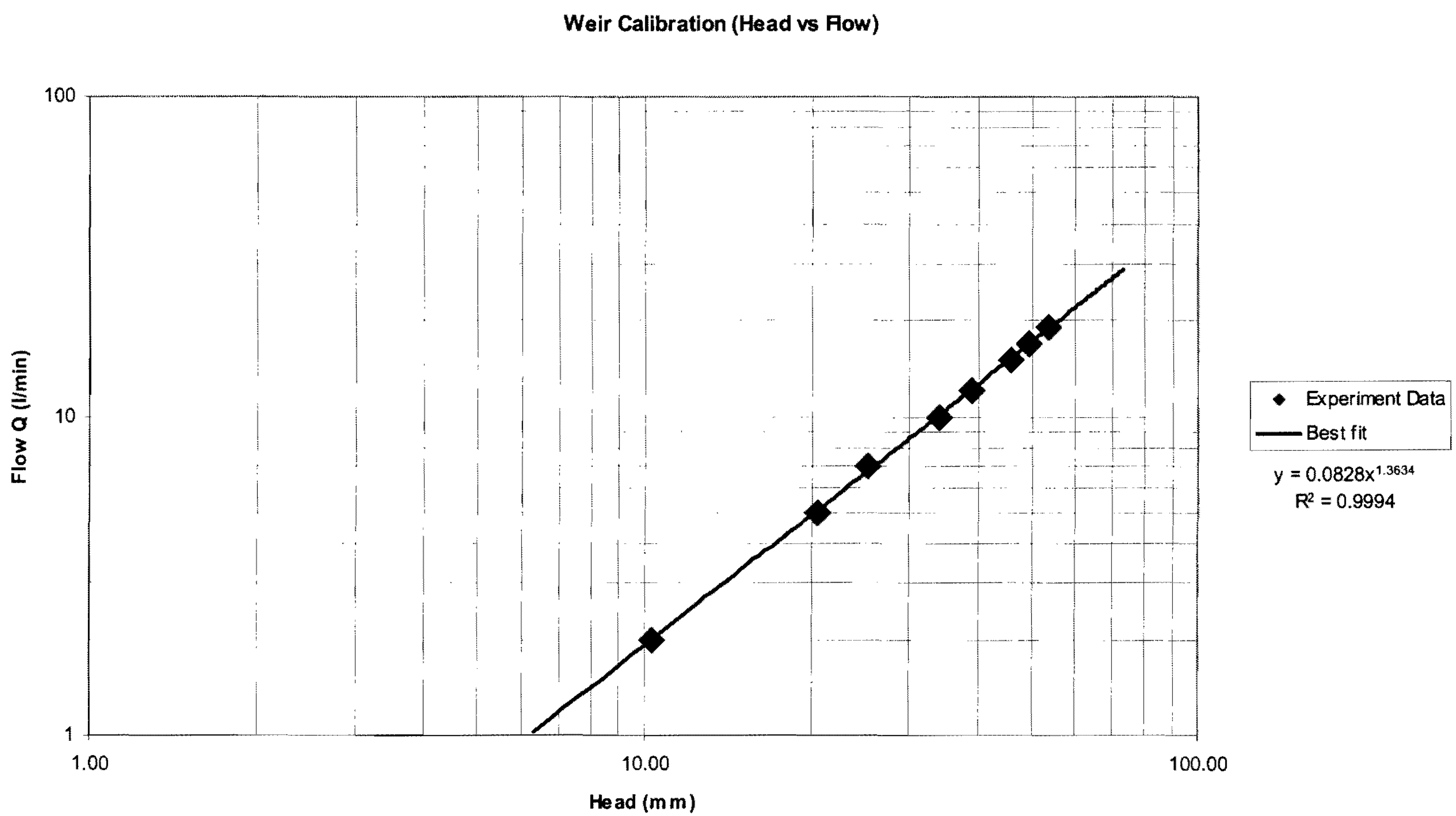
Appendix A Kuching Airport IDF Curve



Appendix B H313 Hydrology Apparatus Weir Calibration



Appendix C Laplace Transform

The Laplace transform of a function f(t) is denoted by L {f(t)} and is defined as the integral of f(t) e^{-st}

between the limits t=0 and t=8

$$f(s) = \mathscr{L}[f(t)] = \int_0^{\infty} f(t)\, e^{-st}\, dt$$

where the function f(t) is transformed to f(s)

