Study on groundwater recharge characteristics at reclaimed land site

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Study on Groundwater Recharge Characteristics at Reclaimed Land Site

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SUMMARY

A thorough understanding of rainfall recharge processes and their influencing factors is essential for management of groundwater systems. This research aims to investigate the rainfall recharge characteristics at an unconfined sandy aquifer, the Changi reclaimed land, which is situated at the eastern coast of Singapore.

Through time series analysis of simultaneous rainfall and water table measurements, the relationship between rainfall and water table fluctuation at the reclaimed land was found to be strongly influenced by the percolation rate (essentially the vertical flow velocity) of the surface rainwater to reach the water table. Using a deterministic unsaturated zone model, the VS2DI, an extensive study was carried out to further investigate the effects of various meteorological and hydrogeological factors on the rainfall-recharge relationships, the gross recharge rates and the threshold rainfall values for recharge. From the VS2DI simulations, the residence time of rainwater within the vadose zone was found to govern the rainfall-recharge relationships, gross recharge percentages and the threshold rainfall values for recharge at the unconfined sandy aquifer. The potential loss of percolating rainwater through soil evaporation was found to be directly proportional to the residence time. The residence time of rainwater within the vadose zone depends on the percolation rate (vertical flow velocity) of rainfall on the soil surface to the water table, which was found to be a combined function of rainfall intensity and vadose zone thickness.

To assess the feasibility of developing the Changi reclaimed land as a potential groundwater source, reliable estimation of long term rainfall recharge rates is of critical importance. Compared to VS2DI simulations and water table time series analysis, empirical relationships for recharge rates are more efficient in view of their relatively low computational time and efforts. Hence, this research also develops empirical relationships between the measured rainfall rates, the vadose zone thickness and the recharge rates. These empirical

regression relationships are then used to estimate the long term recharge rates at the Changi reclaimed land. The reliability of the empirical relationships was evaluated by comparing their estimated recharge rates with those from VS2DI simulations, and from time series analysis of water table fluctuations. Using the empirical relationships, the probable range of mean annual net recharge percentage for Changi reclaimed land was estimated based on ten (10) years of daily rainfall intensity data.

Time series analysis of water-table fluctuation is a widely-accepted approach for estimating rainfall recharge rates at unconfined aquifers. This method was used as one of the benchmarking methods (in addition to VS2DI simulations) to investigate the reliability of the empirical relationships for recharge estimations. To estimate rainfall recharge rate using time series analysis of water-table fluctuations, the specific yield of the aquifer needs to be estimated. As part of the present study, a new procedure was developed for estimating the specific yield of the study site. Compared to laboratory measurements, the new approach developed is less time consuming and uses readily obtainable data. The specific yield values estimated using this approach were found to agree well with field measurements and the typical ranges of specific yield from the literature.

Prior to using the VS2DI model for recharge studies, the model needs to be calibrated and verified against field measured soil moisture profiles. Instead of manual calibration, a more efficient radial basis function (RBF) neural network was developed in the present study to estimate the parameter values of the van Genuchten's water retention model and the saturated hydraulic conductivity for the study site. The calibrated parameter values were validated against field and laboratory measurements.

For VS2DI calibration and simulations, open water evaporation rates are required as input variables for simulation of soil evaporation during the recharge process. The Penman's model is generally accepted to give the best estimates for open water evaporation, as energy supply and vapor transport are often the limiting factors. However, the Penman's model requires a

comprehensive set of meteorological data, and this often restricts its practical application. As part of the present study, simplified evaporation models, including radiation-based models, mass transfer models, temperature-based models, and artificial neural network (ANN) models were evaluated for their applicability in estimating open water evaporation rates for the study site. Among the tested models, only radiation-based and ANN models were found to yield reliable hourly and daily open water evaporation rates. Correlation studies between the pan evaporation measurements and the meteorological factors further show that energy driven evaporation is the predominant evaporation mechanism at the study site. Therefore, the radiation-based and ANN models are efficient alternatives for estimating open evaporation rates for the study site, as compared to the comprehensive Penman's model.

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percentage

LIST OF SYMBOLS

AC	Alternate current
ANN	Artificial neural network
ANOVA	Analysis of variance
ASR	Aquifer Storage and Recovery
A	Intermediate output of RBF
a	Area of flow
BPN	Backpropagation neural network
b	Bias coefficient of neural network
CI	Confidence interval
CPT	Cone penetration test
CWP	Clean Water Program
C_c	Coefficient of grading
C_u	Uniformity coefficient
C^*	Dimensionless parameter
C_m	Specific moisture capacity
D	Monthly rainfall depth
D_{EX}	Rainwater depth exposed to soil evaporation
D_L	Total rainwater depth lost through soil evaporation
df	Degree of freedom
dW'/dt	Changing shape of water moisture content over time
d_{50}	Effective grain size
E	Error
E_a	Actual soil evaporation rate
E_{ar}	Aerodynamic driven evaporation
E_p	Average daily potential evaporation
ET^{gw}	Direct groundwater evaporation
e_a	Actual vapor pressure
e_s	Saturation vapor pressure
F -critical	Critical factorial value, which when is exceeded by F -statistic, the null hypothesis is rejected; otherwise the null

	hypothesis is accepted.
F -statistic	Factorial value of treatment
f	Frequency
GR	Gross recharge
g	Gravity acceleration (9.81m/sec ²)
H	Depth to water table
HA	Pressure potential of the atmosphere
H_d	Total hydraulic potential
H_o	Null hypothesis
h	Soil pressure head in [L]
h_b	Bubbling or air entry pressure potential
I	Rainfall intensity
i	Index for a particular day
j	Index for day
K_S	Saturated hydraulic conductivity
K_r	Relative hydraulic conductivity
k	Time lag
k_i	Coefficient to incorporate rainfall cluster effect
LM	Levenberg-Marquardt
LSE	Least squares errors
MS	Mean square
MSE	Mean square error
M_w	Molecule weight of water (0.018 kg/g-mol)
m	Truncation point
N	Sample size
n	Length of time series
PEV	Potential evaporation rate
P -value	The smallest level of significance that leads to rejection of null hypothesis
ΔQ^{gw}	Net ambient groundwater flow
q	Source-sink term

R	Universal gas constant (8.31 kg.m ² /sec ²)
R^2	Coefficient of determination
RBF	Radial basis function neural network
RH	Relative humidity
RMSE	Root mean square error
R_n	Net groundwater recharge
R_S	Global radiation flux
$r(k)$	Auto-correlation function
$r_{xy}(k)$	Cross-correlation function
S	Standard deviation of the sample
SE	Soil evaporation ratio
$S(f)$	Spectral density function
S_P	Sensitivity coefficient
SS	Sum of squares
SSE	Sum of squares errors
S_S	Specific storage
S_y	Specific yield
$\overline{S_{y \text{ point}}}$	Average of the estimated “point” specific yields
S_{point}	Standard deviation of the estimated “point” specific yields
$S_{y \text{ areal}}$	“Areal” specific yield
S_{Lower}	Specific yield corresponding to the lower bounds of 95%CI of the effective grain size d_{50}
S_{upper}	Specific yield corresponding to the upper bounds of 95%CI of the effective grain size d_{50}
s	Surface resistance
s_e	Soil saturation
T	Air temperature
TMLT	Time step multiplier
TRED	Time step reduction factor
t_R	Average residence time

$\overline{U}_z$	Average vertical flow velocity
V	Fluid volume
VZ	Vadose zone thickness
w	Weight vector
$\overline{X}$	Sample mean
X_i	The data point
X_{max}	The data with maximum value
X_{min}	The data with minimum value.
x	Single event value
$\overline{x}$	Mean of the events
y	Single output event
y_j	Final response of RBF
$\overline{y}$	Mean of the output event
Z	Standard normal distribution
z	Depth from the ground surface
α'	Significant level
α	Fitting parameter of van Genuchten water retention model
α_a	Albedo value
β	Fitting parameter of van Genuchten water retention model
λ	Fitting parameter of Brooks-Corey water retention model
τ_i	Treatment effect.
ψ	Soil suction head in kPa
ΔT	Temperature change
Δ	Psychrometric constant
γ	Gradient of the saturated pressure curve at air temperature
ρ	Liquid density
θ	Input vector to RBF
θ_r	Specific retention/residual moisture content
θ_s	Porosity

μ	Mean of population
σ	Standard deviation of the population
σ_x	Standard deviation of input time series
σ_y	Standard deviation of output time series

CHAPTER 1

INTRODUCTION

1.1 Background and literature review

Since the 1960s, shallow coastal areas around the Singapore island have been gradually reclaimed to meet increasing demand for land due to rapid economic development. As the reclaimed lands are filled with high porosity materials (i.e. medium to coarse sands) up to depths exceeding 15m, they provide a potential for subsurface storage and recovery of water, and hence a potential water source. Groundwater recharge studies are important for evaluating the feasibility of utilizing these man-made aquifer systems as potential water sources. A thorough understanding of the recharge characteristics at the reclaimed lands is a pre-requisite for predicting the long term natural rainfall recharge rates, and hence the potential yield of the aquifer systems.

For reliable estimation of rainfall recharge rates, factors influencing the recharge processes need to be considered in groundwater recharge modeling. Rainfall recharge processes could be categorized into lithology-controlled recharge, climate-controlled recharge and variably controlled recharge (Sanford, 2002). Variably controlled recharge process is controlled by both the lithology of the subsurface (lithology-controlled) and the amount of rainwater available at the land surface (climate-controlled). Among these three processes, variably controlled recharge is the most common. This is because both the climatic and lithology controls are often present concurrently and the recharge process may sometimes alternate temporarily between these two controls (Sanford, 2002).

Under semi-arid and arid conditions, climate-controlled recharge appears to be the predominant process in unconfined loamy aquifers. The semi-arid and arid climates are characterized by low rainfall depths and high evapotranspiration rates. Under the semi-arid climate, Kendy et al. (2003) and Kendy et al. (2004) found that groundwater recharge at a loamy aquifer was not

a constant fraction of rainfalls, but rather the fraction increases with the rainfall intensity. For their unconfined loamy aquifer, groundwater recharge was found to depend strongly not only on precipitation and irrigation, but also on evapotranspiration. Antecedent soil moisture content and the temporal distribution of rainfalls were observed to have more significant impact on the groundwater recharge compared to the total quantity of precipitation. The influence of rainfall intensity on recharge rates at their loamy aquifer could be attributed to the low rainfall intensity and high evapotranspiration rates in a semi-arid climate. Due to the low infiltration capacity of loamy aquifers, light rainfalls tend to be lost through high evapotranspiration rates, and thus recharge events are mainly contributed by intense rainfall events. For heterogeneous aquifers with low hydraulic conductivity, Russo et al. (2001) observed that small recharge at the soil surface enhances longitudinal and transverse flows, which consequently reduce groundwater recharge from the vadose zone.

Likewise, climatic conditions have also been found to have a significant impact on the recharge threshold value for rocky aquifers. The recharge threshold value refers to the minimum rainfall depth required to initiate groundwater recharge. A rainfall recharge threshold value is generally required to initiate preferential flows at fractured rocky aquifers (Gburek and Folmar, 1999). Preferential flow through fissure networks has been known to be the predominant mechanism for groundwater recharge at rocky aquifers, and depends strongly on the degree of weathering of the bedrocks (Chand et al., 2004). Recharge threshold value at fractured karst aquifers was found to be high (20mm/day) in semi-arid climate (Ayalon et al., 1998), and lower (6.5mm/day) in tropical climate (Jones and Banner, 2003). For a karst aquifer in the temperate region, Jocson et al. (2002) found that light rainfalls (<0.6mm/day) tend to be lost entirely to evapotranspiration, and recharge events are mainly contributed by heavy rainfalls (>5.0mm/day), which promote rapid flows via fissure networks.

Unlike semi-arid and arid climates, rainfall events in the equatorial region are generally characterized by high intensity and evapotranspiration

rates. Compared to loamy aquifers, the sandy aquifer of the reclaimed land is much more permeable. The significance of evapotranspiration loss during the rainfall recharge process still remains unknown for unconfined sandy aquifers. This is because intense rainfall in the equatorial region may be able to infiltrate and percolate rapidly to the water table, due to the high hydraulic conductivity of sands. This may further lead to low evapotranspiration losses during the percolation process. Further studies are hence needed to investigate the combined effects of intense rainfalls and high evapotranspiration rates on recharge rates for an unconfined sandy aquifer under the equatorial climate. The probable range of recharge threshold values has also not been investigated for unconfined sandy aquifers in the equatorial climate, even though recharge threshold values have been estimated for fractured karst aquifers under the different climatic conditions. A good understanding of the factors influencing the recharge processes and a reliable estimation of recharge threshold value for an unconfined sandy aquifer are of critical importance for estimating natural rainfall recharge rates at reclaimed lands in Singapore.

In addition, the rainfall-recharge relationships for unconfined sandy aquifers have not been investigated, even though there have been studies carried out by Wu et al. (1996) for a heterogeneous soil profile. The soil profile studied by Wu et al. (1996) consists of a fine sand texture overlaid with loamy and clayey soils. Recharge events were found to correspond well to individual rainfalls, with small time-lags between them, when the water table was shallow (vadose zone thickness below 1.5m). For intermediate depth of water table (vadose zone thickness between 1.5 to 4.5m), recharge events were observed to be produced only by a concentrated rainfall cluster. A concentrated rainfall cluster refers to a group of individual rainfalls which produces an integrated (i.e., continuous, not isolated) recharge event.

For a heterogeneous soil profile, the rainfall-recharge relationships appear to depend strongly on the vadose zone thickness, as shown in studies by Wu et al. (1996). Unlike their heterogeneous soil profile, the unconfined sandy aquifers of the reclaimed lands in Singapore were filled using fairly

homogeneous sands. The significance of the influence of vadose zone thickness on the rainfall-recharge relationships may be different between a homogeneous sand profile and a heterogeneous soil profile overlaid with less permeable soils. Sands allow for high infiltration and percolation rates of rainwater. This may reduce the influence of vadose zone thickness on the rainfall-recharge relationships in unconfined sandy aquifers. Conversely, the top layer of clayey and loamy soils in the heterogeneous soil profile could retard the rainwater infiltration and percolation processes. This flow retardation could magnify the influence of vadose zone thickness on the rainfall-recharge relationships in the heterogeneous soil profile. Hence, rainfall-recharge relationships for unconfined sandy aquifers still remain largely unknown. An extensive investigation on the rainfall-recharge relationships at the unconfined sandy aquifers is needed to understand better the recharge characteristics, and enable reliable estimation of rainfall recharge rates at the reclaimed lands.

Reliable methodologies for estimating rainfall recharge are essential for investigating the feasibility of utilizing the reclaimed lands as potential water sources. As it is difficult to determine which among a wide variety of techniques is likely to provide the most reliable estimates, the application of multiple techniques has recently been emphasized for groundwater recharge estimates (Grismer et al., 2000; Scalon et al., 2002). Estimating groundwater recharge using combination of different estimation approaches is termed as “the application of multiple techniques” in groundwater studies.

Environmental tracers such as chloride are a common method for estimating low and long term recharge rates in semi-arid and arid regions (e.g. Bromley et al., 1997; Scalon 1991, 2000), mainly due to the lack of other more suitable alternatives. However, chloride tracer is not applicable for coastal unconfined aquifers, which are subjected to seawater intrusion (Mzila, 2003). The chloride tracer method is not applicable for unconfined aquifers that are subjected to salt intrusion and rock-water interactions (Wood and Sanford, 1995; Abu-Jaber, 2001), as the method assumes rainfall is the sole chloride source into the aquifer systems. In addition, the method requires a reliable

estimation of the mean chloride concentration of rainfall (Edmund et al., 2002), which could vary spatially and temporally due to fluctuating chloride contents in the Earth's atmosphere. In recent years, isotope tracers (such as ^3H , ^{14}C , ^{18}O) have been widely used in recharge estimations (e.g. Le Gal La Salle et al., 2001; Shivanna et al., 2002; Boronina et al., 2005). Compared to chloride tracer, conservative isotope tracer is applicable for unconfined aquifers exposed to salt intrusion problems. However, isotope tracer methods involve substantial efforts in collecting groundwater samples and in analyzing the isotopic contents. An extensive overview of current research and application in isotope hydrology can be found in Gibson et al. (2005).

Groundwater recharge estimation using numerical models provides an alternative to the tracer methods. Numerical models based on the Richards' equation are an effective tool for studying water transport processes within the vadose zone (e.g. Pan et al., 1997; Revelli and Ridolfi, 2000; Russo et al., 2001). The models' flexibility in integrating various forms of site heterogeneity, initial conditions, boundary conditions and controlling factors into the solution domains enables them to generate precise soil water variables within the vadose zone. However, their application for estimating long term or regional groundwater recharge remains difficult due to the vast amount of computational loads and time required in solving the highly nonlinear partial differential equations, even with the simplification of one-dimensional vertical flow (Dawes and Hatton, 1993; Romano et al., 2001; Beverly and Croton, 2002). The numerical solutions become highly time-consuming when fine grid spacing (van Dam and Feddes, 2000) and small initial time step (Lappala et al., 1993) are required for obtaining stable and accurate solutions. Fine grids and small time steps are generally required for simulations that involve soil evaporation and infiltration.

Compared to models based on the Richards' equation, water balance models are efficient for estimating long term groundwater recharge. As the water balance equations are the sole equations to be solved, the computational loads and time are reduced significantly, leading to their wide applications in

regional scales up to the order of thousands of kilometer squares (Gheith and Sultan, 2002; Kendy et al., 2003; Xu and Li, 2003; Sun and Cornish, 2005). However, the water balance method requires extensive data on the groundwater flow components and reliable estimates on evapotranspiration rate. This is because recharge is estimated by the residual of all the known components in the water balance equation. Using a conceptual rainfall-runoff model, Fazal et al. (2005) demonstrated that rainfall recharge could be estimated based only on rainfall, evaporation and water table level data. Nevertheless, their proposed model contains a large number of parameters (14 parameters), most of which are empirical.

Time series analysis of water table fluctuation (herein referred to as the water-table fluctuation method) provides another efficient alternative to models based on the Richards' equation. Although the water-table fluctuation method requires only time series of water table level for recharge estimations, a representative estimate of the aquifer specific yield is a pre-requisite for obtaining reliable recharge rate estimates. However, specific yield is not an aquifer constant property, but varies as a function of depth to water table (Childs, 1960). Difficulties in distinguishing noises caused by atmospheric pressure, entrapped air and tidal influences (Healy and Cook, 2002) from the rainfall induced water-table fluctuations could introduce further uncertainties into the estimations.

Empirical relationships between rainfall, soil properties and recharge rates could be an efficient method for estimating the long term groundwater recharge rates. Compared to tracer techniques, numerical modelling, water balance models and water table-fluctuation method, groundwater recharge estimation using empirical relationships involve much lower computational cost and time. Empirical relationships could thus be a useful tool for estimating long term groundwater recharge. The linear regression equations of rainfall - recharge developed by Wu et al. (1996) and the response function model developed by Wu et al. (1997) seem to be efficient estimation methods, as they need no numerical solution and require minimum input data (rainfall and open

water evaporation) for obtaining recharge estimates. Nevertheless, the practical applications of their methods are quite limited. This is because their equations were developed for a heterogeneous soil profile overlaid with top layers of clayey and loamy soils. The rainfall-recharge relationships could be different between a homogeneous sand profile and a heterogeneous soil profile overlaid with loamy soils, due to the significant difference in infiltration capacity between sandy and loamy soils. Moreover, the not commonly-used soil parameters in Wu et al.'s relationships further complicate the application of their equations to the present reclaimed land. The six parameters of the response function model (Wu et al., 1997) are not commonly-used soil parameters that could be inferred from soil textures, but could only be determined through numerical simulations or measurements. Furthermore, two of these parameters are not constant values but vary as a function of rainfall intensity. Therefore, new empirical relationships need to be developed for estimating long term natural rainfall recharge at the reclaimed lands.

Because of uncertainties associated with each recharge estimation approach, the use of multiple approaches is thus recommended to constrain the range of recharge estimations. In many cases, different approaches may complement each other and help to refine the conceptual modeling of the recharge process (Scalon et al., 2002). Examples of multiple approaches include the use of various tracers in the vadose zone and numerical modeling (Yang et al., 1999; Abu-Jaber, 2001; Le Gal La Salle et al., 2001); and the use of tracer test and water table fluctuation method (Lee and Lee, 2000). In the present research study, two well-established approaches, i.e. deterministic unsaturated zone modelling and the water table fluctuation method, were used to evaluate the reliability of the empirical relationships developed for the Changi site, in estimating natural rainfall recharge at the site. Deterministic unsaturated zone modelling based on the Richards equation provides estimates of potential recharge to the water table by taking into considerations factors influencing the recharge processes within the vadose zone. On the other hand, water table fluctuation method provides the net groundwater recharge

contributed by rainfall events based on time series analysis of the water-level fluctuations.

To obtain reliable estimates of groundwater recharge using the water table-fluctuation method, a representative value of specific yield for the reclaimed land needs to be determined. Curve matching between draw down data from well pumping tests and analytical solutions from groundwater modeling are among the widely accepted techniques for specific yield estimation. Non-uniqueness in result interpretations in curve matching (Freeze and Cherry, 1979, Section 8.6) is a major drawback of this method. Nonlinear least squares (Heidari and Moench, 1997), genetic algorithm (Lee et al., 2002) and inverse modeling (Chen and Chen, 2003) have been used recently to reduce the subjectivity in visual curve matching. However, errors inherent in the assumptions behind the development of the analytical models and other numerical errors of the solution algorithms could lead to unrealistic estimates of the aquifer parameters. Kollet and Zlotnik (2005) found that the conceptualization of flow above the falling water table, aquifer heterogeneity and return flow could lead to unrealistic and highly variable estimates. High installation cost of observation and pumped wells often make the pumping tests prohibitive for recharge studies. Compared to curve matching technique, estimation of specific yield using volume-balance method needs relatively low computational efforts. However, the value of specific yield was observed to increase as the pumping period increased (Nwankwor et al., 1984). This phenomenon is attributed to delay yield of water from the unsaturated zone (Akindunni and Gillham, 1992; Nwankwor et al., 1992; Lee et al., 2001) and flows from the zones outside the depression cone (Neuman, 1987). Incorrect assumption on the shape of the depression cone could also introduce further errors into the specific yield estimate (Lee et al., 2001).

Laboratory or field estimation of the porosity and the specific retention/residual moisture content is a widely used alternative approach to the pumping tests. Nevertheless, laboratory or field measurement is relatively time consuming, especially when the number of samples is large due to site

heterogeneity. The typical ranges of specific yield based on soil texture can be found in most textbooks (e.g. Todd, 1980, Table 2.5; McWhorter and Sunada, 1977, Table 2.2; Domenico and Schwartz, 1990, Table 4.2; Fetter, 1994, Table 4.4; Walton, 1987, Table C4; Walton, 1996, Table 8). However, a distinct classification of soil texture is generally not feasible for natural soils, especially when the soils are composed of different soil textures with varying composition percentages. Although there are typical curves relating specific yield to grain size (Todd, 1959, Figure 2.6; Raghunath, 1987; Figure 4.3), these curves ignore the effect of depth to water table (Childs, 1960), and assume the specific yield value depends solely on the grain size. Although water budget approach (Gburek and Folmer, 1999; Naik and Awasthi, 2003) does not require soil classification, extensive data on the groundwater flow components, evaporation and recharge rates are needed.

In view of the short comings of the field pumping tests and laboratory tests discussed above, a new estimation method was developed in the present research for estimating the areal specific yield of the reclaimed lands. The new method is useful as it requires relatively low computational efforts and uses readily available data, such as sieve analysis results. Results of sieve analysis are a common standard component of site investigation reports. This minimizes the computational and measurement costs. To ensure reliable estimation of specific yield, effect of depth to water table on the specific yield value and variations in grain sizes inherent in natural soil profiles are taken into consideration in developing the new estimation method.

In addition to the water table-fluctuation method, deterministic unsaturated zone modeling was also used to produce recharge estimates at the reclaimed land. The recharge estimates from unsaturated zone modeling serve as the benchmark for validating the reliability of the empirical relationships developed in this study. For deterministic unsaturated zone modeling, open water evaporation rates are required as input variables, for simulations of evapotranspiration rates during the recharge process. Reliable estimations of

open water evaporation rates are important to enable reliable estimations of evapotranspiration, and hence reliable recharge estimates.

Direct measurement of evaporation rates using evaporation pan is the most widely accepted method. However, this approach requires regular maintenance for reliable measurements. Measurements of small time step evaporation, such as hourly evaporation rates, are relatively difficult. Measuring devices with a high resolution are needed, as hourly evaporation rates are often in an order of less than one millimeter (mm). Evaporation models using meteorological factors as input variables thus provide a practical alternative for estimating short time step evaporation rates, as small time step meteorological variables are relatively easy to be measured and readily available.

The Penman's model is generally accepted to give the best estimate for open water evaporation, as energy supply and vapor transport are often the limiting factors (Chow et al., 1988, Section 3.5). Nevertheless, the vast amount of computational efforts needed, and the requirement of a comprehensive set of meteorological data (Hargreaves and Allen, 2003) often restrict its practical applications. For areas with a temperate climate, simplified mass transfer models (Singh and Xu, 1997), radiation-based models (Xu and Singh, 2000) and temperature-based models (Xu and Singh, 2001) have been found to be capable of providing good estimates of daily and monthly open water evaporation. Among these simplified evaporation models, mass transfer models were found to perform best for areas with a temperate climate (Singh and Xu, 1997). In a temperate climate, the vapor pressure deficit was found to correlate best with pan evaporation at all time steps, i.e. hourly, daily, 10-day and monthly time scales (Xu and Singh, 1998). However, all these models are highly empirical. Recalibration of the model parameters is necessary for the models to be applicable outside the region where they were originally calibrated (Xu and Singh, 1997; Xu and Singh, 2000; Xu and Singh, 2001).

Artificial Neural Network (ANN) has recently been widely used in modeling daily soil evaporation (Han and Felker, 1997), daily

evapotranspiration (Kumar et al., 2002), daily pan evaporation (Keskin and Terzi, 2006; Kisi, 2006; Sudheer et al., 2002) and daily actual crop evapotranspiration (Sudheer et al., 2003). Using temperature data alone, Sudheer et al. (2002) found that a properly trained ANN model could reasonably estimate the evaporation values for a study area in the temperate region. ANN models are superior to the conventional regression models, as ANN does not require any predetermination of regression forms. This advantage becomes more promising when the problem at hand is too complex to be represented using regression equations. However, the physical interpretation of ANN architecture, and the optimum data required for training and for adaptive learning still require further investigations (ASCE, 2000).

Although previous studies have shown that the radiation-based models, mass transfer models, temperature-based models and ANN models generally perform well for areas with a temperate climate; their applicability in modeling open water evaporation rates has not been evaluated in an equatorial climate. It is likely that the predominant meteorological factors affecting evaporation mechanisms in the equatorial region could be different from those in the temperate region. Part of the present study is therefore to evaluate the applicability the simplified evaporation models and the ANN models for estimating open water evaporation for the reclaimed lands in Singapore. Compared to the comprehensive Penman's model, the simplified evaporation models and the ANN models are more useful when limited meteorological data are available.

Prior to using unsaturated zone modelling for estimating groundwater recharge at the reclaimed land, the model needs to be calibrated and verified. The parameters to be calibrated include the water retention function and unsaturated hydraulic conductivity function. Direct measurements of soil hydraulic parameters, via laboratory or field experiments, are generally time-consuming and labor intensive. The problem of over parameterization (Beven, 1989; Woolhiser, 1996) further limits a purely deterministic modeling of heterogeneity. The principle of effective soil hydraulic parameters has been

found to be applicable for the prediction of average flow and transport behavior in a heterogeneous (Wildenschild and Jensen, 1999) and a layered (Jhorar et al., 2004) soil systems. The principle of effective soil hydraulic parameters has therefore been widely adopted for delineating soil properties at the scale of model application.

Inverse modelling, which involves optimizing parameters through minimization of the difference between the predicted and the observed variables, has recently been used for estimating effective soil hydraulic parameters (e.g. Inoue et al., 2000; Moench, 2003; Abbasi et al., 2004; Farcas et al., 2004; Tsou et al., 2005; Viotti et al., 2005). Manual model calibration, involving a 'trial and error' approach, is generally a tedious and time consuming process. Although nonlinear regression analysis is applicable for calibrating multiple parameters, an appropriate regression form relating the model parameters to the calibration variables is very difficult to be determined. To achieve global optimization, a large number of combinations must be tried out. Manual calibration becomes extremely tedious when the number of probable combinations increases dramatically due to increased number of parameters to be optimized. Moreover, the calibration results could be influenced by the model user's subjectivity and understanding of the system being modeled (Botterweg, 1995).

Compared to manual calibration, automatic calibration (e.g. Sonnenborg et al., 2003; Jhorar et al., 2004; Kowalsky, 2004; Eckhardt et al., 2005) is much more efficient where adjustments of parameters are executed automatically based on a specified search scheme and numerical measures of the goodness-of-fit. Incorporation of multiple objectives or multiple criteria (Madsen, 2000; Yu and Yang, 2000; Madsen, 2003) into the search algorithm further improves the robustness of the resulting models (Anderton et al., 2002).

With the availability of optimization algorithms such as AUTOCAL (DHI, 2005) and PEST (Doherty, 2004), automatic calibration could be executed without integrating the optimization algorithm into the model at code level. These algorithms generally require template files, instruction files and an

input control file to enable them to effectively ‘take control’ of the model during inverse modeling. This is not an overwhelming computational overhead when the number of calibration parameters is large due to site heterogeneity. However, the model to be calibrated must be capable of being run to completion without requiring user intervention. These requirements for AUTOCAL and PEST could be unattainable if the mesh size or time step needed to achieve stable solutions fall beyond the user-specified ranges during the optimization process. This happens when the mesh size or time step needed to achieve stable solutions vary significantly with the values of calibration parameters.

During the calibration of the unsaturated zone model for the reclaimed land, different mesh sizes and time steps were observed to be required to achieve stable solutions for the different values of calibration parameters. Simulations were observed to halt during the calibration process when the user-specified ranges of time step or mesh size had been exceeded. In order to continue the simulations, the user-specified ranges need to be redefined and smaller mesh size or time steps need to be used to achieve stable solutions. Under such a situation, auto calibration tools such as PEST and AUTOCAL are not applicable, as they require the model being calibrated to run to completion without any user intervention. Due to the requirement for user intervention during calibration, a new calibration algorithm was developed in the present research.

Artificial neural network (ANN) could be an effective alternative to manual calibration, as ANN does not require any predetermination of regression forms. ANN becomes an alternative to automatic calibration when the model to be calibrated is incapable of being run to completion without user intervention. ANN works as an external calibration algorithm, which is not integrated into the numerical model. More importantly, ANN has the ability of being generalized when appropriate network architecture has been selected, trained and tested properly (Haykin, 1999, Chapters 1 and 2). A good

generalization capability is important to ensure global optimization and reduce the number of simulations required for network training.

From the literature review presented above, there are areas relating to groundwater recharge studies, which remain not well understood, especially for unconfined sandy aquifers in an equatorial climate. The present research scope is very much motivated by the need to address these deficient areas, and to enable evaluation of the feasibility of developing the unconfined sandy aquifers in Singapore as potential water sources. The identified deficient areas which are addressed in the present research program are as summarized below:

1. Knowledge on rainfall recharge characteristics for unconfined sandy aquifers in an equatorial climate is still limited.
 - (i) In a semi-arid climate, previous studies on unconfined loamy aquifers show that light rainfalls tend to be lost through evapotranspiration, and groundwater recharge is contributed mainly from intense rainfall events. The high rainfall intensity in the equatorial region and the high permeability of sands may lead to different rainfall recharge characteristics;
 - (ii) The probable range of rainfall threshold value for recharge has not been established for unconfined sandy aquifers in the equatorial climate, although recharge threshold values have been estimated for fractured karst aquifers under different climatic conditions. Reliable estimation of recharge threshold value is important for rainfall recharge estimations; and
 - (iii) The rainfall-recharge relationships have not been investigated for unconfined sandy aquifers. Previous studies on rainfall-recharge relationships carried out by Wu et al. (1996) for a heterogeneous soil profile are not representative for unconfined sandy aquifers. Rainfall-recharge relationships may be different between their heterogeneous soil profile and the highly permeable homogeneous sands profile of the present study site.

2. Empirical relationships between meteorological factors, soil properties and recharge rates are efficient for estimating long term rainfall recharge rates at the study site. However, no empirical relationship currently exists for estimating rainfall recharge rate at unconfined sandy aquifers. Linear rainfall-recharge relationships developed by Wu et al (1996) and the response model developed by Wu et al. (1997) for a heterogeneous soil profile are not applicable to the present study site. The present study will develop empirical relationships for estimating the long term rainfall recharge rates at the unconfined sandy aquifers of the reclaimed lands.
3. Time series analysis of water table-fluctuations is a well-established method for recharge estimations. In this research study, this method was used to benchmark the reliability of empirical relationships developed for estimating rainfall recharge at the reclaimed land. This method requires accurate estimation of the aquifer specific yield. The well-established pumping and laboratory tests for specific yield determination are generally time-consuming and labor intensive. The present study will develop a new procedure for specific yield estimation, which involves low computational efforts and uses sieve analysis results readily from site investigation reports. The new procedure is considered as more reliable. It takes into consideration the effect of depth to water table on the specific yield, and the variations in grain sizes inherent in natural soils.
4. Deterministic unsaturated zone modeling is a well-established method for recharge estimations. In this research work, the method was used as the second benchmarking tool for evaluating the reliability of the empirical relationships developed for estimating long term rainfall recharge. Unsaturated zone modeling requires open water evaporation rates as input variables for evapotranspiration simulations. Simplified radiation-based models, mass transfer models, temperature-based models and artificial neural networks (ANN) have been shown by previous researchers to be

capable of estimating open water evaporation rates in the temperate regions. The present study evaluates the applicability of such simplified models for estimating open water evaporation rates in the equatorial region. The predominant evaporation mechanisms in the equatorial region could be different from those in the temperate region.

5. Prior to applying the unsaturated zone model for recharge estimation, the model needs to be calibrated and verified. Auto calibration tools such as PEST and AUTOCAL could provide effective alternatives to tedious manual calibration for the model. However, PEST and AUTOCAL require the model to be run to completion during calibration without any user intervention. During the calibration of the unsaturated zone model for the reclaimed land, user intervention was found to be necessary to redefine the user-specified ranges of time step or mesh size for the model. Auto calibration tool such as PEST and AUTOCAL hence could not be used. In this study, a new calibration algorithm for the unsaturated zone model is developed.

1.2 Objectives and scope of this research work

The present research program is very much guided by the desire to address the deficiencies in the current understanding of rainfall recharge processes in an unconfined sandy aquifer in the equatorial region; as discussed in Section 1.1.

The objectives and scope of the present research study are stated more specifically as follows.

1. To investigate the rainfall recharge characteristics at an unconfined sandy aquifers created from fairly homogeneous sand fills. The rainfall-recharge characteristics to be investigated include:

- (i) The influence of various meteorological and hydrogeological factors on the rainfall-recharge relationships, particularly the recharge rates at the reclaimed lands;
 - (ii) The probable range of recharge threshold values for the unconfined sandy aquifers; and
 - (iii) The quantitative rainfall-recharge relationships for the unconfined sandy aquifers.
2. To develop empirical relationships between meteorological factors, soil properties and recharge rates. These regression relationships developed are applied to estimate the long term rainfall recharge rates at the reclaimed land. The empirical relationships derived are validated against recharge estimates using other well-established approaches, including deterministic unsaturated zone modeling and the water table-fluctuation method.
 3. To develop a new procedure for estimating the representative specific yield of the unconfined sandy aquifer. This new method developed requires relatively low computational efforts and uses readily available data, such as sieve analysis results. The new method is used to estimate the specific yield of the study site. Specific yield is needed for estimating recharge rates using time series analysis of water table fluctuations.
 4. To evaluate the applicability of simplified radiation-based models, mass transfer models, temperature-based models and artificial neural network models (ANN) in modelling open water evaporation rates in the equatorial region. Open water evaporation rates are important input variables for the deterministic unsaturated zone model.
 5. To develop an efficient algorithm for calibrating and verifying the deterministic unsaturated zone model to the study site. The unsaturated

zone model was used as a benchmarking tool to validate the empirical relationships developed for estimating rainfall recharge rates at the reclaimed lands. The calibrated unsaturated zone model was also used to investigate the rainfall-recharge characteristics at the reclaimed land.

1.3 The study site

A suitable study site has first to be selected for scope of study as defined in Section 1.2. The study site needs to meet the following criteria:

1. The study site must be an unconfined sandy aquifer in the equatorial region; and
2. Substantial data must be available on hydrogeological and meteorological characteristics of the site.

The Changi reclaimed land (Figure 1.1) was chosen as the study site for the present research. The Changi reclaimed land site is situated along the eastern coast of Singapore island. It has an area of about 26km² and experiences an equatorial climate characterized by high temperature and high intensity rainfall. The mean annual rainfall at the study site is about 2400 mm. The reclaimed land was created from compaction of medium to coarse marine sands to depths of 7 to 15m. Underlying the sand fill layer is a thin layer of very soft marine clay with traces of seashell fragments (Mzila, 2003), which serves as the aquiclude of the overlying unconfined sandy aquifer. Beneath the marine clay layer is a confined aquifer with an overall thickness from 5 to 15m (Mzila, 2003). This research is restricted to the upper unconfined aquifer of the Changi reclaimed land site.

Figure 1.1 The Changi reclaimed land

The Changi reclaimed land site can basically be divided into two parts by a 20m wide concrete drain at the middle of the reclaimed land, as shown in Figure 1.1. The area to the east of the concrete drain is herein referred to as the 'eastern part' of the reclaimed land, while the area to the west of the concrete drain is referred to as the 'western part'. The land surface on the eastern part is nearly bare. Bush grasses can be found distributed unevenly at the western part.

No permanent abstraction well exists at or adjacent to the site. The site is drained by temporary drains. The aquifer system is exposed to the influence of coastal tidal fluctuations along its north, east and south boundaries. The water table generally slopes towards the open seas in the north, east and south, and towards an unlined open drain along the inland boundary of the reclaimed land.

Twenty-three (23) soil samples were collected by the Clean Water Programme (CWP, a 3-year research programme funded by A*STAR of Singapore) research team at different depths from 4 locations (C1 to C4) as shown in Figure 1.1. Each soil sample was collected using the ‘coring’ method and weighed about 2 to 4 kg. The results of sieve analyses as carried out by the CWP research team are shown in Table 1.1. The 95% confidence interval of the t – distribution for the effective grain size (d_{50}) was found to range from 0.375 to 0.461mm. A two-factor factorial experiment without replication was carried on the effective grain sizes (d_{50}) of the soil samples. From ANOVA (Analysis of Variance) results (for $\alpha' = 0.05$) as shown in Table 1.2, there is no sufficient evidence to conclude that the effective grain sizes d_{50} at these locations are significantly different from each other, as the values of F -statistic are smaller than the values of F -critical with high P -values (Montgomery and Runger, 2007, Chapter 14). The definitions for F -statistic, F -critical and P -value could be found in Table 1.2. In other words, the study area could be assumed as lithologically homogeneous in both the vertical and horizontal directions.

From the CPT (Cone Penetration Test) conducted by the CWP research team at locations LCPT307, LCPT701 and M2-275 (Figure 1.1), the sandfills were observed to be lithologically homogeneous, as shown in Figure 1.2. This result is consistent with the results from sieve analyses, as shown in Tables 1.1 and 1.2. The sandfills comprise mainly moderately to highly compressed sands with relative density between 70 to 98% (Schmertmann, 1978; Figure 5). The existence of a thin layer of very silty soils close to the ground surface (Figure 1.2) could basically be viewed as a local heterogeneity, as no constant trend of silty layer was observed either from the sieve analysis results or the CPT tests.

Table 1.1. Results of Sieve Analysis by the CWP Research Team

Depth (m)	d_{50} (mm)	C_u	C_c	Fine Sand (0.06- 0.2mm)	Composition (%)		
					Medium Sand (0.2- 0.6mm)	Coarse Sand (0.6 – 2 mm)	Gravel (2-60mm)
<u>Location C1</u>							
1.5	0.423	1.924	0.996	5.0	72.0	23.0	0.0
3.0	0.423	3.110	2.686	15.0	48.5	24.0	12.5
4.5	0.577	4.208	0.859	10.0	41.2	31.3	17.5
6.0	0.385	2.671	0.905	15.0	60.0	17.5	7.5
7.5	0.365	2.203	0.891	15.0	65.5	14.5	5.0
9.0	0.404	2.604	0.988	15.0	55.7	24.3	5.0
<u>Location C2</u>							
1.5	0.423	2.703	0.946	12.5	52.6	19.9	15.0
3.0	0.269	2.563	0.789	30.0	52.4	12.6	5.0
4.5	0.577	5.307	0.612	10.0	41.5	33.5	15.0
6.0	0.462	3.104	1.046	10.0	50.0	30.0	10.0
7.5	0.462	3.005	0.856	15.0	46.0	29.0	10.0
9.0	0.423	2.604	0.988	15.0	50.5	27.0	7.5
<u>Location C3</u>							
1.5	0.350	2.000	1.549	5.0	66.5	21.0	7.5
3.0	0.423	2.275	1.182	7.5	69.5	18.0	5.0
4.5	0.307	2.370	0.941	25.0	56.2	13.8	5.0
7.5	0.500	3.604	0.901	10.0	46.0	24.0	20.0
10.0	0.327	2.225	0.801	17.5	68.2	6.8	7.5
11.0	0.365	2.445	0.729	17.5	57.5	20.0	5.0
<u>Location C4</u>							
1.5	0.327	2.335	0.763	20.0	56.0	19.0	5.0
3.0	0.212	1.852	1.092	40.0	55.5	4.5	0.0
4.5	0.577	3.627	0.909	10.0	42.0	38.0	10.0
6.0	0.578	4.208	0.859	10.0	41.9	30.6	17.5
7.0	0.462	2.107	0.958	5.0	57.5	30.0	7.5

Notes:

C_u is uniformity coefficient; C_c is coefficient of grading; and d_{50} is effective grain size

Table 1.2. ANOVA Results for Two-Factor Factorial Experiment without Replication

<i>Source of Variation</i>	<i>SS</i>	<i>df</i>	<i>MS</i>	<i>F-statistic</i>	<i>P-value</i>	<i>F- critical</i>
Rows treatment (Depth effect)	0.08534	4	0.02134	2.13896	0.13843	3.25916
Columns treatment (Location effect)	0.01083	3	0.00361	0.36191	0.78168	3.49030
Error	0.11970	12	0.00998			
Total	0.21588	19				

Notes:

1. SS is sum of squares; df is degree of freedom; MS is mean square (equals to SS/df); F -statistic is factorial value of treatment; P -value is the smallest level of significance that leads to rejection of null hypothesis (refer to Montgomery and Runger, 2007, Chapter 14); and F -critical is the critical factorial value, which when is exceeded by F -statistic, the null hypothesis is rejected, otherwise the null hypothesis is accepted.
2. In this analysis, the null hypothesis, $H_0: \tau_1 = \tau_2 = \tau_3 \dots \dots \dots = \tau_i = 0$ where τ_i is the treatment effect.

Figure 1.2. CPT results and inferred relative density for locations: (a) LCPT307; (b) M2-275; (c) LCPT 701 (by the CWP Research Team)

Table 1.2. ANOVA Results for Two-Factor Factorial Experiment without Replication

Source of Variation	SS	df	MS	F-statistic	P-value	F- critical
Rows treatment (Depth effect)	0.08534	4	0.02134	2.13896	0.13843	3.25916
Columns treatment (Location effect)	0.01083	3	0.00361	0.36191	0.78168	3.49030
Error	0.11970	12	0.00998			
Total	0.21588	19				

Notes:

3. *SS* is sum of squares; *df* is degree of freedom; *MS* is mean square (equals to SS/df); *F-statistic* is factorial value of treatment; *P-value* is the smallest level of significance that leads to rejection of null hypothesis (refer to Montgomery and Runger, 2007, Chapter 14); and *F-critical* is the critical factorial value, which when is exceeded by *F-statistic*, the null hypothesis is rejected, otherwise the null hypothesis is accepted.
4. In this analysis, the null hypothesis, $H_0: \tau_1 = \tau_2 = \tau_3, \dots, \tau_i = 0$ where τ_i is the treatment effect.

1.4 Research methodology

The rainfall recharge characteristics at the Changi reclaimed land site were studied using two different approaches, i.e. the empirical approach and the deterministic approach.

The empirical approach used is based on time series analysis and auto-spectral analysis. Time series analysis has been widely used for estimating groundwater recharge (Goes, 1999; Ketchum et al., 2000; Healy and Cook, 2002), for acquiring regional information of an aquifer system (Padilla and Pulido-Bosch, 1995; Larocque et al., 1998), and for studying recharge processes of unconfined aquifers (Leduc et al., 1997; Lee and Lee, 2000). Auto-correlation analysis and cross-correlation analysis are two useful time series analysis methods to elucidate the characteristics of the time series being studied. Auto-correlation analysis is generally applied to investigate the linear dependency and the memory effect of a time series. Cross-correlation analysis can indicate the inter-relationship between an input time series and an output time series.

Through transforming a time series into signals in the frequency domain, the auto-spectral analysis is useful for identifying the periodic wave components that contribute significantly to the time series signal. Shih et al. (1999), Shih et al. (2000) and Shih and Lin (2002) demonstrated the usefulness of spectral analyses for studying the response characteristics of water table fluctuations, and for investigating the major factors causing seawater and groundwater fluctuations at their study areas.

Time series and spectral analyses require relatively low computational efforts and time, compared to deterministic modeling which involves model calibration and numerical computations. The attractiveness of time series analysis in groundwater studies lies in its simplicity and ease of use where knowledge of flow mechanisms through the vadose zone is not required. The empirical approach was therefore used as a model-independent analysis to give a first-order indication on the recharge characteristics at the Changi reclaimed land. The purposes of carrying out auto-correlation, cross-correlation and auto-spectral analyses in this research work are as follows.

1. Auto-correlation analysis on time series of groundwater-level fluctuations was carried out to investigate the characteristics of groundwater-level fluctuations at the Changi reclaimed land.
2. Cross-correlation analysis between time series of rainfalls (as input time series) and water table fluctuation (as output time series) was carried out to study the influence of rainfall patterns and vadose zone thickness on the:
 - (i) interdependency between rainfalls and groundwater-level fluctuation at the Changi reclaimed land; and
 - (ii) percolation rate (essentially the vertical flow velocity) of rainwater recharge from the soil surface to the underlying water table at the Changi reclaimed land.

3. Cross-correlation analysis between time series of coastal tidal fluctuation (as input time series) and water table fluctuation (as output time series) was carried out to investigate the influence of coastal tides on the water table fluctuation at the Changi reclaimed land.
4. Auto-spectral analysis on time series of water table fluctuation was carried out to identify the frequency bands of the wave components contributed by the rainfall recharge and coastal tides. Identification of frequency bands of the wave components is essential for design of noise filter to generate the time series of rainfall-induced water table-fluctuation (herein referred to as the filtered water-table fluctuation). Based on the filtered water-table fluctuation, the net recharge percentage was estimated for the Changi reclaimed land, using the water table-fluctuation method. The influence of rainfall patterns and the vadose zone thickness on the net recharge percentage was then investigated for the Changi reclaimed land.

Prior to applying the water table-fluctuation method for net recharge estimation, a representative value of specific yield for the aquifer needs to be estimated. A new procedure for estimating specific yield was developed. The new method was used to estimate the specific yield of the Changi reclaimed land. The reliability of the new method was evaluated by comparing its specific yield estimate against those from literature and field measurements.

Data required for the empirical studies include time series of rainfall, water table fluctuation and coastal tidal fluctuation. For estimating the specific yield of the Changi reclaimed land using new procedure developed, results of sieve analysis are required.

Although the empirical approach allows the inter-relationships between rainfall recharge, coastal tides and water table-fluctuation to be elucidated for the Changi reclaimed land, the approach does not explain the physical processes behind the inter-relationships. In other words, the empirical approach is a “black box” method, and is incapable of providing insights into the

physical processes taking place within the vadose zone. The physical processes involve in rainfall recharge include infiltration, percolation and soil evaporation within the vadose zone.