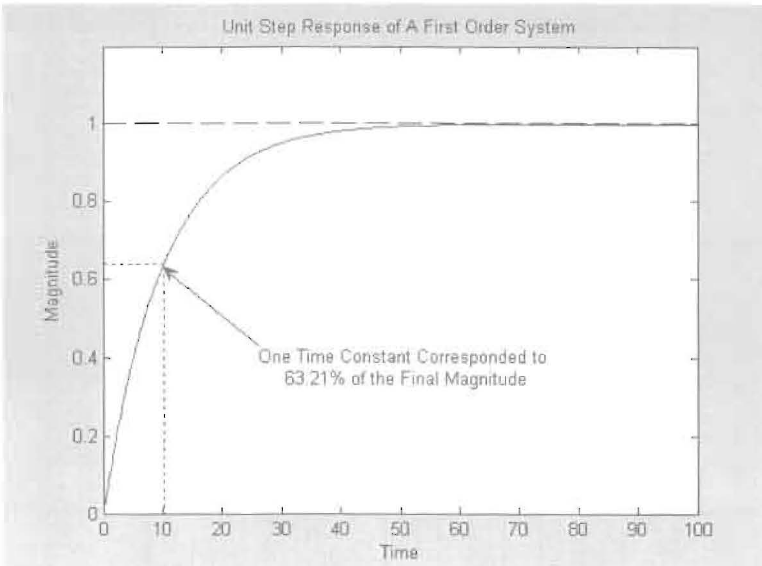
Standard Transforms

$f(t)$	$\mathscr{L}[f(t)] = f(s)$
a	a/s
e^{at}	$1/(s - a)$
sin at	$a/(s^2 + a^2)$
cos at	$s/(s^2 + a^2)$
sinh at	$a/(s^2 - a^2)$
cosh at	$s/(s^2 - a^2)$
t^n	$n!/(S^{n+1})$

Further details of Laplace transform can be found in Stroud (1990).

Appendix D First Order Step Response

The function $f(t) = K_r(1 - e^{-t/T})$ is the inverse Laplace transform of a first order transfer function injected with a unit step input at zero initial condition. The function is represented in the plot and the table below. The response curve reaches approximate one percent of the final value (K_r) at five time constants (T). If the time of the plot was extended to infinity, which is the limit of the Laplace Transform, then the response curve will reach 100 percent of the final value (K_r).



$K_r = 1, T = 10$	
t	$f(t) = K_r\,(1 - e^{-t/T})$
0	0
10	0.6321
20	0.8647
30	0.9502
40	0.9817
50	0.9933
∞	1

Appendix E Data Logging Sheet

UNIMAS
Experiment Manual - Hydrology Model of Extensive Green Roof for Kuching
Prepared by LIEW Ke-Bo (05031271) FRST Version 3.0

DATA LOGGING SHEET

Flow rate: 6 / 20 l/min for 10 minute; Roof Type (Conventional/Green)

Roof Gradient (1 to 60 / 200) ; Test Number (1 / 2 / 3 / 4 / 5)

Steady State Reading				Non-Steady State Reading			
Time (min)	Rotameter (liter/min)	Head above weir (mm)	Flow (l/min)	Time (sec)	Rotameter (liter/min)	Head above weir (mm)	Flow (l/min)
0						0	
1						5	
2						10	
3						15	
4						20	
5						25	
6						30	
7						35	
8						40	
9						45	
10						50	
11						45	
12						40	
13						35	
14						30	
15						25	
16						20	
17						15	
18						10	
19						5	
20						0	

5

Appendix F Photographs

Plate 1: Overview of the experimental setup

Plate 2: Front view of the experimental setup

Plate 3: Layers of the green roof

Plate 4: Another view of the layers of the green roof

Plate 5: The green roof used in the experiment

Plate 6: The concrete flat roof used in the experiment