In order to provide physical explanations for the observations from the empirical approach, a deterministic modeling approach, which models the physical processes within the vadose zone, is needed. Therefore, deterministic unsaturated zone modeling was carried out as the second approach to elucidate the rainfall recharge processes. More specifically, the deterministic unsaturated zone modeling was carried out to:

1. investigate the influence of various meteorological and hydrogeological factors on the gross recharge percentage at the Changi reclaimed land. Gross recharge percentage refers to the remaining portion of rainwater reaching the water table after losses through evapotranspiration within the vadose zone. The meteorological factors considered include rainfall intensity, relative humidity, potential evaporation and air temperature. The hydrogeological factors considered include the vadose zone thickness, the saturated hydraulic conductivity and the parameters of the van Genuchten's water retention function.
2. obtain the probable recharge threshold values for the Changi reclaimed land under the different vadose zone thicknesses. The recharge threshold value refers to the minimum rainfall depth required to initiate groundwater recharge.
3. investigate the relationships between the rainfall intensity and the gross recharge percentage for the Changi reclaimed land.
4. provide possible physical explanations for the observed inter-relationships in the empirical approach.

In the present research, the VS2DI model (Hsieh et al., 2000) was used for the unsaturated zone modeling. VS2DI is a Richards equation-based numerical model for simulating fluid flow in a variably saturated porous medium. VS2DI assumes a single-phase (i.e. fluid phase) transport of water and ignores water vapor transport within the vadose zone. Numerous studies (e.g. Shurbaji et al., 1995; Boulet et al., 1997; Yamanaka et al., 1998) have shown that dry surface evaporation occurs beneath the soil surface and vapor transport is the main mechanism governing the rate of dry surface evaporation. However, liquid water flow is generally the rate-limiting process in soil evaporation except when the soil is too dry, in which case the total evaporation rate may be negligible anyway (Saravanapavan and Salvucci, 2000). Hysteresis effects during the wetting and drying cycles are not considered in VS2DI. Hysteresis effect generally needs to be considered in describing the dynamics of water distribution within the capillary fringe, where capillary pressure fluctuations associated with cyclic water table movements are the primary concern (Lehmann et al., 1998; Nielsen and Perrochet, 2000). For cases where soil moisture is the primary variable of interest, in particular the time-averaged moisture, the use of non-hysteresis Richards equation with a single-valued mean retention curve was found to be adequate (Stauffer and Kinzelbach, 2001; Werner and Lockington, 2003). The structural shortcoming of VS2DI in neglecting vapor transport and hysteresis effects thus does not influence the simulation results significantly. In conclusion, VS2DI model is an appropriate simulation tool for studying soil moisture dynamics within the vadose zone.

Prior to using VS2DI as a tool for investigating the rainfall recharge characteristics at the Changi reclaimed land, the model needs to be calibrated and verified. For calibration of VS2DI, open water evaporation rates need to be integrated into the model as input variables for evapotranspiration simulations. Accurate estimations of open water evaporation rates are necessary for accurate estimations of the model parameters. Errors in estimation of open water evaporation rates could lead to unrealistic or non representative values of the model parameters.

Simplified evaporation models, including radiation-based models, mass transfer models and temperature-based models, and artificial neural networks (ANNs), were developed and evaluated for their applicability in estimating the hourly and daily open water evaporation rates at the Changi reclaimed land. To evaluate the accuracy of the simplified evaporation models and ANNs, values estimated from these models were compared with those from the comprehensive Penman's model. Through correlation analyses, the predominant open water evaporation mechanism was also elucidated for the Changi reclaimed land.

Data required to develop and evaluate the evaporation models for the Changi reclaimed land include daily pan evaporation, solar radiation, relative humidity, air temperature and wind speed. The daily pan evaporation data are used to calibrate the albedo value in the Penman's model. The calibrated Penman's model is then used to generate reliable open water evaporation rates, which are used as benchmark values for evaluating the simplified evaporation models. The input variables for the evaporation models include solar radiation, relative humidity, air temperature and wind speed.

The estimated open water evaporation rates were then used as input variables for calibration and verification of VS2DI. An inverse modeling approach was developed to calibrate VS2DI against the field measured volumetric soil moisture profiles. The calibrated and verified VS2DI model was then used as a study tool to elucidate rainfall-recharge processes within the vadose zone. The model was also used to generate data on gross recharge percentages, which were then used to develop empirical relationships for recharge estimation. The reliability of empirical regression relationships for recharge estimations were evaluated by comparing their estimates against those from the water table-fluctuation method and the calibrated VS2DI simulations. The regression relationships were then applied to estimate the long term rainfall recharge percentage at the Changi reclaimed land.

1.5 Data collection

The data used in the present research work are as described below.

(i) Time series of water table elevations

Time series of water table elevations was needed for estimating rainfall recharge rates at the study site using the water table fluctuation method. The time series was also used for investigating the rainfall recharge characteristics using the empirical approach.

To obtain time series of water table elevations, twenty (20) observation wells (PVC standpipes) with an inner diameter of 50mm were installed by the CWP Research Team at the reclaimed land site, as shown in Figure 1.3.

To prevent phreatic zone drainage (Moench, 1994), all the observation wells are deep wells with their bases at 6 to 9m below the ground surface. The observation wells are screened within the saturated region of the unconfined aquifer with a screening length of 10 to 20cm, which consists of openings with a diameter of 5 to 10mm. The screened parts of the observation wells were wrapped by stainless steel wire mesh ($106\ \mu\text{m}$) to prevent in-situ sands from entering the observation wells, but yet allow free flow of water between the aquifer and the wells. The top ends of the observation wells were covered with end caps to prevent interference from rain water.

15-minute interval water table elevations were measured by the CWP Research Team using hydrostatic pressure transducers (Model 6508C, Unidata[®]) equipped with automatic loggers (STARLOGGER 6004C, Unidata[®]) in all the observation wells. The pressure transducers are factory calibrated and compensated for temperature effects. However, the sensor is not compensated for density change in water caused by temperature change. The density change is only significant in water where large temperature changes occur in the range of 20 to 60°C (Chow et al., 1988; Chapter 2). From in-situ measurements, soil temperature at the study site was found to fall between 24 and 35°C (carried out

by the CWP research team). Suppose the maximum water temperature at the study site could reach up to 35°C, the density change caused by the temperature change is just about 0.59% $[(1-(0.99567+0.9925)/2) \times 100\%]$. Obviously, the effect of temperature change on water density change is generally insignificant at the study site.

Figure 1.3 Locations of observation wells

The measured 15-minute groundwater-elevations of a day were averaged to compute the daily groundwater elevation. Error introduced from this approach is negligible, as the differences between the highest and the lowest groundwater elevations in a day during the study period (September 2003 to February 2004) are small, i.e. less than 0.02m. Water level elevations measured at observation well P015 represent the coastal tidal levels at the Changi reclaimed land. Time series of daily water table elevations collected between 1 September 2003 and 29 February 2004 are listed in Appendix A.

(ii) Time series of rainfall depths

Time series of rainfall depths collected were necessary for studying the rainfall recharge characteristics at the reclaimed land using the empirical approach.

To obtain time series of rainfall depths, 15-minute interval rainfalls were measured by the CWP Research Team using a tipping bucket rain gauge (Model 6506A, Unidata[®]) equipped with an automatic logger (STARLOGGER 6004C, Unidata[®]). The rain gauge is factory calibrated. The rain gauge was installed next to observation well M2-12 so that the measured rainfalls could be representative of the experimental plot at the eastern part of the reclaimed land, where the M and C series-observation wells were installed. The daily rainfall depths were obtained through integration of the measured 15-minute rainfalls within a day. Time series of daily rainfall depths collected between 1 September 2003 and 29 February 2004 are listed in Appendix A.

(iii) Results of sieve analysis

For specific yield estimation using the new procedure developed in this study, results of sieve analysis need to be collected for the Changi reclaimed land.

To obtain sieve analysis results, twenty-three (23) soil samples were collected by the CWP research team at different depths from 4 locations (C1 to C4) as shown in Figure 1.1. The results of sieve analysis are listed in Appendix E. Summary on the sieve analysis results can be found in Table 1.1.

(iv) Volumetric soil moisture content and soil suction head

Volumetric soil moisture content and soil suction head were collected for calibration and verification of VS2DI. The data was also needed for validation of the specific yield estimated using the new procedure developed.

For volumetric soil moisture contents and soil suction head, an EnviroSMART soil water content probe from Campbell Scientific Inc. was

installed at location M2-12 for measuring volumetric soil moisture contents at depths of 10, 30, 60, 100, 130, 170, 180 and 200cm below the ground surface. The multi-sensors of the probe measure soil water contents by utilizing the principle of high frequency capacitance, which has been proven to be highly sensitive and robust for field-scale, real time, soil water research (Starr and Paltineanu, 1998; Fares and Alva, 2000). Almost 99% of the readings are taken within 10cm radius from the outside of the access tube.

Five 229 soil water potential probes from Campbell Scientific Inc. were installed at 5 different depths, i.e. 10, 30, 100, 130 and 200cm below the ground surface for measuring the corresponding soil suction heads. Prior to installation at the site, the 229 soil water potential probes were pre-calibrated in the laboratory to obtain the $|\psi| - \Delta T$ relationship for each probe, where $|\psi|$ is soil suction head in kPa and ΔT is the temperature increase over a period of time. Each 229 probe was calibrated for soil suction heads between -10 and 1500kPa by placing the probe into a soil sample placed in a 15bar pressure plate. A 229 probe calibrated using a soil sample collected at a particular depth, was then installed at the depth where the soil sample was collected. A detail discussion on the calibration procedures of the probes can be found in Campbell Scientific Inc. (1999). Measurements of volumetric soil moisture content and its corresponding soil suction head are listed in Appendix C. Measurements of volumetric soil moisture profiles for VS2DI calibration and verification are listed in Appendix B.

(v) Meteorological data

Meteorological data used in the present research include solar radiation, air temperature, relative humidity and wind speed. These data were used to estimate open water evaporation rates, which were needed as input variables for calibration and verification of VS2DI.

For measurements of meteorological factors, a meteorological station was installed at location M2-12. All the measurements were carried out at a 15-

minute time interval. Solar radiation fluxes were measured using the LI200X Pyranometer from Campbell Scientific Inc. The LI200X Pyranometer measures incoming solar radiation with a silicon photovoltaic detector mounted in a cosine-corrected head. The silicon photovoltaic solar cell generally provide reliable estimates of solar fluxes, where its temperature sensitivity is low and its spectral response does not cause significant error (Kerr et al., 1967). The LI200X Pyranometer is factory-calibrated against an Eppley Precision Spectral Pyranometer to measure sun plus sky radiation. Relative humidity and air temperature were measured using the HMP45C Temperature and Relative Humidity Probe from Campbell Scientific Inc. Wind speed was measured using the 03001-5RM Young Wind Monitor from Campbell Scientific Inc. Rotation of the 4-blade helicoids-shaped propeller produces AC wave signal with a frequency proportional to the wind speed. All of the measurement devices were connected to a Campbell Scientific CR10X data logger installed at location M2-12. Measurements of meteorological data used for VS2DI calibration and verification are listed in Appendix B. Detail specifications of all the measurement devices are summarized in Appendix F.

(vi) Historical data from the Changi Meteorological Station

Historical data from the Changi Meteorological Station were used for evaluation of the simplified evaporation models and estimation of the long term rainfall recharge rates at the Changi reclaimed land. Meteorological variables measured continuously at this station include the solar radiation, air temperature, relative humidity, rainfall depth, pan evaporation and surface wind speed. The hourly data of solar radiation, air temperature, relative humidity and surface wind speed in year 2003 were used for evaluation of the evaporation models. The daily mean air temperature, relative humidity and surface wind speed were obtained by averaging the hourly measurements within a day. The total daily solar radiation data were obtained through integration of the hourly measurements within a day. The pan evaporation data

were measured on a daily time scale. Daily rainfall depths (from 1 January 1994 to 31 December 2003) from the Changi Meteorological Station were used as input variables for estimating long term rainfall recharge percentages at the Changi reclaimed land.

1.6 Layout of the thesis

Chapter 1 gives an overall view on the background, motivation, objectives and scope of the present research, the lithology and climatic conditions of the study site, the research methodology and the data collection needed for the studies. A critical literature review is also presented in this chapter to identify current deficient areas in the understanding of groundwater recharge.

Chapter 2 presents the development of a new procedure for estimating a representative value of specific yield for the Changi reclaimed land. The specific yield is needed for empirical modeling of the recharge process. Chapter 3 presents works relating to modeling of open water evaporation rates. The open water evaporation rates estimated were used for VS2DI calibration and verification. Calibration and verification of VS2DI are presented in Chapter 4.

Chapters 5 and 6 focus on studies on rainfall recharge characteristics at the Changi reclaimed land. Chapter 5 focuses on rainfall recharge studies using the empirical approach, while Chapter 6 focuses on rainfall recharge studies using the deterministic approach. Chapter 7 presents the development of empirical method for long term estimation of recharge rates at the Changi reclaimed land. Chapter 8 summarizes all the major findings and achievements obtained from this research work. Recommendations for future work are also addressed in Chapter 8.

CHAPTER 2

ESTIMATION OF AREAL SPECIFIC YIELD

2.1 Introduction

Time series analysis of groundwater table, referred to in this thesis as the “water table-fluctuation method”, is one of the well-established methods for estimating rainfall recharge at unconfined aquifers. In this study, the method is applied to investigate the rainfall recharge characteristics, and estimate the rainfall recharge rates at the Changi reclaimed land. A key input parameter required in the water table-fluctuation method is the areal specific yield of the aquifer. The areal specific yield for the study site hence needs to be estimated reliably. In this chapter, a new procedure is developed and applied to estimate the areal specific yield of the study site.

2.2 Methodology

2.2.1 Definition of specific yield

The specific yield in the present study is based on Meinzer (1923)’s definition, that the specific yield of a soil is the ratio of water volume which drains from a saturated soil by gravity force to the total volume of the soil. This definition can be represented as follows:

$$S_y = \theta_s - \theta_r \quad (2.1)$$

where S_y is the specific yield, θ_s is the porosity and θ_r is the specific retention. This definition neglects the water volume held by capillary forces within the capillary fringe and assumes a constant specific yield. However, specific yield could be variable, depending on the depth to water table below

the ground surface (Childs, 1960). Incorporating the effect of capillary fringe, Duke (1972) proposed the following equation:

$$S_y = \theta_s - \theta(H) \quad (2.2)$$

where H is the depth to water table below the ground surface and $\theta(H)$ could be estimated using water retention model. In the present study, the van Genuchten's water retention model was used, as it had been found to be accurate for practical applications (Stephens and Rehfeldt, 1985), and very useful even for porous materials exhibiting sharp curvature near saturation (Alessi et al., 1992). The van Genuchten's water retention model is as shown below:

$$\theta(H) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha H)^\beta\right]^{\frac{1}{\beta}}} \quad (2.3)$$

where θ_r is the residual moisture content (specific retention), θ_s is the saturated moisture content (porosity), and α and β are the fitting parameters. Referring to Equations (2.2) and (2.3), specific yield becomes zero when H equals to zero, as $\theta(0)$ equals to θ_s . Conversely, specific yield approximates to Meinzer (1923)'s definition (i.e. $\theta_s - \theta_r$) for large values of H , as $\theta(H)$ approximates to θ_r when H becomes large. In other words, specific yield is zero when water table is at the ground surface, and becomes magnified as the depth to water table increases. Specific yield attains a maximum value which equals the effective porosity (i.e. $\theta_s - \theta_r$), and becomes constant when the depth to water table increases beyond a certain value, which depends on the soil textures.

Dos Santos and Youngs (1969) extended the work of Childs (1960) by accounting for the changing shape of water moisture profile above the water table over time. Definition of specific yield considering the time factor is as shown below:

$$S_y = \frac{dW'/dt}{dH/dt} + \theta_s - \theta(H) \quad (2.4)$$

where dW'/dt is the variation of water moisture with time. In their study, the dW'/dt factor was found to be negligible for sandy soils. The specific yield value for a particular depth to water table at the study site could therefore be estimated reliably by coupling Equation (2.2) with Equation (2.3), without taking into consideration the dW'/dt factor in the estimation. The coupled equation is as shown below:

$$S_y = \theta_s - \left[\theta_r + \frac{(\theta_s - \theta_r)}{[1 + (\alpha H)^\beta]^{\frac{1}{\beta}}} \right] \quad (2.5)$$

2.2.2 Construction of specific yield-effective grain size curves

Using Equation (2.5) and the published values of the van Genuchten's parameters, the specific yield profile could be constructed for a given soil texture. The specific yield - effective grain size curve at a given H value could then be constructed by plotting the specific yields of the different soil textures against their effective grain sizes (d_{50}) at that H value. The computational procedures for constructing the specific yield – effective grain size curves are illustrated in Figure 2.1. Each of these curves could be fitted by a regression equation.

Figure 2.1. Procedures for constructing specific yield- effective grain size curve

2.2.3. Computation of “point” specific yield

The constructed specific yield – effective grain size curves or their regression equations could be used for estimating the specific yield of each of the soil samples. Suppose 25 soil samples are collected systematically from a study site as illustrated in Figure 2.2. These samples are collected at 5 different locations (locations A1 to A5), at from 5 different depths to water table at each location (say depths H1 to H5). Sieve analyses are conducted to determine the effective grain size (d_{50}) of each of the soil samples. The specific yield for each of the

soil samples could be estimated using the constructed specific yield – effective grain size curve/regression equation, using its effective grain size and depth to water table as input variables. The estimated specific yields of the soil samples are regarded as “point” specific yields, applicable to the locations where the soil samples are collected. The procedures for computing the “point” specific yields of a study area are illustrated in Figure 2.2.

2.2.4 Transformation of “point” specific yields into “areal” specific yield

The number of possible “point” specific yields for a study site could theoretically be infinite, as the volumes of the soil samples are much smaller than the entire volume of the study site. In other words, the “point” specific yields within a study site could be regarded as a population with an infinite size. Averaging the “point” specific yields within a study site arithmetically would yield an “areal” specific yield of the site. This is an assumption made in the present procedure. Since it is not feasible to obtain all the “point” specific yields for the entire study site, the “areal” specific yield has to be inferred from the “point” specific yields of limited soil samples.

The Central Limit Theorem states that even if the probability distribution of a population is unknown, the sample distribution with a sample mean $\bar{X}$ will still be approximately normal with mean μ and variance σ^2/N , provided the sample size is large (Montgomery and Runger, 2003, Chapter 7), where μ is the mean of the population, σ is the standard deviation of the population and N is the sample size. This assumption is justified if the normality plot of the sample values shows almost a straight line.

When the sample size is large (generally more than 30) and the variance of the population is known, a $100(1 - \alpha')\%$ confidence interval (CI) on μ is given by:

$$\bar{X} - Z_{\frac{\alpha'}{2}} \cdot \frac{\sigma}{\sqrt{N}} \leq \mu \leq \bar{X} + Z_{\frac{\alpha'}{2}} \cdot \frac{\sigma}{\sqrt{N}} \quad (2.6)$$

where $Z_{\alpha'/2}$ is the upper $100\alpha'/2$ percentage point of the standard normal distribution.

Figure 2.2. Procedures for computing "point" specific yields

However, the variance of the population is often unknown and the sample size is usually small in most engineering problems. Therefore, Equation (2.6) has limited applications for most engineering problems, and the t – distribution with $N-1$ degrees of freedom is normally used instead. A $100(1 - \alpha')$ % confidence interval (CI) on μ based on t – distribution is given by:

$$\bar{X} - t_{\frac{\alpha'}{2}, N-1} \frac{S}{\sqrt{N}} \leq \mu \leq \bar{X} + t_{\frac{\alpha'}{2}, N-1} \frac{S}{\sqrt{N}} \quad (2.7)$$

where $t_{\frac{\alpha'}{2}, N-1}$ is an upper-tail $100\alpha'$ percentage point of the t – distribution with $N - 1$ degrees of freedom, and S is the standard deviation of the sample. The t – distribution approximates the normal distribution when the degree of freedom is close to infinity, indicating a large sample size.

In this case, $\bar{X}$ is the average of the “point” specific yields, S is the standard deviation of the “point” specific yields, μ is the “areal” specific yield and N is the number of soil samples. For convenience, the notations in Equation (2.7) are replaced with notations related to specific yield to produce the following equation for transforming the “point” specific yields into an “areal” specific yield:

$$\bar{S}_{y_{point}} - t_{\frac{\alpha'}{2}, N-1} \frac{S_{point}}{\sqrt{N}} \leq S_{y_{areal}} \leq \bar{S}_{y_{point}} + t_{\frac{\alpha'}{2}, N-1} \frac{S_{point}}{\sqrt{N}} \quad (2.8)$$

where $\bar{S}_{y_{point}}$ is the average of the “point” specific yields, S_{point} is the standard deviation of the “point” specific yields, $S_{y_{areal}}$ is the “areal” specific yield and N is the number of soil samples.

The precision of the confidence interval is $2t_{\alpha'/2, N-1} S_{point} / \sqrt{N}$. This means that in using the $\overline{S}_{y\ point}$ to estimate the “areal” specific yield, the error $E = \left| \overline{S}_{y\ point} - S_{y\ areal} \right|$ with $100(1 - \alpha')$ % confidence is:

$$E = \frac{2t_{\alpha'/2, N-1} S_{point}}{\sqrt{N}} \quad (2.9)$$

Referring to Equation (2.9), the precision of the confidence interval appears to be dependent on the sample size N and the site heterogeneity, indicated by S_{point} . This implies that a better accuracy could be obtained if the site is fairly homogeneous and the sample size is big. By assuming a value for S_{point} , Equation (2.9) could be used for choosing the sample size.

2.3 Application of the proposed method

2.3.1 Published values of van Genuchten' parameters

Instead of using laboratory experiments to obtain the van Genuchten's water retention parameters for the study site, the published values of Wildenschild and Jensen (1999) were used for constructing the specific yield profiles of the sand fill. They measured the retention curves of five homogeneous sands, ranging from coarse sand (sand 3) to fine sand (sand 00), using the automated syringe pump methods. An extensive description of the methods and their calibration works can be found in Wildenschild et al. (1997) and Wildenschild and Jensen (1999). The values of their calibrated water retention parameters and the corresponding effective grain sizes are summarized in Table 2.1. The effective grain sizes of the five homogeneous sands were estimated from the grain size distribution curves of Wildenschild and Jensen (1999). The effective grain sizes of these homogeneous sands range from 0.391 to 0.838 mm.

Table 2.1. Published Values of Parameters of van Genuchten’s Water Retention Model and Effective Grain Sizes (Wildenschild and Jensen, 1999)

Sand Notation	d_{50} (mm)	C_u	Parameter of Van Genuchten			
			α (1/cm)	β	θ_s	θ_r
00	0.391	1.17	0.026	8.0	0.360	0.094
0	0.406	1.33	0.024	8.3	0.369	0.060
1	0.575	1.71	0.044	12.0	0.370	0.014
2	0.636	1.20	0.060	9.7	0.367	0.014
3	0.838	2.00	0.098	7.8	0.363	0.005

Notes: C_u is uniformity coefficient; and d_{50} is effective grain size

2.3.2 Estimation of the “areal” specific yield

By substituting the published values of the van Genuchten’s model into Equation (2.5), the specific yield profiles of the five homogeneous sands were constructed as shown in Figure 2.3.

Figure 2.3. Specific yield profiles for five homogeneous sands

From the constructed profiles, it appears that the apparent specific yields of the five homogeneous sands achieve their maximum values, i.e. effective porosity, at a shallow water table depth of about 1m below the ground

surface. Fine sands (sand 00 and sand 0) were observed to achieve the maximum specific yield at a slightly deeper depth than coarse sands (sand 1, sand 2 and sand 3).

Figure 2.4 Specific yield – effective grain size curves of the study site

Based on the procedures described in Section 2.2.2, the specific yield – effective grain size curves for different values of H were constructed (Figure 2.4). A good-fitting quadratic relationship could generally be observed between the specific yield and the effective grain size. These curves are applicable for sands with effective grain size ranging between 0.2 to 1.0 mm. As the effective grain sizes of the soil samples in the present study (0.232 to 0.630 mm) lie within this range, these curves could be applied for estimating the “point” specific yields of the soil samples. From differentiation of the regression equations, the d_{50} values corresponding to the maximum values of the curves were found to fall around 0.722 mm, i.e. within the range of coarse sands (0.6 to 2 mm). This result shows consistency with the typical curves found in Todd (1959, Figure 2.6) and Raghunath (1987, Figure 4.3), though d_{10} (the grain size in which the cumulative total, beginning with the coarsest material, reaches

10% of the total sample) was used as the horizontal axis in their curves instead of d_{50} used in the present study.

The curve with a H value of 1 m basically represents the effective porosity – effective grain size relationship. This is because the apparent specific yields of the homogeneous sands achieve their maximum values, i.e. effective porosity, at a shallow water table depth of about 1m below the ground surface (see Figure 2.3). This curve is therefore applicable for estimating “point” specific yields whenever the H value exceeds 1.0 m. Since the depths to water table at the study site varied between 1.5 to 4.0 m, the curve with a H value of 1 m was therefore applied for computing the “point” specific yields of all the soil samples at the study site.

As the study site has been shown to have a fairly homogenous soil texture (from the ANOVA and CPT, Section 1.3), the estimated “point” specific yields of all the soil samples were included for estimating the “areal” specific yield. A 95% confidence interval of t - distribution for the “areal” specific yield was computed using the built-in statistical tool of Microsoft Excel. The “areal” specific yield was found to range from 0.27 to 0.31. An almost straight line in the probability plot of the “point” specific yields (Figure 2.5) justifies the normal distribution assumption of the Central Limit Theorem. The discrepancies between the sample values and the straight line was most likely due to the soil samples not being collected from the site in a randomized order, as it is not feasible to collect a soil sample at a deeper depth before collecting the soil sample above it.

Figure 2.5. Probability plot of the estimated “point” specific yields

2.4 Field measurement

To assess the reliability of the present method in estimating the “areal” specific yield, the field porosity and specific retention at the study site were measured indirectly through curve-fitting between the measured volumetric soil moisture contents and soil suction heads collected at location M2-12. Works on the curve-fitting and the reliability of the fitted values of the parameters are discussed in Section 4.4.1. The fitted values of effective soil hydraulic parameters are summarized in Table 2.2. The value of the indirectly measured specific yield (which equals the effective porosity) is therefore about 0.32, which is close to the estimated range using the present method, i.e. 0.27 to 0.31.

By comparing the lower and upper bounds of the estimated range of the areal specific yield against the field measurements, a deviation of 3.2 to 18.5% was observed between the estimated values and the field measurements. The specific yield range of (0.27 – 0.31) represents the 95% confidence interval of the areal specific yield for the experimental plot (bounded by the 4 corners C1

to C4, as shown in Figure 1.1). In order words, there is a 95% probability that the “true” areal specific yield will fall within this range. The “true” value of the areal specific yield will never be known. On the other hand, the field measurement of 0.32 represents a localized value. This is because the field measurement was carried out at one point near the centre of the experiment plot (M2-12 as shown in Figure 1.3).

Table 2.2 Fitted Effective Soil Hydraulic Parameters for the In-Situ Sandy Soils

Parameter	Fitted value	95% Confidence Interval
θ_s	0.375	0.3734 – 0.3774
θ_r	0.052	0.052*
α (1/cm)	0.02244	0.02201 – 0.02288
β	1.721	1.716 – 1.725

Notes: * 0.052 is the upper bound of the range set for searching θ_r . The typical range (0.005 – 0.052) for θ_r was used as the bound in the searches

The deviation ranging from 3.2 to 18.5% between the estimated values and the field measurements is not excessive, as estimation of specific yield is normally associated with high uncertainty. A much larger deviation (18 to 32%) has been reported in other studies on homogeneous sands, when different techniques are used to estimate specific yield (Healy and Cook, 2002, Table 1).

2.5 Discussions

To ascertain that the estimated ‘areal’ specific yield is representative for the study site; a 95% confidence interval of the effective grain size was computed for the study site. The 95%CI was found to range from 0.375 to 0.461 mm. Substituting the lower and upper bounds of this confidence interval into the regression equation (for $H = 1.0$ m) produces a specific yield range from 0.28 to 0.32. This range is close to the range estimated from the present method

(0.27 to 0.31). Therefore, the “areal” specific yield estimated using the present procedure corresponds well to the average effective grain size of the study site.

The typical ranges of specific yield for sands from the literature are summarized in Table 2.3.

Table 2.3 Typical Range of Specific Yield for Sands

	Typical range
<u>Sand, coarse</u>	
Fetter (1994)	0.20 – 0.35
Walton (1987; 1996)	0.20 – 0.35
<u>Sand, medium</u>	
Fetter (1994)	0.15 – 0.32
Walton (1987;1996)	0.15 – 0.30
<u>Sand, fine</u>	
Walton (1987; 1996)	0.10 – 0.30
<u>Sand</u>	
Raghunath (1987)	0.10 – 0.30

A clear-cut sand texture classification for the soil samples in the present study is difficult, as all the samples contain significant proportions of coarse, medium and fine sands, and gravels (refer to Table 1.1). The compositions of coarse, medium and fine sands and gravels range from 19 to 26%, 50 to 59%, 11 to 18% and 6.4 to 11%, respectively. Hence, the soil samples could not be categorized under any of the standard sand textures. Instead of using the wide ranges (more than 0.15) of specific yield suggested in the literature, the present procedure produces a narrower range of specific yield estimate for the study area, i.e. 0.04, and a high confidence level of 95%. Besides, the estimated specific yield lies within the typical ranges in the literature, and is close to the field measurement.

Although numerous methods utilizing the water retention parameters (Dos Santos and Youngs, 1969; Duke, 1972, Healy and Cook, 2002) and specific yield – grain size relationship (Todd, 1959, Figure 2.6; Raghunath, 1987, Figure 4.3) have been proposed for estimating the specific yield of

unconfined aquifers, none of these methods considers the variability in soil grain sizes inherent in natural soil conditions. Estimation using a small number of soil samples or simple average of the soil samples does not produce a convincing estimate of the representative specific yield. The uncertainty associated with these methods becomes more pronounced when the number of soil samples is small and the standard deviation of the variability is large.

The data required for the present procedure, i.e. effective grain sizes, can be obtained readily, as sieve analyses are a common standard component of site investigation reports. Since the cost and time involved for obtaining the soil grain size distribution curves are relatively low, more soil samples could be analyzed. Thus, a sufficiently large number of “point” specific yields, distributed over a large study area, could be used for estimation of the “areal” specific yield. The present method is able to produce a more reliable estimate of the “areal” specific yield, as a large number of soil samples, and the inherent variability in natural soil conditions, are integrated in the estimation procedure.

In conclusion, this chapter demonstrates a new procedure for reliable estimation of aquifer specific yield using published values of the van Genuchten’s water retention parameters and the effective grain sizes of soil samples. The method developed was used to estimate the areal specific yield of the Changi reclaimed land. The estimated range of areal specific yield (i.e. 0.27 – 0.31) will be used in the water table-fluctuation method for estimating net recharge percentages in Chapter 5.

CHAPTER 3

MODELLING OPEN WATER EVAPORATION RATES

3.1 Introduction

Deterministic unsaturated zone modeling requires open water evaporation rates for simulation of evapotranspiration losses during percolation, which directly affects the rainfall recharge rate. Simplified evaporation models such as radiation-based models, mass transfer models, temperature-based models and artificial neural network (ANN) have been shown by previous researchers to be able to provide good estimates of open water evaporation rates in the temperate regions. Compared to the comprehensive Penman's method, these models are more applicable when limited meteorological data are available. This chapter investigates the applicability of these simplified models and ANN in the equatorial region. Once verified, these simplified models can be used to generate open water evaporation rates to support deterministic unsaturated zone modelling of the study site.

3.2 Review of simplified evaporation models

3.2.1 Radiation-based models

The radiation-based models could be categorized in terms of the following general forms of equations (Xu and Singh, 2000), denoted as Model A_R to Model D_R below:

$$\text{Model A}_R: \quad E = a_1 \frac{\Delta}{\Delta + \gamma} R_s - a_2 \quad (3.1)$$

$$\text{Model B}_R: \quad E = a_1 (T - a_2) R_s \quad (3.2)$$

$$\text{Model C}_R: \quad E = a_1 R_s \quad (3.3)$$

$$\text{Model D}_R: \quad E = a_1 \frac{\Delta}{\Delta + \gamma} R_N \quad (3.4)$$

where E is the evaporation rates (in mm), R_S is the incoming total solar radiation (in 0.01 MJ/m^2), T is the air temperature (in $^{\circ}\text{C}$), Δ is the gradient of saturated vapor pressure curve (in $\text{Pa}/^{\circ}\text{C}$), γ is the psychometric constant (in $\text{Pa}/^{\circ}\text{C}$), and a_1, a_2 are the equation coefficients. R_N is the net radiation and is approximated by $(1 - \alpha_a)R_S$, assuming negligible radiation emission and conduction, and α_a is the albedo value.

These generalized equations, except for model C_R , require temperature and solar radiation for estimating open water evaporation rates. Different from the generalized equations of Xu and Singh (2000), these equations assume a constant value for latent heat, and lump this constant into the coefficient a_1 to ease the computational procedures. The fifth generalized equation of Xu and Singh (2000) was not evaluated in the present study, as it requires relative humidity as an additional input variable. The present study evaluates radiation-based models, which need only two or less meteorological parameters as input variables.

3.2.2 Mass transfer models

Singh and Xu (1997) generalized mass transfer models into seven forms of equations. Five of the seven generalized equations, denoted below as Model A_M to Model E_M are as follows:

$$\text{Model A}_M: \quad E = a_1 (e_s - e_a) \quad (3.5)$$

$$\text{Model B}_M: \quad E = a_1 U (e_s - e_a) \quad (3.6)$$

$$\text{Model C}_M: \quad E = a_1 (1 - \exp(-U))(e_s - e_a) \quad (3.7)$$

$$\text{Model D}_M: \quad E = a_1(1 + a_2 U)(e_s - e_a) \quad (3.8)$$

$$\text{Model E}_M: \quad E = a_1(T + 25)^2(100 - RH) \quad (3.9)$$

where e_s is the saturated vapor pressure (in Pa.), e_a is the actual vapor pressure (in Pa.), U is the surface wind velocity (in m/s) and RH is the relative humidity (in %).

The other two generalized equations are excluded from the present study, as they require dew point temperature, which is not readily available. The saturation vapor pressure, e_s and the actual vapor pressure, e_a could be approximated by:

$$e_s \approx 611 \exp\left(\frac{17.27T}{237.3 + T}\right) \quad (3.10)$$

$$e_a \approx e_s RH \quad (3.11)$$

3.2.3 Temperature-based models

Most of the temperature-based models could be generalized into the following two forms (Xu and Singh, 2001):

$$E = a_1 T^{a_2} \quad (3.12)$$

$$E = a_1 d_1 T(a_2 - a_3 RH) \quad (3.13)$$

where d_1 is the day length and a_1 , a_2 and a_3 are the equation coefficients.

The temperature-based model evaluated in the present study is Equation (3.12). Equation (3.13) is excluded from the evaluation, as it requires relative humidity as an additional input variable.

3.2.4 Artificial neural network (ANN) models

The architectures of the ANN models developed in the present study are discussed here. More theories on ANN can be found in Han and Felker (1997),

Kumar et al. (2002), Sudheer et al. (2002, 2003), and in textbooks on neural networks (e.g. Haykin, 1999, Chapter 4).

In the present study, a multi-layer feed forward network with back propagation algorithm was developed to predict the hourly and daily open water evaporation rates at the study site. The feed forward networks had been proven to be generally successful for identifying highly non-linear (input-output) relationships without the need of a thorough understanding of the physical processes involved (van den Boogaard and Mynett, 2004). The schematic diagram for a multi-layer feed forward network is shown in Figure 3.1.

Figure 3.1 The schematic diagram of the ANN (4-6-1) model structure

The network consists of three layers, namely an input layer, a hidden layer and an output layer. The number of neurons in the input layer depends on the number of input variables used for the estimations. The output layer contains only one tan-sigmoid neuron, producing the corresponding hourly evaporation rates for a given input vector. The tan-sigmoid function constrains the output values within a range from -1 to $+1$. The hidden layer contains a

number of tan-sigmoid neurons. The optimum number of the neurons in this layer was determined based on the mean square error (MSE) between the predicted values and the measured values during the testing process. Neurons with nonlinear transfer function in the hidden and output layers allow the network to learn the nonlinear relationships between the input and the output vectors. The multi-layer feed forward networks were trained using the Levenberg-Marquardt (LM) back propagation algorithm. This algorithm provides fast convergence for function approximation problems (MATLAB, 2003). The development of the ANN models was executed using the neural network toolbox of MATLAB.

3.3 Climate dataset

Hourly meteorological data for year 2003 from the Changi Meteorological Station were used in the present study. The average monthly values of these meteorological variables are as summarized in Table 3.1.

Table 3.1 Average Monthly Values of Main Climatic Parameters and Pan Evaporation at Changi Meteorological Station, Singapore (2003)

Month	Climatic Parameters				
	Total incoming solar radiation	Relative humidity	Surface wind speed	Air temperature	Pan Evaporation
	(0.01 MJ/m2)	(%)	(m/s)	(°C)	(mm)
Jan	1492.26	86.9	2.5	26.7	129.37
Feb	1732.68	85.1	2.7	27.1	137.42
Mar	1894.29	83.7	2.3	28.1	152.10
April	1490.07	86.7	1.1	27.9	98.40
May	1615.16	81.7	1.7	29.2	147.77
June	1640.70	78.6	2.5	28.9	161.07
July	1515.39	81.7	2.7	28.1	145.70
Aug	1633.10	83.1	2.5	28.2	147.87
Sept	1522.33	84.8	1.8	27.6	118.50
Oct	1549.61	84.9	1.7	27.6	126.38
Nov	1351.50	87.3	1.0	27.1	86.59
Dec	1406.77	87.2	2.1	26.6	114.27

Meteorological variables measured continuously at this station include solar radiation, air temperature, relative humidity, rainfall depth, pan evaporation and surface wind speed. The daily mean air temperature, relative humidity and surface wind speed were obtained by averaging the hourly measurements within a day. The total daily solar radiation data were obtained through integration of the hourly measurements within a day. The pan evaporation data were measured on a daily time scale.

3.4 Generation of dataset for hourly evaporation rates

As hourly evaporation rates are difficult to be measured, daily evaporation rates at the station were measured using an evaporation pan. Using the measured hourly meteorological data, the Penman's model was applied to generate the hourly evaporation dataset. The Penman's model is regarded as the most complete model for open water evaporation, taking into consideration both energy driven and aerodynamic driven evaporation mechanisms (Chow et al., 1988, Section 3.5). The Penman's model is as shown below.

$$E_p = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma} E_{ar} \quad (3.14)$$

where γ is the psychrometric constant, Δ is the gradient of the saturated pressure curve at air temperature, E_r is the solar energy driven evaporation rate, E_{ar} is the aerodynamic driven evaporation rate and E_p is the potential open water evaporation.

Howard and Lloyd (1979) found that evaporation rates estimated from the Penman's model are sensitive to the albedo value. To generate unbiased evaporation estimates, an optimum albedo value hence needs to be calibrated. Using the Penman's model, hourly evaporation estimates within a day were computed for different albedo values and were summed up to yield daily evaporation estimates. A surface roughness height of 0.035cm, within the typical range from 0.01 to 0.06 cm (Chow et al., 1988, Table 2.8.2), was fixed

in the computations. Comparison between the estimated and the measured daily evaporation rates are shown in Figure 3.2.

Figure 3.2 Estimation of unbiased albedo value

An albedo value of 0.1259 was found to yield unbiased evaporation estimates, as this value produces a straight line with a slope of one. The larger values of albedo, i.e. 0.1660 and 0.2273, underestimate the evaporation rates by producing straight lines with slopes larger than one. The lower value of albedo, i.e. 0.050, overestimates the evaporation rates by producing a straight line with a slope lower than one. The ‘best fit’ albedo value of 0.1259 is within the typical range for water body of 0.07 – 0.14 (Tindall and Kunkel, 1999, Table 9.4).

From the sensitivity tests, the hourly evaporation estimates were found to be highly sensitive to solar radiation and albedo value, but insensitive to air temperature, surface wind speed, relative humidity and surface roughness height, as shown in Figure 3.3. Nevertheless, daily evaporation rate was found to be quite insensitive to albedo value. The calculated daily evaporation rates vary from +1.8% to -1.5% of the measured evaporation rates for albedo values

over a range of 0.05 to 0.2273. The ranges of parameters used for the sensitivity tests are shown in Table 3.2.

Figure 3.3 Sensitivity test of Penman's model for hourly evaporation estimates

For comparison purpose, the parameters were standardized into dimensionless parameters as follows:

$$C^* = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \tag{3.15}$$

where C^* is the dimensionless parameter, X_i is the data point, $X_{\max}$ is the data with maximum value and $X_{\min}$ is the data with minimum value.

Table 3.2 Range of Parameters Used for the Sensitivity Test	
Parameter	Tested Range
Global radiation (0.01 MJ/m ²)	5 - 500
Relative humidity (%)	40 - 100
Air temperature (°C)	20 - 35
Surface wind speed (m/s)	0.5 - 15
Albedo (Dimensionless)	0 - 1.0
Surface roughness height (cm)	0.01 - 0.06

3.5 Results and discussions

3.5.1 Correlation studies

Correlation studies between the pan evaporation values and the meteorological variables were carried out to identify the predominant climatic factors which influence the evaporation rates significantly. The meteorological factors investigated include solar radiation, relative humidity, air temperature and surface wind speed on both the hourly and daily time scales. The results of the correlation studies are shown in Figure 3.4 and Figure 3.5 for the hourly and daily time scales respectively. For ease of comparison, the values of pan evaporation and meteorological variables were standardized through (Xu and Singh, 1998):

$$Z_i = \frac{X_i - \bar{X}}{S} \quad (3.16)$$

where Z_i is the standardized parameter, $\bar{X}$ is the data mean, S is the standard deviation. To have a direct comparison between pan evaporation and relative humidity, the values of relative humidity were standardized through Equation (3.17) instead of Equation (3.16), as relative humidity is inversely proportional to pan evaporation.

$$Z_i = \frac{\bar{X} - X_i}{S} \quad (3.17)$$

Solar radiation was found to correlate most strongly with pan evaporation on both the hourly and daily time-scales. Relative humidity shows fairly good correlation with pan evaporation on a daily time-scale, but demonstrates poor correlation with a significant lag on an hourly time-scale. Air temperature correlates poorly with pan evaporation on both time-scales. No significant correlation with pan evaporation was observed for surface wind speed on both the time-scales. For verification purpose, analyses of correlation

coefficients were carried out between the pan evaporation and the meteorological variables using the entire dataset of 2003. The results of the analyses are consistent with the graphical observations, as shown in Table 3.3.

Table 3.3 Correlation Coefficients between Pan Evaporation and the Meteorological Variables

Meteorological Variable	Time scale	
	Hourly	Daily
Solar radiation	0.99410	0.88088
Relative humidity	-0.61994	-0.87166
Air temperature	0.67912	0.72852
Surface wind speed	0.59587	0.60046

Figure 3.4 Correlation plots between hourly pan evaporation estimates and: (a) hourly solar radiation; (b) hourly relative humidity; (c) hourly air temperature; (d) hourly surface wind speed

Unlike in temperate regions (Xu and Singh, 1998), solar radiation was found to be the main climatic factor controlling the hourly and the daily evaporation rates at the Changi reclaimed land. This implies that energy driven

evaporation is the predominant evaporation mechanism. This is likely due to the surface wind speed being low, and the relative humidity consistently high near the study site. This could explain the poor correlation between the hourly pan evaporation and the hourly air temperature, relative humidity and the wind speed.

Figure 3.5 Correlation plots between daily pan evaporation estimates and: (a) daily solar radiation; (b) daily relative humidity; (c) daily air temperature; (d) daily surface wind speed

The diurnal variations of the total evaporation, the energy driven evaporation and the aerodynamic driven evaporation rates were computed using the calibrated Penman's model, as shown in Figure 3.6. The results further show that energy driven evaporation mechanism is predominant near the study site. Almost 85% of the total evaporation was contributed by the energy driven mechanism. Aerodynamic driven mechanism was found to be predominant only when there was no solar radiation, but its evaporation values during these periods were relatively negligible anyway.

Figure 3.6 Diurnal variations of energy driven evaporation, aerodynamic driven evaporation and total evaporation: (a) 25 Jan 2003; (b) 29 Dec 2003

3.5.2 Calibration and verification of the simplified hourly-models

Using the hourly meteorological and pan evaporation data of January 2003 (192 data points), the simplified hourly-models were calibrated. The hourly mass transfer models and the hourly temperature-based model could not be calibrated successfully. The coefficients of calibration, R^2 of the hourly mass transfer and temperature-based models were only about 0.40 and 0.11 respectively. The unsuccessful calibrations of these models are consistent with the observations from the correlation studies in 3.5.1. Poor correlation of the hourly evaporation rates with the hourly air temperature and relative humidity leads to low regression coefficients for these models.

The calibrated radiation-based models were verified using data from February 2003 to December 2003. The estimated values of hourly evaporations from all the four radiation-based models show close agreements with those estimated from the Penman's model, as shown in Figure 3.7. Model A_R generally gives the best estimates of hourly evaporation rates, as it includes a coefficient a_2 which accounts for the aerodynamic driven evaporation rates. The radiation-based models were also calibrated using the entire datasets of 2003. This is to verify the consistency of the data and to study the effect of the

dataset size used for calibration on model accuracy. The calibrated coefficients of the models using January 2003 dataset and the entire 2003 dataset are shown in Table 3.4.

Figure 3.7 Testing on 720 data points for the hourly radiation-based models calibrated with 192 data points: (a) Model A_R ; (b) Model B_R; (c) Model C_R; (d) Model D_R

The results show that use of larger datasets in the calibration process does not improve the accuracy of the calibrated models significantly, as the increments in R^2 are not significant. The calibrated coefficients were generally comparable except for Model B_R. These imply that once the coefficients are calibrated using the historical data, the calibrated radiation-based models could be applied with sufficient confidence for estimating future hourly evaporation rates for the same meteorological station.

Table 3.4 Coefficients and Accuracy of the Hourly Radiation-Based Models

Model	Calibration using dataset of January 2003 (192 data points)			Calibration using entire dataset of 2003 (912 data points)		
	Plot of E_{Model} vs $E_{\text{Penman's}}$ (Verification: 720 data points)			Plot of E_{Model} vs $E_{\text{Penman's}}$ (Calibration: 912 data points)		
	Calibrated coefficient	Slope	R^2	Calibrated coefficient	Slope	R^2
A_R	$a_1 = 0.003986$ $a_2 = -0.014473$	0.9970	0.9904	$a_1 = 0.003930$ $a_2 = -0.021240$	0.9944	0.9909
B_R	$a_1 = 0.000102$ $a_2 = 1.759434$	1.0225	0.9871	$a_1 = 0.000064$ $a_2 = -13.662839$	0.9923	0.9885
C_R	$a_1 = 0.002782$	0.9790	0.9855	$a_1 = 0.002808$	0.9908	0.9860
D_R	$a_1 = 0.004674$	0.9970	0.9874	$a_1 = 0.004655$	0.9922	0.9881

3.5.3 Calibration and verification of the simplified daily-models

Using the daily meteorological data and the measured pan evaporation data of January 2003 (25 data points), the simplified daily-models were calibrated. The models were then verified using the entire 2003 dataset. The temperature-based model could not be calibrated because of its low R^2 of 0.1273. This was mainly due to the poor correlation between the daily mean air temperatures and the daily evaporation rates, as shown in 3.5.1.

Among the radiation-based models, only Model A_R and Model B_R are acceptable for modeling the daily evaporation rates at the Changi reclaimed land. These two radiation-based models show relatively high agreement with the measured values as shown in Figure 3.8. The accuracy of the daily radiation-based models seems lower compared to the hourly radiation-based models. The daily evaporation could not be estimated accurately using the solar radiation and temperature data alone, as the influence of relative humidity on evaporation rates becomes more significant on a daily time-scale.

Among the mass transfer models, only Model C_M and Model D_M produce acceptable estimates, as shown in Figure 3.9. However, the accuracies of these two models are not quite acceptable for applications, as energy driven

evaporation mechanism is still the predominant evaporation mechanism at the Changi reclaimed land on a daily time-scale.

Figure 3.8 Testing on 319 data points for the daily radiation-based models calibrated with 25 data points: (a) Model A_R ; (b) Model B_R; (c) Model C_R; (d) Model D_R

Figure 3.9 Testing on 319 data points for the daily mass transfer models calibrated with 25 data points: (a) Model C_M ; (b) Model D_M

Table 3.5 Coefficients and Accuracy of the Daily Radiation-Based Models

Model	Calibration using dataset of January 2003 (25 data points)			Calibration using entire dataset of 2003 (344 data points)		
	Plot of E_{Model} vs E_{measured} (Verification: 319 data points)			Plot of E_{Model} vs E_{measured} (Calibration: 344 data points)		
	Calibrated coefficient	Slope	R^2	Calibrated coefficient	Slope	R^2
	A_R $a_1 = 0.004093$ $a_2 = 0.655202$	0.9806	0.7218	$a_1 = 0.004125$ $a_2 = 0.759548$	0.9686	0.7461
B_R	$a_1 = 0.000394$ $a_2 = 20.578868$	0.9377	0.8344	$a_1 = 0.000319$ $a_2 = 19.661463$	0.9778	0.8299
C_R	$a_1 = 0.002608$	0.9198	0.5716	$a_1 = 0.002720$	0.9636	0.5954
D_R	$a_1 = 0.004122$	0.9774	0.6157	$a_1 = 0.004673$	0.9623	0.6335

Table 3.6 Coefficients and Accuracy of the Daily Mass Transfer Models

Model	Calibration using dataset of January 2003 (25 data points)			Calibration using entire dataset of 2003 (344 data points)		
	Plot of E_{Model} vs E_{measured} (Verification: 319 data points)			Plot of E_{Model} vs E_{measured} (Calibration: 344 data points)		
	Calibrated coefficient	Slope	R^2	Calibrated coefficient	Slope	R^2
	A_M $a_1 = 0.008244$	1.1407	0.6645	$a_1 = 0.007026$	0.9618	0.6595
B_M	$a_1 = 0.002853$	0.9377	0.6030	$a_1 = 0.002668$	0.8776	0.6078
C_M	$a_1 = 0.008988$	1.0765	0.7780	$a_1 = 0.008085$	0.9654	0.7775
D_M	$a_1 = 0.005873$ $a_2 = 0.145801$	1.0942	0.7567	$a_1 = 0.005900$ $a_2 = 0.081298$	0.9620	0.7374
E_M	$a_1 = 0.000109$	1.1092	0.6309	$a_1 = 0.000096$	0.9623	0.6301

The calibrated coefficients of the radiation-based models and the mass transfer models, using the January 2003 dataset and the entire 2003 dataset for calibration, are shown in Table 3.5 and Table 3.6 respectively. Use of longer dataset in the calibration process does not improve the accuracy of the daily radiation-based models significantly, as the increments in R^2 are insignificant. Similarly, no improvement in accuracy was observed for the daily mass transfer models through use of longer dataset for calibration. This means that

the accuracy of the models depends strongly on the form of the equation rather than the size of data used for calibration.

3.5.4 Training and testing of ANN Models for hourly evaporation estimations

Using different meteorological factors as input variables, three multi-layer feed forward ANN models were developed for predicting the hourly evaporation rates. The first model used the complete set of meteorological data, i.e. solar radiation, relative humidity, air temperature and wind speed as input variables. The second model used solar radiation and air temperature as input variables. The third ANN model estimated hourly evaporation rates using only solar radiation.

The dataset were split into two parts, namely the training set and the testing set. The January 2003 dataset, with 192 data points, were used to train the ANN models for different number of neurons in the hidden layer. The number of epochs used in the trainings was 10,000, as the MSE (Mean Square Error) of the trainings were observed to reach their minimum value within 10,000 epochs. These ANN models were then tested using the datasets from February 2003 to December 2003. From trial and error, the optimum architectures for the first, second and third ANN models were found to be 4-6-1, 2-6-1 and 1-4-1 respectively.

It appears that the ANN architecture that produces the lowest MSE during the training process does not necessary produce the lowest MSE during the testing process. This could be due to overtraining of the network. The performance of the networks was found to deteriorate when the number of neurons was increased beyond the optimum number. This might be due to over parameterization of the network, since the number of connection weights increases as the number of neurons increases. The predicted values of all the three models generally show close agreements with those from the Penman's

model, as shown in Figure 3.10. The good prediction capability of the trained networks was probably due to the neurons of the hidden layer of the developed networks being capable of partitioning the transfer function completely, such that each hidden neuron response is a sub-domain within the transfer function domain (Sudheer and Jain, 2004).

Figure 3.10 Testing on 720 data points for the hourly ANN models trained with 192 data points using: (a) the complete meteorological data, 4-6-1; (b) solar radiation and air temperature, 2-6-1; (c) solar radiation, 1-4-1 as the input variables

Sensitivity tests were carried out on the first ANN model, as shown in Figure 3.11. The sensitivity results are consistent with those conducted on the Penman's model, as shown in Figure 3.3. This implies that the properly trained ANN model is capable of mimicking the nonlinear behavior of the Penman's model. This further suggests that the hidden neurons of the trained ANN model could have captured the physical behaviors of the evaporation processes (Jain et al., 2004).

Figure 3.11 Sensitivity tests on nonlinear ANN model (4 – 5 – 1) for hourly evaporation estimates

The simulated diurnal patterns by the three ANN models are shown in Figure 3.12. The first ANN model produces the most accurate estimates. It is capable of simulating the diurnal variations in evaporation rates close to those from the Penman's model for both the energy driven and aerodynamic driven evaporations. The accuracy of the second model is comparatively lower than the first model, as the variation patterns during the no solar radiation periods are not fully captured. The second ANN model simulates the variations of aerodynamic driven evaporations during those periods based solely on the air temperature variations. The third ANN model is the least accurate. It is not able to simulate the variations of the aerodynamic driven evaporation, but instead

approximates the evaporation rates during the no solar radiation periods with a constant value of 0.012799mm.

Figure 3.12 Diurnal variations of evaporation simulated by ANN model: (a) using the complete meteorological data, 4-6-1; (b) solar radiation and air temperature, 2-6-1; (c) solar radiation, 1-4-1 as the input variables

3.5.5 Training and testing of ANN Models for daily evaporation estimations

As for hourly evaporation simulations in 3.5.4, three multi-layers feed forward ANN models using different meteorological factors as input variables were developed for predicting the daily evaporation rates.

The ANN model using the complete set of meteorological data as input variables was trained with different amount of data points. The trained ANN model was then tested against the remaining data points. The slopes and the determination coefficients R^2 of the plots between the predicted and the measured evaporation rates are shown in Table 3.7. The ANN model was found to perform well when about 140 data points were used for training. Using R^2 values as an indicator for accuracy, models trained using less than 140 data points are generally less accurate. Using too few data points in the training process generally leads to poor generalization by the network (ASCE, 2000).

Table 3.7 Accuracy of the Daily ANN Model Using the Complete Meteorological Data with Different Amount of Data Points

Training Data points	Data Period	Plot of E_{ANN} vs $E_{measured}$ (Testing)	
		Slope	R^2
82	Jan – Mar	0.96499	0.83801
111	Jan - April	0.98664	0.88262
141	Jan – May	1.01392	0.92104
170	Jan – June	1.00867	0.93186
199	Jan – July	0.97877	0.92313

The ANN models using different meteorological factors as input variables were also trained using 199 data points. The trained models were then tested against the remaining 145 data points. The best ANN architecture was found to be 4-5-1, 2-3-1 and 2-4-1 for the first, second and third ANN models.

Sensitivity tests were carried out on the first ANN model, as shown in Figure 3.13. The tests show that the daily evaporation estimates were highly sensitive to solar radiation and relative humidity. These results are consistent with observations from the correlation studies, implying that a properly trained ANN model is capable of mimicking the nonlinear relationship between the daily evaporation rates and the meteorological factors.

Figure 3.13 Sensitivity tests on ANN model (4-5-1) using the complete meteorological as the input variables for daily evaporation estimates

The correlation between the predicted and the measured daily evaporation rates for the testing data set are shown in Figure 3.14. The third ANN model was found to experience a great improvement in accuracy when relative humidity was included as input variable instead of air temperature. This was due to the increasing influence of relative humidity on evaporation on a daily time-scale, as shown in the correlation studies in 3.5.1. This indicates that the selection of appropriate input variables is essential to produce a reliable ANN model, beside of the amount of data size used for network training.

Figure 3.14 Testing on 145 data points for daily ANN models trained with 199 data points using: (a) all meteorological data (4-5-1); (b) solar radiation and air temperature (2-3-1); (c) solar radiation and relative humidity (2-4-1) as the input variables

3.6 Comparison of simplified models with ANN models

The accuracy of all the evaluated models for the hourly and daily time-scales was summarized in Table 3.8 and Table 3.9 respectively.

Table 3.8 Comparison in Accuracy between the Radiation-Based Models and the ANN Models for Hourly Evaporation Rates Estimations

Input variables	Radiation-based models (calibrated using 192 data points)		ANN models (trained using 192 data points)	
	Plot of E_{ANN} vs E_{Penman} 's (Testing on 720 data points)		Plot of E_{ANN} vs E_{Penman} 's (Testing on 720 data points)	
	Model	R^2	Model	R^2
R_S, T	A_R	0.9904		
	B_R	0.9871	2-6-1	0.9912
	D_R	0.9874		
R_S	C_R	0.9855	1-4-1	0.9869

Note: R_S is incoming total solar radiation and T is air temperature.

TABLE 3.9 Comparison in Accuracy between the Simplified Models and the ANN Models for Daily Evaporation Rates Estimations

Input variables	Simplified models (calibrated using 25 data points)		Non-linear ANN models (trained using 199 data points)
	Plot of E_{ANN} vs $E_{measured}$ (Testing on 319 data points)		Plot of E_{ANN} vs $E_{measured}$ (Testing on 145 data points)
	Model	R^2	R^2
R_S, T	A_R	0.7218	
	B_R	0.8344	0.8435
	D_R	0.6157	
R_S	C_R	0.5716	Not carried out
RH, T	A_M	0.6645	Not carried out
	E_M	0.6309	
RH, T, U	B_M	0.6030	
	C_M	0.7780	Not carried out
	D_M	0.7567	
R_S, RH	-		0.8958

Note: R_S is incoming total solar radiation; RH is relative humidity; T is air temperature and U is surface wind speed.

With the same input variables, the properly trained feed forward ANN models for hourly evaporations were found to perform better than the radiation-based models in term of accuracy. By including air temperature as an input variable in addition to solar radiation, the ANN model is able to produce the diurnal variation patterns of aerodynamic driven evaporations during no solar radiation periods, as shown in Figure 3.12. This is not possible with the radiation-based models. The radiation-based Model A_R , could only approximate the aerodynamic driven evaporations as a constant rate through its constant coefficient a_2 . The other radiation-based models are not capable at all of estimating the aerodynamic driven evaporation during the no solar periods.

Using the same input variables, i.e. solar radiation and air temperature, the ANN models for daily evaporation are not superior to the radiation-based models. To achieve a comparable accuracy as the radiation-based models, the ANN models require a training data size that is much larger than the data size used for calibrating the radiation-based models. However, the ANN models were found to be superior to both the radiation-based models and the mass transfer models when relative humidity was included as an input variable. As solar radiation and relative humidity correlate significantly with pan evaporation on a daily time-scale, neither the radiation-based models nor the mass transfer models are capable of producing reliable estimates of daily evaporation rates. Under such a circumstance, ANN models become more relevant, as it could include any of the significant influencing factors as input variables.

3.7 Summary

In summary, for estimating hourly evaporation rates at the Changi reclaimed site, only radiation-based models were found to be applicable. Hourly estimates from all the four radiation-based models show close agreement with those estimated from the Penman's model. The mass transfer models and the temperature-based models do not yield reliable estimates for the hourly

evaporation rates, as the hourly evaporation rates correlate poorly with air temperature and relative humidity. Using the same input variables, properly trained feed forward ANN models perform better than radiation-based models. ANN models were able to reproduce the diurnal variation patterns of aerodynamic driven evaporation during no solar radiation periods. This is not possible with radiation-based models.

For modeling the daily evaporation at the Changi reclaimed land, among all the simplified models, only Model A_R and Model B_R of the radiation-based models are acceptable. The accuracy of the daily radiation-based models is low compared to the hourly radiation-based models. This is mainly attributed to the significant influence of relative humidity on affecting evaporation rates on a daily time-scale. Although the accuracy of the mass transfer models was found to be higher on a daily time-scale, it is still not considered acceptable for applications. Energy driven evaporation mechanism is still the predominant mechanism at the Changi reclaimed land on a daily time scale. Using same input variables, i.e. solar radiation and air temperature, the ANN models for daily evaporation are not superior to the radiation-based models. However, the ANN model was found to be superior when relative humidity was included as an additional input variable.

Unlike in temperate regions, energy driven evaporation was found to be the predominant evaporation mechanism at the Changi reclaimed land. This could explain the poor correlations between the hourly pan evaporation and the hourly air temperature, relative humidity and wind speed.

In conclusion, only ANN models and radiation-based models could be used as alternatives to the Penman's model for estimating open water evaporation rates at the Changi reclaimed land. An albedo value of 0.1259 is recommended for adoption in the Penman's model, as this albedo value was observed to produce unbiased estimates of open water evaporation rates. The Penman's model with an albedo value of 0.1259 was applied to generate open evaporation rates for the calibration and verification of VS2DI for the Changi reclaimed land in Chapter 4.

CHAPTER 4

CALIBRATION AND VERIFICATION OF DETERMINISTIC UNSATURATED ZONE MODEL

4.1 Introduction

As discussed in 1.4, a deterministic unsaturated zone model is needed to investigate the physical processes taking place within the vadose zone of the Changi reclaimed land. Prior to using the unsaturated zone model for recharge estimations, the model needs to be calibrated and verified against field measured soil moisture profiles. Due to the need for user intervention during calibration of the model, auto-calibration tools such as PEST and AUTOCAL were found to be not applicable. A solution algorithm is hence developed in this Chapter for calibrating and verifying the model. The present study demonstrates that a Radial Basis Function (RBF) Neural Network is able to serve as an alternative to manual and auto-calibration, when the model requires user intervention during the calibration process.

4.2 Numerical Model

4.2.1 Governing equations

VS2DI Version 1.1 (Hsieh et al., 2000) was applied as the deterministic unsaturated zone model in this research study. The rationales of choosing VS2DI for modeling rainfall recharge processes within the vadose zone of the Changi reclaimed land have been explained in 1.4. The nonlinear total hydraulic potential-dependent Richards equation is the governing equation for fluid flow in VS2DI. The nonlinear Richard's equation (Lappala et al., 1993) is as shown below:

$$V\{\rho[c_m + s_e S_s]\} \frac{\partial H_d}{\partial t} - \rho \sum_{k=1}^{\tilde{m}} a_k K_s K_r(h) \frac{\partial H_d}{\partial n_k} - \rho q V = 0 \quad (4.1)$$

where V is the fluid volume; ρ is the liquid density; c_m is the specific moisture capacity; s_e is the saturation degree of the porous medium, q is the source-sink term accounting for liquid added to or taken away from the volume V ; K_s is the saturated hydraulic conductivity; K_r is the relative hydraulic conductivity as a function of soil pressure head, h ; a is the area of flow; S_s is the specific storage; and H_d is the total hydraulic potential.

Water retention, specific moisture capacity and relative hydraulic conductivity functions serve as the auxiliary equations for solving the nonlinear Richards equation. The algebraic equations available in VS2DI for representing the auxiliary functions include those developed by van Genuchten (1980), Brooks and Corey (1964) and Haverkamp and others (1977). Rainfall recharge and soil evaporation could be simulated simultaneously in VS2DI. The actual soil evaporation rates are computed implicitly by the program as the upward flux driven by pressure potential gradient between the soil and the atmosphere:

$$E_a = \begin{cases} K_s K_r s (HA - h) & ; E_a < PEV \\ PEV & ; E_a \geq PEV \end{cases} \quad (4.2)$$

where E_a is actual soil evaporation rate; K_s is saturated hydraulic conductivity; K_r is relative hydraulic conductivity; s is surface resistance; h is the soil pressure head; PEV is potential evaporation rate defined explicitly by the user; and HA is pressure potential of the atmosphere, which could be estimated through:

$$HA = \frac{RT}{M_w g} \ln RH \quad (4.3)$$

where R and M_w are constants equal to $8.31 \text{ kg.m}^2/\text{sec}^2$ and 0.018 kg/g-mol respectively; T is air temperature in Kelvin; g is acceleration due to gravity (9.81 m/sec^2); and RH is relative humidity in fraction.

Using the measured 15-minute global radiation flux, relative humidity, wind speeds and air temperature as input variables, the Penman's model (Chow et al., 1988) was adopted to estimate the potential evaporation rates. The net radiation fluxes in the Penman's model were approximated by $(1 - \alpha_a)R_S$, assuming negligible emission and conduction losses. The parameter α_a is the albedo value and R_S is the measured global radiation. The calibrated albedo value of 0.1259 from Chapter 3 (3.4) was adopted in the present study.

4.2.2 Model set-up

A "hypothetical" 2-dimensional plot with a width of 0.25m was set up in VS2DI to represent the homogeneous soil profile at location M2-12, where field measurements of volumetric soil moisture contents and soil suction heads were carried out. The "hypothetical plot" is the solution domain in the VS2DI model. The Neumann boundary condition was specified for the upper boundary of the plot. The time varying inflow fluxes specified at the upper boundary represent the measured rainfall intensity. A maximum ponding depth of 100mm was assigned for the upper boundary to allow for surface ponding during intense rainfall events (if any). The Dirichlet boundary condition, specified at zero pressure head, was assigned to the lower boundary of the plot to represent the water table. The locations of the lower boundary were set to a value varying from 2 to 3.5m below the upper boundary, as the vadose zone thickness during the field measurement period varied within this range. The side boundaries of the plot were set as "no flow" boundaries. Volumetric soil moisture profile measured at the start time of the simulation events was used as the initial conditions in the solution domain.

A constant grid spacing of 25mm was defined in the horizontal direction. Vertical grid spacing was variable, being finer (a minimum of 5mm) near the upper and lower boundaries of the plot. Fine grid spacing near the upper boundary is necessary to ensure accurate simulations of (Lappala et al., 1993) soil water fluxes taking place at the boundary. van Dam and Feddes (2000) found that simulations of rainwater infiltration and soil evaporation at the soil surface would only be accurate when a grid spacing of 10mm was used for the upper boundary. Vertical grid spacing at the interior section of the plot was increased to 50mm for computational efficiency.

The intercell average of relative hydraulic conductivity was approximated using the geometric mean approach, as this approach generally produces the most accurate simulations (Lappala et al., 1993; Tindall and Kunkel, 1999, Section 7.7). The arithmetic mean, however, was used in those events where the moisture content at the soil surface was close to the specific retention of the soils. This is necessary to obtain physically reasonable results and prevent numerical oscillations (Brutsaert, 1971). To ensure stable solutions, the time steps were allowed to vary from 0.005 to 10 seconds through the application of time step multiplier (TMLT) and time step reduction factor (TRED). The relaxation parameter defined varied from 0.90 to 1.50. All the rainfall recharge simulations were found to achieve good accuracy of mass balance, with a total mass balance of 0.5 to 3% at the end of simulations, and the mass balance errors during computation time steps were observed to be less than 6%.

The relatively large mass balance error during certain computation time steps (up to 6% in this study) was due to instantaneous changes in the upper boundary conditions. If a finite difference cell beneath the upper boundary is changed from no recharge to downward rainfall recharge or from downward rainfall recharge to upward recharge (soil evaporation), the model will then treat this as an instantaneous change in the boundary conditions. Accompanying this boundary change will be an instantaneous change in water stored within this cell. In VS2DI Version 1.1 (Hsieh et al., 2000), these changes

in storage would be lumped into the mass balance terms thus producing apparently large mass balance errors. This commonly occurred during the first time step of a simulation when there was an instantaneous change in boundary conditions.

In this research work, VS2DI Version 1.1 was used to simulate a process that started with a dry period (upward recharge, i.e. soil evaporation), followed by a continuous rainfall event (downward rainfall recharge) and ending with a dry period (upward recharge). In other words, the simulations involved instantaneous changes in the upper boundary condition. This led to a relatively large mass balance error of up to 6% during the first time step of the simulations. However, this apparently large mass balance did not lead to a large total mass balance error at the end of the simulations (0.5 to 3%), as the mass balance error at other computation time steps (when there was no instantaneous change in boundary condition) were found to be excellent (0.1 to 0.3%).

4.3 Neural network algorithm

In the present study, a RBF network was developed to calibrate the VS2DI model. The schematic diagram of the RBF network architecture is shown in Figure 4.1. The network consists of three layers, namely an input layer, a hidden layer and an output layer. The input layer simply passes the inputs into the hidden layer, which consists of radial basis neurons. The Radial Basis Function is as shown follows:

$$a(\theta) = \Phi(n) = e^{-(nb)^2} \quad (4.4)$$

Instead of using the standardized input, the net input (n) into the RBF hidden layer is the vector distance between its weight vector (w) and the input vector (θ), multiplied by the bias (b). Thus, n is computed through:

$$n = \|w - \theta\| b \quad (4.5)$$

where

$$b = 0.8326 / SPREAD \tag{4.6}$$

After the nonlinear transformation in the hidden layer, the intermediate outputs (a) are further transformed by the linear output layer into the final response (y) as shown below.

$$y_j = \sum_{i=0}^n a_i w_{ij}; j = 1,2,3,...m \tag{4.7}$$

where w_{ij} is the weight between i -th middle layer neuron and j -th output layer neuron, and m is the number of final responses. Prior to being used for nonlinear input-output mapping, the RBF network has to be trained using a set of known input-output samples. In the training procedures, the error function is minimized by adaptively updating all the free parameters (w , b , w_{ij}) in the radial basis neurons and the linear neurons. Training of RBF generally aims to create a network with negligible training errors (MATLAB, 2003).

Figure 4.1 Schematic diagram of Radial Basis Function (RBF) Neural Network

The RBF network combines the advantages of quick learning and fast convergence to the global optimal solution, while back propagation network (BPN) generally requires relatively long training time, and is prone to converge to the local minimum instead of the global minimum (Zaghloul and Abu Kiefa, 2001). The training of RBF needs no training parameters such as learning rate and momentum, but depends on the SPREAD value. The SPREAD value determines the width of an area in the input space to which each neuron responds. The SPREAD value should be large enough to enable the radial basis neurons to respond strongly to overlapping regions in the input space. Nevertheless, the SPREAD value should not be too large such that each neuron responds effectively in the same, large area of the input space (MATLAB, 2003). An appropriate SPREAD value hence needs to be determined to ensure a smooth network function and a good network generalization. As a matter of fact, the RBF network has been found to be an universal approximator in a continuous function space, provided that the radial basis activation function in the hidden layer is continuous everywhere, locally bounded and not a polynomial (Liao et al., 2003). However, the design of RBF network demands a careful selection of input variables, as the network is not good in ignoring irrelevant inputs (Coulibaly et al., 2001).

4.4 Model calibration

4.4.1 Selection of water retention and relative hydraulic conductivity models

Before calibrating the VS2DI model, appropriate algebraic forms of water retention function and relative hydraulic conductivity function need to be determined for the study site. This is important to preserve the overall accuracy of the simulations (Hwang and Powers, 2003). The algebraic forms of water retention function to be evaluated include those developed by Brooks and Corey (1964), Haverkamp and others (1977) and van Genuchten (1980). Data

used in this section are the measured volumetric moisture contents and suction heads collected at M2-12 (see Figure 1.3).

To obtain an effective water retention curve for the vadose zone, data points collected at the 5 different depths (i.e. 10, 30, 100, 130, 200cm) were smoothed out using ‘moving average’ filtering. Using the Least Squares Errors (LSE) method, the water retention models were fitted to the smoothed data points. The fitted models and their residual plots are shown in Figure 4.2. The fitted values of effective soil hydraulic parameters and the R^2 of the three models are summarized in Table 4.1.

Table 4.1. Fitted Soil Hydraulic Parameters for the In-Situ Sandy Soils		
Brooks-Corey (1964)	Haverkamp and other (1977)	van Genuchten (1980)
$\theta_s = 0.3283$ (-4.737 x 10 ⁻⁴ ; 4.737 x 10 ⁴)	$\theta_s = 0.4477$ (0.4428; 0.4526)	$\theta_s = 0.3754$ (0.3734; 0.3774)
$\theta_r = 0.0157$ (0.01783; 0.02165)	$\theta_r = 0.052$ (upper bound)	$\theta_r = 0.052$ (upper bound)
$h_b (cm) = 13.91$ (-6.121 x 10 ⁻⁶ ; 6.121 x 10 ⁶)	$\alpha (cm) = 59.55$ (57.43; 61.66)	$\alpha (1 / cm) = 0.02244$ (0.02201; 0.02288)
$\lambda = 0.3489$ (0.3432; 0.3546)	$\beta = 0.8383$ (0.8304; 0.8462)	$\beta = 1.721$ (1.716; 1.725)
Adjusted $R^2 = 0.984$	Adjusted $R^2 = 0.984$	Adjusted $R^2 = 0.990$

Notes: θ_s is the porosity; θ_r is residual moisture content; h_b is the bubbling or air entry pressure potential; λ, α, β are fitting parameters; Numbers in the parentheses are the lower and upper bounds of the 95% confidence interval.

The Brooks- Corey’s model appears to be the least accurate with the lowest R^2 . Relatively high values of residuals adjacent to zero suction head (see Figure 4.2a) indicates that there are alternative models, which fit the data better. The fitted θ_s and h_b values of Brooks-Corey’s model are highly uncertain with large 95% confidence intervals.

Figure 4.2 Fitted water retention model and its residual plot (a) Brooks-Corey model; (b) Haverkamp et al. model (c) van Genuchten model

Although Haverkamp et al.'s model appear to fit the data well with negligible residual values, the model is not acceptable. The fitted β value of Haverkamp et al.'s model is too small compared to the typical β value for sands, which is about 3.0 to 12 (Wildenschild and Jensen, 1999), and its fitted θ_s value is significantly larger than the typical porosity value for sands.

On the other hand, the fitted values of soil hydraulic parameters for van Genuchten's model were found to be quite well defined. The 95% confidence intervals of the fitted values were generally small. The fitted porosity value is close to the value from laboratory tested value of 0.398, and falls within the typical range for medium to coarse mixed sand of 0.35 to 0.40 (Tindall and Kunkel, 1999, Table 2.5). A maximum field soil moisture content of 0.382 was observed at a depth of 200cm below the ground surface, when the water table was about 205cm below the ground surface. The fitted residual moisture content is reliable, as it is close to the minimum measured field volumetric soil moisture content of 0.0453, after a few days of dry period. The fitted α value falls within the typical range of 0.01 to 0.11 $1/\text{cm}$ for sands. Nevertheless, the fitted β value seems to be much lower than the typical range of 3.0 to 12. Values of θ_s , θ_r and α were therefore applied as prior known information (Merten et al., 2004) to optimize β and saturated hydraulic conductivity (K_s) in the inverse modeling.

In conclusion, van Genuchten (1980) models were adopted as the water retention and relative hydraulic conductivity models for solving the Richards equation in VS2DI. This is consistent with Lappala et al. (1993)'s findings, where the van Genuchten's relative hydraulic conductivity model was found to fit the data for sands very well, but poorly represent the data for clay.

4.4.2 Calibration using radial basis neural network

Instead of searching for a unique and optimum value for K_s and β parameters, the proposed method searches for the upper and lower bounds of these two parameters, such that the simulated results envelop all the measured values. Searching for a unique solution is not always useful, as uniqueness in solution could sometimes lead to erroneous predictions made by a model (Moore and Doherty, 2005). Furthermore, the values of the optimized parameters could vary under different physical and climatic conditions, when different time series or numerical models are used (Mertens et al., in press), when different optimization criteria are defined (Wegehenkel, 2005) and when different boundary conditions are imposed (Hwang and Powers, 2004). The resulting model is considered reliable in representing the physical processes when the optimized parameters satisfy most of the imposed constraints (D'Agnese et al., 1999). Schoups et al. (2005) suggested that large parameter uncertainties could indicate significant errors in model structures, measurements or model inputs.

A moderate continuous rainfall event on 14 September 2004 was selected as the calibration event. 71 combinations of $K_s - \beta$ values were randomly formulated using K_s values from 0.17 to 0.85mm/sec (14.7 to 73.4mm/day) and β values from 1.7 to 3.1. Combinations using β values larger than 3.1 were not considered in the calibration, as the sum of square errors (SSE) between the simulated and the observed soil moisture contents was observed to increase when β value larger than 3.1 was used. The value of 3.1 was hence adopted as the upper bound β value.

Using the formulated $K_s - \beta$ combinations and the fitted parameters $(\theta_s, \theta_r, \alpha)$ as input parameters to VS2DI model, 71 simulation runs were performed. The simulation time was set to 10800 seconds (3 hours). The VS2DI model was calibrated against the measured moisture contents at $z = 100\text{mm}$ and 300mm , at elapsed time (t) of 1800, 2700, 3600 and 5400 seconds. Moisture contents at these depths and elapsed times were chosen, as their

corresponding changes in soil moisture content were noticeable. The responses of soil moisture content to the rainfall recharge were hence represented by 8 $\theta_{z,t}$ values. The measured soil moisture profiles can be found in Appendix B.

The database of 71 computer simulations was randomly divided into a training set (65 simulations) and a testing set (7 simulations). In the training phase, the simulated soil moisture responses ($\theta_{z,t}$) were used as input variables to the RBF neural network, and the corresponding $K_s - \beta$ combinations were set as the targeted outputs, as shown in Figure 4.1. The RBF neural network was trained using SPREAD values varying from 0.001 to 7.50. The measured soil moisture content responses ($\theta_{z,t}$) were then used as input variables to the trained RBF networks for estimating optimum combinations of $K_s - \beta$.

Among the trained networks, only those with SPREAD values of 5, 5.25, 6 and 7 were found to produce physically realistic $K_s - \beta$ combinations. The realistic $K_s - \beta$ combinations are 0.9256mm/sec (79.9m/day)–1.4868, 0.9220mm/sec (79.7m/day)–1.4904, 0.3172mm/sec (27.4m/day)–2.6977 and 0.0717mm/sec (6.2m/day) – 0.0671 for SPREAD numbers of 5, 5.25, 6 and 7, respectively. Networks with other SPREAD values were observed to produce unrealistic $K_s - \beta$ combinations. The estimated $K_s - \beta$ combinations were either negative or far beyond the typical range for sandy soils. Using the testing dataset, the robustness of these 4 trained neural networks was then examined in term of its ability in predicting correct responses. Figure 4.3 shows the comparison between the actual K_s values and the predicted values using the 4 networks for both the training and testing sets. Figure 4.4 shows the comparison between the actual β values and the predicted values for the training and testing data sets. All the training lines almost have slopes close to one, implying negligible errors in the training process. This is not surprising, as training of RBF is aimed at creating a network with negligible training errors (MATLAB, 2003).

Figure 4.3 Comparison between the predicted and the actual (K_s) values for both the training and testing datasets: (a) SPREAD = 5; (b) SPREAD = 5.5; (c) SPREAD = 6; (d) SPREAD = 7

Figure 4.4 Comparison between the predicted and the actual (β) values for both the training and testing datasets: (a) SPREAD = 5; (b) SPREAD = 5.5; (c) SPREAD = 6; (d) SPREAD = 7

The RBF neural network with SPREAD value of 6 was observed to give the most accurate K_S predictions, with a R^2 value for the testing set that was significantly higher than the other trained networks. The calibrated $K_S - \beta$ combination, i.e. 0.3172mm/sec (27.4m/day) – 2.6977, is hence adopted as ‘the calibrated $K_S - \beta$ combination’. For further confirmation, 4 additional simulation runs were carried out for the 4 $K_S - \beta$ combinations. Figure 4.5 shows the sum of square errors at the different elapsed times for the 4 simulation runs. These results further confirm that the calibrated $K_S - \beta$ combination of 0.3172mm/sec (27.4m/day) – 2.6977 is the optimum combination.

Figure 4.5 Sum of square errors corresponding to elapsed time for simulations using the 4 predicted $K_S - \beta$ combinations as input parameters

4.5 Verification and uncertainty analysis

For verification of the calibrated $K_S - \beta$ combination, ten (10) other continuous rainfall events were selected, consisting of mild, moderate and heavy rainfall events. The 15- minute rainfall intensity and the hourly potential evaporation rates of these events are shown in Figure 4.6.

Figure 4.6 Rainfall intensity and potential evaporation rate for the calibration and verification events

The calibrated $K_s - \beta$ combination was found to generally underestimate the soil moisture contents when compared to the measured values; except for the verification events on 22 October 2004 and 14 November 2004 (see Figures 4.7 and 4.8). This observation is not surprising, as it is unlikely that a single $K_s - \beta$ combination can provide good matches for all the verification events. There could however be an upper bound and a lower bound of $K_s - \beta$ combinations, such that the simulated soil moisture contents within these bounds can envelope all the measured soil moisture contents for the verification events. The upper and lower bounds of $K_s - \beta$ combination can be obtained by repeating the previous calibration processes for each event. However, this would require an enormous number of simulations to be carried out to generate input-output databases for training and testing the RBF neural networks.

Instead, a sensitivity test was carried out on the calibration event to obtain a sensitivity coefficient S for β and K_s , which represents the ratio of fractional change in $\theta_{100,1800}$ to the fractional change in parameter β and K_s :

$$S_P = \frac{(\Delta\theta_{100,1800}/\theta_{100,1800})}{(\Delta P/P)}; \quad P = \beta \text{ or } K_S \quad (4.8)$$

To obtain S_{K_S} , β was fixed at 2.6977 (the calibrated value). Different values of K_S varying from 0.17 to 0.85mm/sec (14.7 to 73.4 m/day) were used as input to the VS2DI model to simulate the $\theta_{100,1800}$ values. Similarly, S_β was obtained by fixing K_S at 0.3172 mm/day (the calibrated value), and β was varied from 1.70 to 4.50. The sensitivity coefficient of S_β and S_{K_S} were found to be -0.8096 and -0.2654 respectively.

Rearranging Equation (4.8):

$$\Delta P = \frac{(\Delta\theta_{100,1800}/\theta_{100,1800})}{S_P} \times P; \quad P = \beta \text{ or } K_S \quad (4.9)$$

Assuming the average difference between the measured and the simulated θ_{100} for all the elapsed times could be approximated by its root mean square errors (RMSE), Equation (4.9) could be reformulated into the following forms:

$$\Delta K_S = \frac{(RMSE/\bar{\theta}_{100,t})}{-0.2654} \times 0.3171 \text{ mm/sec} \quad (4.10)$$

$$\Delta\beta = \frac{(RMSE/\bar{\theta}_{100,t})}{-0.8096} \times 2.6977 \quad (4.11)$$

where

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Measured\theta_{100,t} - Simulated\theta_{100,t})^2}{N}}$$

$t = 900,1800,.....900(N) \text{ sec}$

(4.12)

and

$$\bar{\theta}_{100,t} = \frac{\sum_{i=1}^N \theta_{100,t}}{N}$$

(4.13)

Equations (4.10) and (4.11) were used to estimate a K_s value (herein named as “adjusted K_s ”) and a β value (herein named as “adjusted β ”) that provide better matches to the measured soil moisture contents for each verification event. Table 4.2 summarizes the “adjusted K_s ” values and the “adjusted β ” values for the poorly fit verification events. The simulated soil moisture contents based on the calibrated $K_s - \beta$ combination, the “adjusted K_s ”, the “adjusted β ”, the lower bound and the upper bound of $K_s - \beta$ combination for $z = 100$ and 300mm are shown in Figure 4.7 and Figure 4.8, respectively.

Table 4.2 “Adjusted K_s ” and “Adjusted β ” Values for the “Poorly Fit” Verification Events

Rainfall Event	Adjusted	
	K_s (mm/sec)	β
19 Sept 2004	0.183	2.325
21 Sept 2004	0.157	2.251
25 Oct 2004	0.225	2.442
26 Oct 2004	0.178	2.310
12 Nov 2004 (1)	0.171	2.290
12 Nov 2004 (2)	0.199	2.368
1 Jan 2005	0.376	2.861
5 Jan 2005	0.156	2.247
Lower Bound	0.156	2.247
Upper Bound	0.376	2.861

Figure 4.7 Simulated soil moisture contents at $z = 100\text{mm}$ based on various $K_S - \beta$ combinations

Figure 4.8 Simulated soil moisture contents at $z = 300\text{mm}$ based on various $K_S - \beta$ combinations

From the plots, the “adjusted K_S ” and “adjusted β ” values were observed to improve the matches for most of the poorly fit verification events. The improvements were more noticeable at $z = 100\text{mm}$. More significantly, the upper bound $K_S - \beta$ combination ($K_S = 0.376\text{mm/sec}$; $\beta=2.861$) and the lower bound $K_S - \beta$ combination ($K_S = 0.156\text{mm/sec}$; $\beta=2.247$) were found to be able to envelop all the measured values. This implies that the effective K_S and β parameters for the sandy soils of the Changi reclaimed land are likely to

fall within the range of K_S from 0.156 to 0.376mm/sec (13.5 to 32.5m/day) and β from 2.247 to 2.861, respectively.

4.6 Validations

In this section, the calibrated range of K_S (13.5 to 32.5m/day) was compared with results from laboratory and field measurements carried out for the Changi reclaimed land (Tan et al., 2004). The results from measurements are summarized in Table 4.3.

Table 4.3 K_S Obtained by Various Methods (Tan et al., 2004)	
Method	Result
Step drawdown test	25.5m/day
Aquifer pumping test	22 – 50m/day
Slug packer test	20 – 40m/day
Permeability test	10 – 20m/day
Empirical formulas	19 – 40 m/day

The calibrated range of K_S is close to the measured ranges. The difference between the calibrated and the measured values could be explained by various reasons. Spatial scale differences in the different methods could be the most probable reason. Laboratory permeability tests can be considered as point measurements, as the saturated hydraulic conductivity is obtained based on a small volume of soil sample of about 0.001m³. On the other hand, hydraulic conductivity values estimated from aquifer pumping and slug packer test data represent average hydraulic characteristics at many points within a large cylinder volume (Walton, 1987; Butler, 1998). The present inverse modeling approach, based on an intermediate soil volume of 0.020m³, produces a range, which falls between the laboratory permeability measurements and field measurements. However, even on a same spatial scale, the different methods may not yield close estimates. This is because all the techniques

measure the saturated hydraulic conductivity in an indirect way, which depends on the assumptions made in the techniques. This adds to the uncertainty in the K_s estimates.

4.7 Summary

A RBF neural network was developed to calibrate the VS2DI model for the Changi reclaimed land. The RBF neural network was shown to be able to establish realistic optimum $K_s - \beta$ combination values for the calibration event, when appropriate input variables and SPREAD value were carefully selected.

Although the calibrated $K_s - \beta$ combination of 0.3172mm/sec (27.4m/day) – 2.6977 produced a close match between the simulated and measured soil moisture contents for the calibration event, it was found to generally underestimate the soil moisture contents for most of the verification events. An upper bound and a lower bound for the $K_s - \beta$ combination were estimated such that the simulated moisture contents corresponding to these bounds will envelop all the measured values for the verification events. The effective K_s and β parameters for the study site were found to range from 13.5 to 32.5m/day and from 2.247 to 2.861 respectively. This range is in a close agreement with K_s values determined from the laboratory and field measurements. The directly calibrated values of porosity ($\theta_s = 0.3754$), specific moisture content ($\theta_r = 0.052$) and α fitting parameter ($\alpha = 0.022441/cm$) were found to be close to the laboratory and field measurements.

In conclusion, the unsaturated zone model VS2DI was successfully calibrated and verified against the measured soil moisture profile for the Changi reclaimed land. The calibrated VS2DI model will be applied to study the rainfall recharge characteristics at the Changi reclaimed land and to estimate rainfall recharge rates in Chapter 6.

CHAPTER 5

STUDIES ON GROUNDWATER RECHARGE CHARACTERISTICS: EMPIRICAL APPROACH

5.1 Introduction

In this chapter, empirical studies are carried out to investigate the rainfall-recharge characteristics at the Changi reclaimed land. The empirical tools used include auto-correlation, cross-correlation and auto-spectral analyses. The functions of these analyses have been explained in 1.4. The time series of daily rainfall and groundwater level used in the study are for the period from 1 September 2003 to 30 November 2003 and. The time series are shown in Figure 5.1.

Rainfall recharge characteristics at the unconfined sandy aquifer were studied for rainfall events occurring in September, October and November 2003, as these three months showed quite distinct rainfall patterns. Rainfalls in October 2003 were of higher intensities than rainfalls in the other two months. Approximately 64% or about 186mm of the total rainfall depth in October 2003 fell in events with intensity higher than 25mm/day. Although total rainfall depth in September 2003 was close to the total rainfall depth in November 2003, the rainfalls were concentrated in one single event in November 2003. Almost half of the total rainfall depth in November 2003 was recorded during a single event on 5 November 2003, while rainfalls in September 2003 were more uniformly distributed temporally.

Figure 5.1 Daily rainfall depth in (a) September 2003; (b) October 2003; and (c) November 2003

5.2 Study methodology

5.2.1 Auto-correlation analysis

The auto-correlation function quantifies the linear dependency of the successive values over a time period and the memory effect (Angelini, 1997) of the system. The auto-correlation function, $r(k)$ in discrete form is:

$$r(k) = \frac{C(k)}{C(0)} \quad (5.1)$$

$$C(k) = \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(x_{t+k} - \bar{x}) \quad (5.2)$$

where k is the time lag ($k = 0$ to m), n is the length of the time series, x is the single event value, $\bar{x}$ is the mean of the events and m is the truncation point. If the time series is uncorrelated, the auto-correlation function $r(k)$ decreases rapidly and reaches a value of zero within a short time lag. On the other hand, a gently decreasing slope, with nonzero values of $r(k)$ over a long time lag, indicate that the time series has a strong interdependency and long memory effect.

Auto-correlation analyses were carried out on the time series of daily groundwater levels for all the observation wells (Figure 1.3) to investigate the characteristics of groundwater-level fluctuations at the Changi reclaimed land.

5.2.2 Cross-correlation analysis

The cross-correlation function is an indicator of the inter-relationship between the input time series and the output time series. When the series are random or uncorrelated, the cross-correlation function is an impulse response function of the system (in this study, the aquifer) to the input time series (Padilla and Pulido-Bosch, 1995; Laracque et al., 1998). The cross-correlation function, $r_{xy}(k)$ in discrete form is:

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \quad (5.3)$$

$$C_{xy}(k) = \begin{cases} \frac{1}{n} \sum_{t=1}^{n-k} (x_t - \bar{x})(y_{t+k} - \bar{y}), & k > 0 \\ \frac{1}{n} \sum_{t=1}^{n+k} (x_t - \bar{x})(y_{t+k} - \bar{y}), & k < 0 \end{cases} \quad (5.4)$$

where k is the time lag, y is the single output event, $\bar{y}$ is the mean of the output events, σ_x is the standard deviation of input time series and σ_y is the standard deviation of output time series. When $r_{xy}(k) > 0$ for $k > 0$, input time series influences the output time series (Laracque et al., 1998). The cross-amplitude, the maximum value of $r_{xy}(k)$ for $k > 0$, indicates the degree of inter-relationship between the input and the output time series (Padilla and Pulido-Bosch, 1995; Lee and Lee, 2000). The higher the absolute value of the cross-amplitude, the stronger the input and the output inter-relate to each other. The delay, which is the number of time lag between $k=0$ and k at the maximum $r_{xy}(k)$, represents the propagation rate of the input impact to the output point of the system (Lee and Lee, 2000). A short delay indicates a fast propagation of input impact to the output point in the system. In cross-correlation analysis, the system being studied is treated as a “black box” where the observed input and output time series are the only inference on how the system works (Kim et al., 2000).

Two cross-correlation analyses were carried out for the following purposes:

1. Cross-correlation analysis between time series of rainfalls (as input time series) and time series of water table fluctuation (as output time series) to study the influence of rainfall patterns and the vadose zone thickness on:
 - (i) correlations between rainfalls and groundwater-level fluctuation at the Changi reclaimed land; and
 - (ii) percolation rate, or vertical flow velocity, of surface rainwater to the groundwater at the reclaimed land.

2. Cross-correlation analysis between time series of coastal tidal fluctuation (as input time series) and time series of water table fluctuation (as output time series) to investigate the influence of coastal tides on the water table fluctuation at the Changi reclaimed land.

For the first (1) correlation analysis, cross-correlation plots (r_{xy} as y-axis; k as x-axis) between daily rainfalls and daily groundwater-level fluctuations were derived for observation wells at the eastern part of the reclaimed land site. These include observation wells C1, C3, C4, M2-07, M2-08, M2-13, M2-19, M2-22 and M1-04 (Figure 1.3). The values of cross-amplitude and delay were then extracted from the cross-correlation plots. The relationship between cross-amplitude and average monthly thickness of vadose zone were used to investigate the influence of vadose zone thickness and rainfall pattern on the relationships between rainfalls and groundwater-level fluctuation. Likewise, the relationship between delay and average monthly thicknesses of vadose were applied to study the percolation rate of surface rainwater to the groundwater through the vadose zone. The study assumed a homogeneous antecedent saturation condition for the area (about 2km^2) within which the 9 observation wells were located. This assumption is justified for a lithologically homogeneous area of about 2km^2 in the equatorial region, as significant water content variability in homogeneous soils happens only when the soil is exposed to a long period of dry condition (Harter and Zhang, 1999). Under bare soil surface and homogeneous antecedent saturation conditions, the responses of water table to rainfall recharge could be a function of both rainfall pattern and vadose zone thickness. Observation wells within the western part of the reclaimed land were excluded in the analyses. The uneven distribution of bush grasses in the western part could introduce uncertainty into the analyses, by creating heterogeneous antecedent saturation conditions within the vadose zone.

To investigate the influence of coastal tides on groundwater-level fluctuations, the second (2) cross-correlation analysis was carried out for

observation wells C1, C3, C4, M1-04, M2-07, M2-08, M2-13, M2-19, M2-22 and M3-01 (Figure 1.3). Daily coastal tidal fluctuations from observation well P015 (Figure 1.3) were used as the input time series. Groundwater-level fluctuations for the other 10 observation wells were used as the output time series. Cross-correlation plots (r_{xy} as y-axis; k as x-axis) between the daily coastal tidal fluctuation and daily groundwater-level fluctuations were derived. The values of cross-amplitude were extracted from the cross-correlation plots. The relationship between the cross-amplitude and the distance of the observation wells from the tidal source were used to investigate the influence of coastal tides on the water table fluctuation. Distances of observation wells M3-01, M2-19 and M2-22 from the tidal source were measured perpendicularly from the unlined temporary drain, as they were more directly exposed to tidal level fluctuations in the drain. Distances of the other observation wells from the tidal source were measured perpendicularly from the shoreline.

5.2.3 Auto-spectral analysis

The auto-spectral analysis transforms signals in the time domain into signals in the frequency domain through Fourier transformation of the auto-correlation function. The periodic wave components that contribute significantly to the time series signal can be ascertained by identifying the peaks of the spectral density function (Fleming et al., 2002). The spectral density function, $S(f)$ in discrete form is:

$$S(f) = 2 \left[1 + 2 \sum_{k=1}^m D(k) r(k) \cos(2\pi f k) \right] \quad (5.5)$$

$$D(k) = \frac{\left(1 + \cos \pi \frac{k}{m} \right)}{2} \quad (5.6)$$

where f is the frequency and it equals to $j/2m$ ($j = 1$ to m), k is the time lag, and m is the truncation point. The regulation time, similar to the passing band in a

signal treatment, quantifies the duration of the influence of the input stress and serves as an indicator of the length of the impulse response of the system (Laracque et al., 1998; Lee and Lee, 2000).

Auto-spectral analyses were carried out for all the observation wells to elucidate the frequency bands of the various components of the signals. From the analyses, the wave component contributed by rainfall recharge was found to have a lower frequency band compared to the wave component induced by offshore tides. The wave component contributed by rainfall recharge appears to have a frequency band between 0 and 0.0938cycle/day, while the frequency band for wave component induced by coastal tides lies between 0.0625 and 0.5000cycle/day (this is discussed in more detail in Section 5.3.4). A low pass filter was hence applied to filter out the tidal-induced level fluctuation to generate the time series of filtered (rainfall-induced) groundwater-level fluctuations. The filtered groundwater-level fluctuations were then used for estimating the monthly net recharge percentages.

5.2.4 Estimation of monthly net recharge percentage

Based on Sophocleous (1991)'s definition, gross recharge (GR) can be obtained as follows:

$$GR = S_y \Delta h + ET^{gw} + \Delta Q^{gw} \quad (5.7)$$

where S_y is specific yield of the unconfined aquifer; Δh is groundwater level change induced by rainfall recharge (i.e. the filtered groundwater level); ET^{gw} is groundwater evaporation; and ΔQ^{gw} is net ambient groundwater flow. Rearranging Equation (5.7), net groundwater recharge (R_n) can be obtained through:

$$R_n = GR - ET^{gw} - \Delta Q^{gw} = S_y \Delta h \quad (5.8)$$

Therefore, net recharges can be estimated from the rainfall induced groundwater-level changes as in Equation (5.8), which is the basis of the “water-table fluctuation method” as referred to in this report.

Based on Equation (5.8), the monthly net groundwater recharge percentages $R_n(\%)$ at the study site were computed using:

$$R_{upper}(\%) = \frac{\sum_{j=1}^{k-1} (S_{upper})_j \Delta h_j}{D} \times 100\% \quad (5.9)$$

$$R_{Lower}(\%) = \frac{\sum_{j=1}^{k-1} (S_{Lower})_j \Delta h_j}{D} \times 100\% \quad (5.10)$$

$$\Delta h_j = \begin{cases} \Delta h_j; \Delta h_j > 0 \\ 0 & \Delta h_j \leq 0 \end{cases} \quad (5.11)$$

where S_{upper} and S_{Lower} are specific yields corresponding to the upper and lower bounds of 95%CI of the effective grain size d_{50} for the study site; D is the monthly rainfall depth; j is the index for day and k is the number of day in a month. The values of S_{Lower} (0.27) and S_{upper} (0.31) from studies in Chapter 2 were used to estimate net groundwater recharge percentage using Equations (5.9) to (5.11).

5.3 Results and discussions

5.3.1 Influence of vadose zone thickness and rainfall pattern on rainfall-groundwater level fluctuation relationship

The correlations among cross-amplitude, rainfall pattern and vadose zone thickness are shown in Figure 5.2. Cross-amplitudes in October 2003 and November 2003 appear to decrease exponentially as the thickness of vadose zone increases. Under intense rainfall events during these two months, the

vadose zone thickness plays a significant role in attenuating the impacts of the high rainfall intensity. Compared to November 2003, cross-amplitudes in October 2003 were slightly higher when the vadose zone thickness was larger than about 2m. This effect is magnified as the vadose zone thickness increases beyond 2m, but is diminished when vadose zone thickness is below 2m.

Figure 5.2 Relationships among cross amplitude, rainfall pattern and vadose zone thickness

This observation implies that under an intermediate vadose zone thickness (more than 2m), water table responds more closely to a concentrated rainfall cluster compared to isolated rainfall events. A concentrated rainfall cluster refers to a group of individual rainfalls producing an integrated (continuous) recharge event.

Under shallow water table conditions (less than about 2m), the water table seems to respond similarly to both the rainfall patterns. Unlike in the present unconfined sandy aquifer, Wu et al. (1996) found that water tables in loamy and clayey unconfined aquifers correlates well to intense rainfall events when the vadose zone thickness is less than 1.5m. Under an intermediate vadose thickness (more than 1.5m in their case), the water table was observed to correlate well to a concentrated rainfall cluster but poorly to isolated rainfall events.

Cross-amplitudes in September 2003 are significantly lower than those in the other two months, with a maximum value of about 0.40. The low cross-amplitude values in September 2003 imply that the unconfined sandy aquifer attenuates strongly the impacts of low intensity rainfall events, when the vadose zone thickness is larger than about 2.5m.

5.3.2 Influence of vadose zone thickness and rainfall pattern on rainwater percolation rate

Figure 5.3 shows the correlations among delay (lag), rainfall pattern and vadose zone thickness.

Figure 5.3 Relationships among delay (lag), rainfall pattern and vadose zone thickness

Delays in October 2003 and November 2003 were found to be directly proportional to the vadose zone thickness. Under intense rainfall events in these two months, vadose zone thickness plays a significant role in delaying the percolation of surface rainfalls to the water table. Under an intermediate vadose zone thickness (more than 2m), rainfalls contributed by a series of concentrated rainfall clusters in October 2003 appear to percolate more rapidly to the water table compared to rainfalls contributed by an isolated intense rainfall event in November 2003. This behavior is magnified when the vadose zone thickness increases. Under shallow water table conditions (less than 2m), no significant

difference was observed in the percolation rate of surface rainwater to the water table between October 2003 and November 2003.

This observation provides a logical explanation for the observation in 5.3.1. Under shallow water table conditions (less than 2m), the response of the water table to an intense rainfall recharge is very fast, leading to a close correlation between them, i.e. a high value of cross-amplitude. Due to this fast response, rainfall recharge from individual intense rainfall events could be separated from one another. A shallow water table is hence able to respond well to both the rainfall patterns in October 2003 and November 2003. When the vadose zone thickness increases, the percolation time increases, and the water table is not able to respond separately to individual intense rainfall events in a cluster. There is a tendency for an integrated recharge event to be generated by a group of individual rainfalls clustering around a large rainfall event. This leads to higher values of cross-amplitude in October 2003 compared to those in November 2003, for intermediate vadose zone thicknesses. For low intensity rainfall events in September 2003, delays are generally high, exceeding 4 days. The slow percolation rate of surface rainwater to the water table during this period leads to low values of cross-amplitude in September 2003.

A similar explanation could be applied to rainfall-recharge characteristics in unconfined aquifers overlaid with loam, light clay and heavy clay, as observed by Wu et al. (1996). Compared to sandy aquifers, percolation rate of surface rainfall in soils with a low hydraulic conductivity is much lower. The water table under an intermediate vadose zone thickness is hence not capable of responding separately to intense rainfall events in a cluster. Consequently, the impacts of individual rainfall events in a rainfall cluster 'merge' to produce an integrated recharge event, resulting in the water table responding to a rainfall cluster.

'Delays' or lags in the unconfined sandy aquifer are generally in the order of days when the vadose zone thickness is larger than 2m. A minimum delay of slightly less than a day was observed for intense rainfall events in

October 2003 and November 2003 when the water table was about 2m below the ground surface. Gburek and Folmar (1999) observed a much higher rainfall recharge percolation rate in an unconfined fractured rocky aquifer. Water table at 6m below the ground surface was found to respond within 1 to 2 hours after the onset of rainfall, and reached its maximum elevation about 4 to 16 hours later. The high discrepancy in delays observed in the two studies is mainly due to the difference in recharge mechanism between the two aquifer systems. Preferential flow via fracture networks, associated with a high percolation velocity, is the predominant recharge mechanism in rocky aquifers, while soil matrix flow through the highly compacted sand fills is the predominant recharge mechanism at the present Changi reclaimed land.

5.3.3 Influence of vadose zone thickness and rainfall pattern on monthly net recharge percentage

Figure 5.4 shows the monthly net recharge percentages at the study site, estimated using Equations (5.9) to (5.11).

A non-uniform distribution of recharge rates was observed, especially on the western part of the reclaimed land. The highly non-homogeneous auto-correlation plots, as shown in Figure 5.5, indicate that recharge characteristic at this area is non-uniform. This could be attributed to the uneven distribution of bush grasses. On the other hand, rainfall recharge rates under a bare soil condition in the eastern part were generally more uniform, as reflected in the homogenous auto-correlation plots in Figure 5.6.

Although the eastern part of the reclaimed land site has a lithologically homogeneous soil profile with a bare surface, a fully uniform recharge pattern was not observed. Significantly lower recharge percentages were observed for observation wells M2-19 and M2-22, which were near to the unlined open drain. This observation could be due to the influence of tidal level fluctuations in the open drain, which could impose significant effects on groundwater discharge (Ataie-Ashtiani et al., 2001).

Figure 5.4. Monthly net groundwater recharges percentages in: (a) September 2003; (b) October 2003; and (c) November 2003

Figure 5.5 Auto-correlation functions of daily groundwater-level fluctuations for observation wells at the western part of reclaimed land: (a) October 2003; and (b) November 2003

A rainfall pattern characterized by a series of intense rainfall clusters as in October 2003 appears to yield higher net recharge percentages. Although the total rainfall depth in September 2003 and November 2003 were close, the net recharge percentages in September 2003 were significantly lower than those in November 2003. This implies that groundwater recharge is not a simple direct proportion of the total rainfall depth, but is strongly influenced by the rainfall pattern.

Figure 5.6. Auto-correlation functions of daily groundwater-level fluctuations for observation wells at the eastern part of reclaimed land: (a) September 2003; (b) October 2003; and (c) November 2003

This observation is most likely attributed to the difference in percolation rate of surface rainfall recharge under different rainfall patterns, as discussed in 5.3.2. Under an intermediate vadose zone thickness, the large delay during low intensity rainfalls in September 2003 increases the residence time of the percolating rain water in the vadose zone, leading to high soil evaporation losses. For an intermediate vadose zone thickness, the rainwater contributed mainly by one intense rainfall event in November 2003 percolated much faster to the water table, hence lower potential for soil evaporation losses. Similarly, the rainwater contributed by a series of intense rainfall clusters in October 2003 percolated rapidly to the water table. The rapid transfer of percolated rainwater to the water table reduces soil evaporation losses, leading to higher recharge percentages. Potential evaporation rates were generally high during the study period, where more than half of the pan readings at the Changi Meteorological Station ranged between 3.7 and 6.7mm/day.

From these analyses and discussions, the recharge percentages at the reclaimed land were found to depend strongly on the percolation rate of surface rainwater to the groundwater, which depends on both the rainfall pattern and the vadose zone thickness.

5.3.4 Influence of coastal tidal fluctuations on groundwater level fluctuations

From cross-correlation analyses as presented in Figure 5.7, the water table responses were generally independent of the tidal fluctuations, and the cross-amplitudes were generally small.

However, the cross-amplitude for observation well M3-01 was quite significant. A plot relating the cross-amplitude and the distance from the tidal source is shown in Figure 5.8. Distances for observation wells M3-01, M2-19 and M2-22 were measured perpendicularly from the unlined open drain, as they

were more directly exposed to tidal fluctuations in the drain. Distances for the other observation wells were measured perpendicularly from the shoreline.

Figure 5.7 Cross-correlation plots using daily coastal tidal fluctuations in November 2003 as input time series for observation wells (a) M2-19, M2-22, M3-01; and (b) M1-04, M2-07, M2-08

It is apparent that groundwater-level fluctuations were not correlated to coastal tidal fluctuations for the Changi reclaimed land site, except close to the unlined drain at M3-01. The propagation of tidal fluctuations inland is rapidly dampened out within a short distance of about 150m from the tidal source, as shown in Figure 5.8. This observation is consistent with results from spectral analyses as shown in Figure 5.9. Almost all the observation wells have negligible frequency densities beyond 0.0938cycle/day, except observation wells M3-01, which is exposed to tidal fluctuations in the unlined open drain.

Figure 5.8 Effect of coastal tidal fluctuations from tidal source

Figure 5.9. Auto-spectral functions of groundwater-level fluctuations in:
(a) September 2003; and (b) November 2003

Previous studies (e.g. Li et al., 2000; Ataie-Ashtiani et al., 2001) on the wave interaction between ocean and landward aquifer, have found that coastal tidal fluctuations have a noticeable effect on the land-ocean boundary, but are

rapidly dampened out as the distance from the shore increases. Li et al. (2002) found that shoreline with a rhythmic shape reduces the wave propagation of the coastal tidal fluctuations. The highly compacted reclaimed land is expected to have a relatively small pore size, which tends to retain considerable amount of moisture within the larger capillary fringe as compared to a natural shore. This is supposed to favor the propagation of tides through a zone of significant moisture (Ataie-Ashtiani et al., 2001). This study, however, demonstrates that the Changi reclaimed land, with a straight shoreline created from highly compacted sand fills, is also capable of rapidly dampening out the propagation of coastal tides, compared to natural non-compacted sandy beaches with rhythmic shorelines.

5.4 Summary

The net recharge percentages and the relationship between rainfall and water table-fluctuation were found to depend strongly on the percolation rate of surface rainfall recharge to the groundwater. The percolation rate was found to be a combined function of rainfall pattern and vadose zone thickness. Under intermediate vadose zone thicknesses ($>2.0\text{m}$), rainfall pattern appears to have a noticeable effect on the rainwater percolation rate through the vadose zone. A series of intense rainfall clusters results in high percolation rate with short delay, leading to high correlation between rainfall and water table fluctuation, and high recharge percentages. An isolated intense rainfall event appears to have lower percolation rate, resulting in a weaker correlation between rainfall and water table fluctuation, and a lower recharge percentage. This effect is less obvious in a shallow water table condition, but is magnified as the vadose zone thickness increases. Conversely, low intensity rainfalls tend to produce rainfall recharge with low percolation rates, leading to weak correlation between rainfall and water table fluctuation, and low recharge percentages. The 'percolation rate' concept was able to explain the observed rainfall-recharge

relationship, the correlations between rainfall and water table fluctuation and the recharge percentage distribution at the Changi reclaimed land.

Although the reclaimed land site has a lithologically homogeneous soil profile, the recharge rates were distributed non-uniformly over the site. The uneven distribution of bush grasses the western part of the reclaimed land could have resulted in high variability of recharge percentages distribution. Under a more homogeneous bare soil condition in the eastern part of the site, significantly lower recharge percentages were observed for areas under the influence of coastal tides. The unconfined sandy aquifer was able to rapidly dampen out the wave propagation of coastal tides within a short distance from the tidal source, even though it has a fairly straight shoreline and is created from highly compacted sand fills.

CHAPTER 6

STUDIES ON GROUNDWATER RECHARGE CHARACTERISTICS: DETERMINISTIC MODELLING APPROACH

6.1 Introduction

From the empirical studies in Chapter 5, some characteristics of the relationships between rainfall and water table-fluctuation were elucidated for the Changi reclaimed land. For example, both the vadose zone thickness and rainfall pattern were found to have significant influences on the percolation rate of surface rainwater to the water table. The percolation rate in turn was found to influence significantly the correlation between rainfall and water table-fluctuation and rainfall recharge percentages.

However, the physical processes leading to the observed characteristics could not be investigated using the empirical approach, as the empirical approach is a “black box” method. In order to search for physical explanations for the observed characteristics, a deterministic modeling approach, which models the physical processes taking place in the vadose zone, is required. Deterministic modeling was carried out in this chapter for the following purposes:

1. To investigate the influence of various meteorological and hydrogeological factors on the gross recharge percentage at the Changi reclaimed land. Gross recharge percentage is the portion of rainwater reaching the water table after losses through soil evaporation within the vadose zone.
2. To obtain the probable recharge threshold values for the Changi reclaimed land under the different vadose zone thicknesses. The recharge threshold value refers to the minimum rainfall depth required to initiate groundwater recharge.

3. To investigate the relationships between rainfall intensity and gross recharge percentage for the Changi reclaimed land, and
4. To provide physical explanations for the observed characteristics from the empirical studies in Chapter 5.

A deterministic unsaturated zone model, the VS2DI, was setup to simulate the major physical processes taking place in the vadose zone of the study site. This study is focused on the more homogeneous eastern part of the Changi reclaimed land (Figure 1.3). The land surface of the eastern part of the Changi reclaimed land is nearly bare and flat. No surface ponding has been observed even under very intense rainfalls (exceeding 200mm/day), as the sands at this site are highly permeable (hydraulic conductivity of 13.5 to 32.5m/day; refer to Chapter 4). Therefore, groundwater recharge loss is contributed mainly by soil evaporation before the percolating rainwater reaches the water table, which varies from 1.0 to 4.0 m below the ground surface. The physical processes taking place in the vadose zone are illustrated in Figure 6.1. Soil moisture movement within the vadose zone of a relatively porous soil is mainly vertical, dominated by gravity force, when rainfall intensity is typical of the order of, or less than the saturated hydraulic conductivity of soil (Singh, 1997).

Figure 6.1. Conceptual representation of the gross recharge processes

6.2 VS2DI model setup

The setup of VS2DI model in this study is generally similar to that in Chapter 4, except that an equilibrium moisture profile with pressure head equal to the negative elevation above the water table was assigned as the initial hydraulic condition, instead of the actual measured soil moisture profile.

To ensure stable solutions, the time steps were allowed to vary from 0.26 to 2.6×10^{-9} day through the application of time step multiplier (TMLT) and time step reduction factor (TRED), and the relaxation parameter was set to a value varying from 0.70 to 2.50. The rainfall recharge simulations were considered accurate with a total mass balance error of between 0.1 to 1% at the end of simulations.

The soil hydraulic parameters used in the simulations for the sand texture at the site are the calibrated lower bound $K_S - \beta$ (Chapter 4): $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.002244$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day. This sand texture is referred to here as the “default” sand texture. The lower bounds of β and K_S were selected to yield conservative estimates of gross recharge percentages for the study site.

6.3 Generation of datasets

Based on the meteorological data from the Changi Meteorological Station, statistical analyses were carried out to elucidate the statistical characteristics of the various meteorological factors. These statistical characteristics as summarized in Table 6.1 are typical for an equatorial climate.

Based on the results, four recharge situations were defined, representing different degrees of favorability for gross recharge, as in Table 6.2. The four recharge situations are referred to as the “favorable”, “non-favorable”, “average” and “unknown” situations. The “favorable” situations represent

combination of conditions which intuitively are expected to be favorable for high gross recharge, for example, high rainfall intensity coupled with low evaporation rates. Conversely, the “non-favorable” situations refer to combination of conditions which are expected not to favour high gross recharge, such as low rainfall intensity coupled with high evaporation rates. The “average” situations represent the intermediate conditions between the “favorable” and “non-favorable” situations. The “Unknown” situations represent combination of conditions whose favorability for gross recharge process is not so certain, for example, intense rainfalls coupled with high evaporation rates, or mild rainfalls coupled with low evaporation rates.

The ranges of the variable values for the four recharge situations are shown in Table 6.2. The ranges were determined guided by the statistical characteristics of the variables as shown in Table 6.1. The variable ranges for the “Average” situations were set approximately within the 12.5% and 87.5% percentiles. Variable values below the 12.5% percentile were presumed to be “Low” values, while variable values larger than the 87.5% percentile were presumed as “High” values. The “low” values of air temperature and potential evaporation rate and “high” values of rainfall intensity and relative humidity form the variables ranges for the “Favorable” situations. On the other hand, “high” values of air temperature and potential evaporation rate and “low” values of rainfall intensity and relative humidity form the variable ranges for the “Non-favorable” situations.

Different combinations of variable values were generated randomly within each recharge situation. The numbers of random combination sets generated for the “non-favorable”, “average”; “favorable” and “unknown” situations are 30, 30, 30 and 40 respectively. These combination sets of variable values are used as inputs to the numerical model to generate datasets of gross recharge percentages

Table 6.1 Results of Statistical Analyses for Meteorological Factors at Changi Meteorological Station, Singapore

	Meteorological Factor			
	Daily Rainfall Intensity (mm/day)	Daily Relative Humidity (%)	Daily Air Temperature (°C)	Daily Pan Evaporation (mm/day)
Data period	1994 – 2003	1 Jan 2003 – 31 Dec 2003	1 Jan 2003 – 31 Dec 2003	1994 - 2003
Minimum	0.0	71.9	24.3	0.0
Maximum	211.0	98.2	30.6	9.5
Mean	55.0	84.3	27.8	4.7
Standard deviation	37.5	5.1	1.2	1.8
Range between percentiles 12.5% and 87.5%	25.0 – 76.0	78.2 – 90.7	26.4 – 29.2	2.6 – 6.9

Table 6.2 Range of Variables for Different Degree of Favorability on Gross Recharge Process

Variable	Degree of Favorability			
	Non-Favorable	Average	Favorable	Unknown
Daily Rainfall Intensity (mm/day)	0.2 – 15.0	10.0 – 75.0	65.0 – 211.0	0.4 – 12.2; 15.3 – 134.0
Daily Potential Evaporation Rate (mm/day)	5.0 – 9.5	2.6 – 6.9	0.5 – 4.5	0.2 – 2.5; 6.1 – 9.5
Daily Air Temperature (°C)	28.0 – 31.0	26.0 – 29.0	24.3 – 28.0	24.4 – 30.9
Daily Relative Humidity (%)	71 - 84	78 – 91	84 - 98	71.7 – 94.9
Vadose Zone Thickness (m)	1.5 – 4.0	1.5 – 4.0	1.5 – 4.0	1.5 – 4.0

The daily rainfall intensity was used as input variable at the upper boundary of the VS2DI solution domain. The daily potential evaporation rate is needed for soil evaporation simulations (refer to Equation 4.2). To simulate the actual soil evaporation rates (refer to Equation 4.3), the relative humidity and air temperature were required to compute the pressure potential of the atmosphere (HA). Using the randomly generated combination set of input

variables, simulations were carried out for a continuous one-day rainfall event followed by dry days. The simulations were continued until the outflow rate at the lower boundary of the ‘hypothetical’ solution domain equals to zero. Soil evaporations were simulated continuously throughout the entire simulation period. The gross recharge percentages for the 130 simulations were computed from:

$$GR_i = \frac{\left(\sum_{t=0}^n O_t \right)_i}{D_i} \times 100\% \quad ; i = 0, 1, \dots, 130 \quad (6.1)$$

where GR is gross recharge percentage (%); $\sum_{t=0}^n O_t$ is total outflow at the lower boundary at the end of the simulation period (mm), and is computed directly by the VS2DI model; n is the end of simulation period (day); i is index for combination set of variable values (1 to 130); and D is daily rainfall depth (mm). Besides gross recharge percentage, the simulated vertical flow velocity profiles and soil evaporations were also analyzed to provide physical explanations for the observed recharge characteristics. The simulation results of VS2DI are shown in Appendix E.

6.4 Results and discussions

6.4.1 Correlation studies

To investigate the influence of the various meteorological factors on the gross recharge percentage, correlation analyses were carried out between the factors and the corresponding gross recharge percentages. The analyses were carried out for 4 different ranges of vadose zone thickness. The results of the analyses are shown in Figure 6.2.

Figure 6.2 Correlations between gross recharge percentage and meteorological factors for different ranges of vadose zone thickness

The gross recharge percentage appears to correlate well with rainfall intensity for all the ranges of vadose zone thickness, with correlation coefficients ranging between 0.70 and 0.88. There was no significant correlation between gross recharge percentage and potential evaporation rate, relative humidity or air temperature for shallow water table conditions (vadose thickness below 2.5m), with correlation coefficients generally below 0.40. However, their correlation with gross recharge percentage become more significant when the vadose zone thickness is larger than 2.5m, with the correlation coefficients increasing dramatically as depicted in Figure 6.2.

These results indicate that rainfall intensity has the most significant impact on the gross recharge percentage for a wide range of vadose zone thickness. As soil evaporation is a function of potential evaporation rate, relative humidity and air temperature, the present correlation results indicate that the impact of soil evaporation on gross recharge percentage becomes more significant when the vadose zone thickness is larger than 2.5m.

6.4.2 Rainfall intensity -recharge percentage relationships

The rainfall intensity–recharge percentage relationships for the 4 different ranges of vadose zone thickness are shown in Figure 6.3. It is apparent that the gross recharge percentage increases as rainfall intensity increases. The sensitivity of gross recharge percentage to rainfall intensity is generally high for rainfall intensity lower than 25mm/day, but the influence decreases as rainfall intensity increases. These rainfall intensity-recharge percentage characteristics are well defined by a normal-log relationship, where the coefficients of determination of the curves are generally high as shown in Figure 6.3. The regression equations and their 95% confidence intervals are shown in Table 6.3.

Figure 6.3 Rainfall intensity-recharge percentage relationships for different ranges of vadose zone thickness

For vadose zone thickness lower than 2.5m, the regression equations could generally yield reasonable gross recharge estimates, as the 95% confidence intervals of the equations coefficients are generally narrow. The 95% confidence intervals of the equation coefficients are relatively large for

vadose zone thickness larger than 2.5m. This result is not surprising, as the effects of soil evaporation on gross recharge percentage become significant when the vadose zone thickness is larger than 2.5m, as explained in 6.4.1. This leads to higher uncertainties in the recharge rate estimates when only the rainfall intensity and vadose zone thickness are considered.

Table 6.3 Regression Equations for Rainfall Intensity -Recharge Percentage Relationship

Estimation Equations	Application Range	95% Confidence Interval
For $1.0 < VZ \leq 2.0\text{m}$:		
GR (%) = 0	$I \leq 0 \text{ mm/day}$	a_1 : 10.254 to 13.611
GR (%) = $11.932\ln(I) + 39.046$	$0 < I \leq 165.4 \text{ mm/day}$	b_1 : 33.611 to 44.476
GR (%) = 100	$I > 165.4 \text{ mm/day}$	
For $2.0 < VZ \leq 2.5\text{m}$:		
GR (%) = 0	$I \leq 0.8 \text{ mm/day}$	a_1 : 16.144 to 19.695
GR (%) = $17.920\ln(I) + 4.477$	$0.8 < I \leq 206.5 \text{ mm/day}$	b_1 : -1.731 to 10.685
GR (%) = 100	$I > 206.5 \text{ mm/day}$	
For $2.5 < VZ \leq 3.0\text{m}$:		
GR(%) = 0	$I \leq 1.6 \text{ mm/day}$	a_1 : 15.817 to 22.608
GR (%) = $19.213\ln(I) - 9.585$	$1.6 < I \leq 300.0 \text{ mm/day}$	b_1 : -22.472 to 3.302
GR (%) = 100	$I > 300.0 \text{ mm/day}$	
For $3.0 < VZ \leq 4.0\text{m}$:		
GR(%) = 0	$I \leq 3.4 \text{ mm/day}$	a_1 : 19.944 to 26.541
GR (%) = $23.243\ln(I) - 28.227$	$3.4 < I \leq 248.8 \text{ mm/day}$	b_1 : -41.425 to -15.025
GR (%) = 100	$I > 248.8 \text{ mm/day}$	

Notes:

$GR(\%) = a_1\ln(I) + b_1$; where a_1 and b_1 are regressed coefficients

The vadose zone thickness also appears to influence the gross recharge percentage, being much higher recharge rates for shallow water table conditions (1.0 to 2.5m) compared to intermediate depth water table (2.5 to 4.0m), as depicted in Figure 6.3. The sensitivity of gross recharge percentage to vadose zone thickness is more significant when rainfall intensity is lower (<25mm/day), and decreases as rainfall intensity increases.

6.4.3 Rainfall recharge threshold

The rainfall recharge threshold value is the minimum rainfall depth required to initiate groundwater recharge. From the bounds of the 95% confidence interval of parameters a_1 and b_1 , the regression equations in Table 6.3 were solved by setting the gross recharge percentage to zero, to yield the possible range of recharge threshold values for each range of vadose zone thickness. The estimated ranges of rainfall recharge threshold values are shown in Table 6.4.

For vadose zone thickness less than 2.0m, practically all rainfall intensities are able to initiate gross recharge, as the recharge threshold is very low. The recharge threshold values increase significantly as vadose zone thickness increases. The estimated ranges of recharge threshold were relatively large for intermediate vadose zone thickness (2.5 to 4.0m). This is likely due to amplified effects of potential evaporation, relative humidity and air temperature on gross recharge percentage, as explained in 6.4.1.

Table 6.4 Estimated Ranges of Recharge Threshold Values for Unconfined Sandy Aquifers under the Equatorial Climate	
Vadose Zone Thickness (m)	Range of Recharge Threshold (mm/day)
$1.0 < VZ \leq 2.0$	0 – 0.1
$2.0 < VZ \leq 2.5$	0.5 – 1.1
$2.5 < VZ \leq 3.0$	0.8 – 4.1
$3.0 < VZ \leq 4.0$	1.8 – 8.0

6.5 Physical explanations

6.5.1 Hypothesis setting and validation

This section aims to search for physical explanations to the results obtained in 6.4.

From the simulation results, no surface ponding was observed, which is consistent with field observations at the Changi reclaimed land. As a matter of

fact, rainfall intensity at the study site (0-211mm/day) is much lower than the saturated hydraulic conductivity (13.5 to 32.5m/day) of the site. Surface ponding happens only when rainfall intensity exceeds the saturated hydraulic conductivity of the soils (Chow et al., 1988, Section 4.4). Surface ponding will hence not occur at the study site, and the surface soil remains basically unsaturated. Flow in the vadose zone at the study site is mainly vertical dominated by gravity force, as expected in relatively porous soils when rainfall intensity is of the order of, or less than the soil-saturated hydraulic conductivity (Singh, 1997). With no surface ponding and negligible lateral flows within the vadose zone, the percolating rainfall could be partially lost through soil evaporation before reaching the water table.

The average residence time of the percolating rainwater within the vadose zone can be defined as:

$$t_R = \frac{VZ}{\bar{U}_Z} \quad (6.2)$$

where t_R is the average residence time; VZ is the vadose zone thickness; and $\bar{U}_Z$ is the average vertical flow velocity within the vadose zone, which can be computed from the simulated results of VS2DI.

From the VS2DI simulation results, $\bar{U}_Z$ was found to relate linearly to rainfall intensity, I (Figure 6.4). In other words, intense rainfalls tend to generate faster flow of percolating rainwater through the vadose zone compared to low intensity rainfall:

$$\bar{U}_Z \propto I \quad (6.3)$$

It is reasonable to assume that residence time t_R linearly influences the potential of percolating rainwater to be lost through soil evaporations, or:

$$SE \propto t_R \quad (6.4)$$

where SE is defined as soil evaporation ratio, representing the potential of the percolating rainwater to be lost through soil evaporation.

Figure 6.4 Relationship between vertical velocity of fluid flow and rainfall intensity

Substituting Equation (6.2) into Equation (6.4) yields:

$$SE \propto \frac{VZ}{\bar{U}_z} \quad (6.5)$$

As $\bar{U}_z$ was found to relate linearly to rainfall intensity, Equation (6.3) can be used to substitute $\bar{U}_z$ in Equation (6.5) with I to yield:

$$SE \propto \frac{VZ}{I} \quad (6.6)$$

Partial differentiations of Equation (6.6) are as shown below:

$$\frac{\partial SE}{\partial I} \propto -\frac{VZ}{I^2} \quad (6.7)$$

$$\frac{\partial SE}{\partial VZ} \propto \frac{1}{I} \quad (6.8)$$

Equation (6.6) shows the relationship between SE and VZ or I , while Equations (6.7) and (6.8) indicate the sensitivity of SE to I and VZ respectively.

In the present study, the SE ratio was computed through:

$$SE = \frac{D_L}{D_{EX}} \quad (6.9)$$

where D_L is total rainwater depth lost through soil evaporations, and is computed directly using the VS2DI model; and D_{EX} is rainwater depth subjected to soil evaporation, computed through:

$$D_{EX} = D - \sum_{t=0}^1 O_L \quad (6.10)$$

where D is the total rainwater depth; and $\sum_{t=0}^1 O_L$ is the total rainwater depth flowing out of the vadose zone into the water table at the end of the rain day, which is computed directly using the VS2DI model. From the simulation results, the actual soil evaporation rate was found to be negligible during the actual raining day, but fully meets the atmosphere demand during the first few days following the rainfall event. It then decline rapidly thereafter. This observation is consistent with those of Wallace and Holwill (1997) and Klaassen et al. (1998). Therefore, rainwater depth subjected to soil evaporations can be represented by Equation (6.10), as only rainwater entering the aquifer system within the rain day is not subjected to soil evaporation. The relationship between the computed SE and rainfall intensity is shown in Figure 6.5.

In order to validate the assumption behind Equation (6.4), the computed SE (Figure 6.5) should have the characteristics of Equations (6.6) to (6.8). It is

apparent that the computed SE shows the characteristics of Equation (6.6), where SE decreases as I increases for a particular range of vadose zone thickness. More importantly, the computed SE exhibits the characteristics of Equation (6.7). Its sensitivity to rainfall intensity appears to be very high for low rainfall intensities ($<25\text{mm/day}$), but decreases rapidly as rainfall intensity increases. This dramatic decline in sensitivity is due to the ‘square’ effect of rainfall intensity in Equation (6.7). Its sensitivity to VZ was also found to decrease as rainfall intensity increases, as depicted in Equation (6.8).

Figure 6.5 Rainfall Intensity - SE relationships for different ranges of vadose zone thickness

Therefore, residence time t_R was found to determine directly the SE ratio, which represents the potential of percolating rainwater within the vadose zone to be transported to the soil surface to meet the demands of soil evaporation.

6.5.2 Physical explanations for the correlation results and recharge threshold

As shown in Equation (6.2), increase in vadose zone thickness increases the residence time, t_R . This increases the potential of the percolating rainwater for soil evaporation, SE . The increase in SE directly magnifies the influence of potential evaporation rate, relative humidity and air temperature on the gross recharge percentage, as soil evaporation rate is a function of these factors, as shown in Equations (4.2) and (4.3). This explains the correlation results, where the influence of these factors on gross recharge percentage is magnified as vadose zone thickness increases (Figure 6.2). Likewise, the same explanations can be given for the higher recharge threshold values for higher vadose zone thickness (Table 6.4).

The higher residence time t_R also reduces the total rainwater depth entering the aquifer system within the rain day, leading to a higher portion of rainwater subjected to bare soil evaporations. Simulation results show that the mean proportions of rainwater entering the aquifer system by the end of the rain day are 29.6; 6.4; 0.9 and 0.0% for $1.0 < VZ \leq 2.0\text{m}$; $2.0 < VZ \leq 2.5\text{m}$; $2.5 < VZ \leq 3.0\text{m}$ and $3.0 < VZ \leq 4.0\text{m}$ respectively.

Although the drop from 29.6 to 6.4% is more dramatic than the drop from 6.4 to 0.9%, this dramatic drop (29.6 to 6.4%) did not have a significant impact on the correlation between gross recharge percentage and the meteorological factors (PEV , RH , T). There is no significant increase in the correlation coefficient between $1.0 < VZ \leq 2.0\text{m}$ and $2.0 < VZ \leq 2.5\text{m}$, as shown in Figure 6.2. One possible explanation for this observation is that the percolation of intense rainwater from the soil surface to the shallow water table (1 to 2.5m) is relatively rapid, due to the relatively short distance to percolate through. If the intense rainwater remaining within the vadose zone after the rain day could propagate rapidly to the water table, the effect of soil evaporation on rainwater loss within the vadose zone would be less. Therefore, the proportion of rainwater entering the groundwater at the end of a rain day has a little

influence on the recharge percentage under shallow water table conditions. This may explain the insignificant change in correlation coefficients for PEV , RH and T for $1.0 < VZ \leq 2.0\text{m}$ and $2.0 < VZ \leq 2.5\text{m}$, even though that is a large drop in proportion of rainwater entering the groundwater at the end of a rain day (from 29.6 to 6.4%).

Conversely, intense rainwater needs to percolate through a longer distance to reach the water table under intermediate water table condition (2.5 to 4.0m). The effect of soil evaporation on rainwater loss within this vadose zone is magnified, as rainwater remaining within the vadose zone after the rain day takes a longer time to reach the water table. As a result, a smaller drop in proportion of rainwater entering the underlying groundwater at the end of a rain day (from 6.4 to 0.9%) could be sufficient to exert a significant impact on the gross recharge percentage. This could explain the significant increase in correlation coefficients (Figure 6.2) between the gross recharge percentage and the meteorological factors (PEV , RH , T) when the vadose zone thickness increases from $2.0 < VZ \leq 2.5\text{m}$ to $2.5 < VZ \leq 3.0\text{m}$.

6.5.3 Physical explanations for the rainfall intensity-recharge percentage relationship

Based on Equation (6.2), residence time t_R is inversely proportional to the vertical flow velocity, which relates linearly to rainfall intensity (Figure 6.4). A higher flow velocity, due to higher rainfall intensity results in a lower residence time of rainwater within the vadose zone, and hence a lower potential for soil evaporation SE . This would lead to a higher gross recharge percentage. The impact of rainfall intensity on gross recharge percentage is more pronounced than vadose zone thickness, attributed to the 'square' effect of rainfall intensity on the residence time, as shown in Equation (6.7). This further explains the dramatic decline in the slopes of the $GR-I$ curves as the rainfall intensity increases.

In summary, the gross recharge percentage was found to be a combined function of rainfall intensity and vadose zone, as residence time t_R is a function of these two variables. The residence time t_R concept thus provides a physical explanations for the percolation rate concept in the empirical studies in Chapter 5.

6.6 Sensitivity to soil hydraulic parameters

In this section, the influence of soil hydraulic parameters on gross recharge percentage was investigated. This is done by investigating the sensitivity of $\bar{U}_Z$ to the soil hydraulic parameters, as $\bar{U}_Z$ has been found to have the most significant impact on the residence time t_R . The soil hydraulic parameters to be investigated include $\theta_s, \theta_r, \alpha, \beta$ and K_s .

Sensitivity tests were carried out covering the entire range of sand textures, i.e. 0.25 to 0.50 for θ_s ; 0.005 to 0.100 for θ_r ; 0.001 to 0.011 for α ; 2.247 to 4.300 for β ; and 5 to 75.0 for K_s . Simulations were carried out to generate $\bar{U}_Z$ by changing the values of the 'test' parameter while keeping the values of the other parameters to the calibrated values. The sensitivity tests were carried out for a recharge event with rainfall intensity of 55mm/day and vadose zone thickness of 2.5m. Among the soil hydraulic parameters tested, $\bar{U}_Z$ was found to be sensitive to θ_s and K_s , and fairly sensitive to β , but not sensitive to θ_r and α (Figure 6.6).

The regression equations in Table 6.3 relate the gross recharge percentage to rainfall intensity for a single rainfall event. These equations were developed based on the calibrated lower bound $K_s - \beta$ presented in Chapter 4: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.002244$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day. These conditions are referred to here as the "default" sand texture.

Figure 6.6 Sensitivity of vertical flow velocity to soil hydraulic parameters

The sensitivity plots in Figure 6.6 can be applied to estimate the change in flow velocity ($\Delta \bar{U}_z$) when a certain parameter value is significantly different from the calibrated value.

Suppose a rainfall intensity I produces a vertical flow velocity $\bar{U}_z$ in the “default” sand texture. $\bar{U}_z$ is estimated using equations in Figure 6.4. For a “non-default” texture, the vertical flow velocity in the vadose zone could be significantly different from $\bar{U}_z$, if the parameter values of the soil texture are significantly different from the “default” parameter values. For every parameter, change in vertical flow velocity $\Delta \bar{U}_z$, contributed by the deviation from the “default” parameter value, can be estimated using Figure 6.6. The total change in flow velocity $\sum \Delta \bar{U}_z$, contributed by all “non-default” parameter values, is obtained by summing up all individual $\Delta \bar{U}_z$. The summation of $\bar{U}_z$ and $\sum \Delta \bar{U}_z$ is referred to here as the ‘adjusted flow’ $(\bar{U}_z)_{adj}$. Substituting $(\bar{U}_z)_{adj}$ into the $\bar{U}_z - I$ equations (in Figure 6.4), the equivalent rainfall intensity I_{eq} producing a flow velocity equals the $(\bar{U}_z)_{adj}$, is obtained for the “non-default” sand texture. Finally, the gross recharge percentage GR in

the “non-default” sand texture is estimated from the $GR-I$ equations (Table 6.3) using the I_{eq} as input variable.

This approach was tested for 13 different sand textures, whose soil parameter values were generated randomly based on the typical ranges for sand textures. The values of soil parameters for these 13 sand textures and their rainfall recharge conditions are shown in Table 6.5. Simulations were carried out to yield gross recharge percentages (referred as “ $GR_{simulated}$ ”) for these 13 sand textures.

Although this approach appears to improve the estimations significantly compared to the direct estimations without any adjustments (referred to as “without adjustment” in Figure 6.7), the approach was found to generally underestimate the GR , as shown in Figure 6.8. The simulated GR were found to be 1.0882 times larger than the GR estimated using the “with adjustment” approach. This is most likely due to the simulated $\sum \Delta \bar{U}_z$ not being the same as summing up each $\Delta \bar{U}_z$ arithmetically. In other words, each component $\Delta \bar{U}_z$ may not be related to the $\sum \Delta \bar{U}_z$ linearly. To consider this nonlinearity, the estimated GR is further adjusted by a factor of 1.0882 to yield the final GR estimate. This “further adjustment” was observed to produce unbiased GR estimates (with a slope of one) with a sufficient high value of R^2 .

Figure 6.7 Comparison between the simulated and the estimated values of gross recharge percentage (Without adjustment)

TABLE 6.5 13 Cases Used for Testing the Proposed Approach

Case	Sand texture				K_S (m/day)
	θ_s	θ_r	α	β	
1	0.420	0.035	0.0015	3.10	25.0
2	0.370	0.070	0.0045	3.85	18.0
3	0.320	0.080	0.0036	3.70	32.5
4	0.390	0.044	0.0038	4.00	32.5
5	0.368	0.050	0.0025	2.60	22.0
6	0.355	0.050	0.0030	2.90	15.0
7	0.360	0.045	0.0025	2.60	75.0
8	0.380	0.042	0.0025	3.10	15.0
9	0.400	0.055	0.0028	2.80	13.5
10	0.375	0.052	0.0022	2.25	20.5
11	0.500	0.052	0.0025	3.50	20.0
12	0.310	0.030	0.0058	4.30	55.0
13	0.350	0.055	0.0036	3.50	26.0

Figure 6.8 Comparison between the simulated and the estimated values of gross recharge percentage (With adjustment)

TABLE 6.6 Additional Cases Used for Verifying the Proposed Approach

Case	Sand texture				K_S (m/day)
	θ_s	θ_r	α	β	
14	0.375	0.045	0.0035	3.00	38.0
15	0.280	0.025	0.0035	4.50	16.0
16	0.330	0.048	0.0020	2.80	5.0
17	0.250	0.008	0.0060	2.40	75.0
18	0.280	0.005	0.0080	3.20	7.5

Figure 6.9 Comparison between the simulated and the estimated values of gross recharge percentage (With further adjustment)

To further verify the reliability of the factor of 1.0822 in improving the accuracy of the proposed approach, five (5) additional simulations were carried out for different sand textures using VS2DI. These five additional cases are summarized Table 6.6, namely cases 14 to 18. Figure 6.9 shows that the refined approach is capable of producing unbiased GR estimates, where the GR estimates from the proposed approach have an accuracy of about $\pm 5\%$ and a high R^2 value of 0.9643, when compared with the GR estimates from the VS2DI simulations. Figure 6.10 summarizes the entire computational procedures for estimating gross recharge percentage for “non-default” sand textures.

6.7 Summary

Deterministic modeling was carried out to elucidate the recharge processes within the vadose zone of the Changi reclaimed land.

The correlation analyses in 6.4.1 show that rainfall intensity has the most significant impact on the gross recharge percentage for a wide range of vadose zone thickness. The effects of potential evaporation rate, relative humidity and air temperature on gross recharge percentage were observed to

become noticeable only when the vadose zone thickness is larger than 2.5m. The rainfall intensity-recharge percentage relationships were found to be well defined by a normal-log relationship. Applying the rainfall intensity –recharge percentage relationships, recharge threshold values were estimated for unconfined sandy aquifers under the equatorial climate. The recharge threshold values were found to depend strongly on the thickness of vadose zone.

The concept of residence time of rainwater within the vadose zone was found to be capable of providing physical explanations for the observed characteristics from correlation studies, the rainfall intensity-recharge percentage relationships and the recharge threshold values for the unconfined sandy aquifers. The residence time of the percolating rainwater within the vadose zone, t_R is a combined function of rainfall intensity and vadose zone thickness. The residence time determines directly the potential of the percolating rainwater within the vadose zone to be transported to the surface to meet the demands of soil evaporation (i.e. the SE ratio).

From sensitivity analyses, porosity and saturated hydraulic conductivity were found to have the most significant effects on the gross recharge percentage. Utilizing the concept of residence time t_R and the sensitivity results, an approach was developed to apply the derived rainfall-recharge relationships in Table 6.3 to estimate gross recharge rates of unconfined sandy aquifers. The approach was found to be capable of producing reliable estimates of gross recharge percentage for unconfined sandy aquifers under the equatorial climate.

However, the application of the proposed approach should be restricted to rainfall recharge from a single rainfall event. This is because the rainfall intensity-recharge percentage relationships in Table 6.3 were developed from datasets that were generated for a single rainfall event. As rainfall events in the equatorial area are generally continuous events, further efforts are thus needed to extend the applicability of the rainfall intensity-recharge percentage relationships developed here. The application of these equations in estimating rainfall recharge percentages for continuous rainfall events is discussed in Chapter 7.

Figure 6.10 Computation procedures to estimate GR for “non-default” sand textures

CHAPTER 7

EMPIRICAL METHOD FOR ESTIMATING CONTINUOUS RAINFALL RECHARGE

7.1 Introduction

A reliable estimate of long term rainfall recharge is necessary for investigating the feasibility of utilizing the reclaimed lands as a water source. Compared to tracer techniques, numerical modeling, water balance models and water table-fluctuation method, rainfall recharge estimations using empirical relationships involve lower computational cost and time. Empirical relationships could thus offer a more efficient alternative for estimating long term groundwater recharge.

Rainfall-recharge relationships developed in Chapter 6 (Table 6.3) are only applicable to recharge from a single rainfall event. In order to estimate long term rainfall recharge, a method capable of providing reliable recharge estimates for continuous rainfall events is needed. Further efforts are hence needed to extend the applicability of the rainfall-recharge relationships in Chapter 6 for long term continuous recharge estimation.

This study aims to develop empirical methods for estimating long term rainfall recharge at the Changi reclaimed. Two empirical methods were developed, herein referred to as the GR-I method and the Extended GR-I method. The rainfall intensity-recharge percentage equations developed in Chapter 6 are herein referred to as the GR-I equations (Table 6.3). The empirical method developed using these GR-I equations is herein referred to as the GR-I method. Another set of regression equations were developed in this study, which relate the gross recharge percentage to both rainfall intensity and potential evaporation rate. These are herein referred to as the Extended GR-I equations. The empirical method developed using these Extended GR-I equations is herein referred to as the Extended GR-I method.

The GR-I and the Extended GR-I methods were then applied to estimate the monthly rainfall recharge at the Changi reclaimed land. The accuracy of these two methods was evaluated by comparing their estimates against those from the VS2DI simulations and water table-fluctuation method. The better performing empirical method was applied to estimate the long term rainfall recharge percentage at the Changi reclaimed land.

7.2 Method development

7.2.1 Regression equations

Two sets of regression equations were developed, referred to as the GR-I equations and the Extended GR-I equations. The GR-I equations estimate gross recharge percentage using daily rainfall intensity and vadose zone thickness as input variables. The Extended GR-I equations use daily potential evaporation as an additional input variable. The GR-I equations are the rainfall-recharge equations developed in Chapter 6, as shown in Table 6.3. The Extended GR-I equations are shown in Table 7.1.

These equations were developed based on the gross recharge percentages simulated using VS2DI, as discussed in Chapter 6. The Extended GR-I equations were developed to investigate the significance of including the daily potential evaporation in improving the accuracy of recharge estimations. The normal-log function of the daily potential evaporation (Table 7.1) was found to yield the best results after several attempts of trying different functions. The developed Extended GR-I equations constrain the coefficient b_3 to negative values, as gross recharge percentage is inversely proportional to potential evaporation.

Expectedly, the Extended GR-I equations were found to yield gross recharge values closer to the dataset generated from VS2DI, compared to the GR-I equations. This could be observed from the higher R^2 values of the Extended GR-I estimations (Table 7.1), compared to the GR-I estimations

(Table 6.3). However, this observation is valid only for individual isolated rainfall events, as the dataset of gross recharge percentage were generated for an individual rainfall event. The significance of including the daily potential evaporation in improving recharge estimations for rainfall clusters (i.e. continuous rainfall events) needs further investigations, and is discussed later in Section 7.3.

Table 7.1 Extended GR-I Equations for Estimating Gross Recharge Percentage

Estimation Equations	95% Confidence Interval	R ²
(1) For 1.0 < VZ ≤ 2.0m:		
$GR(\%) = 45.107 + 12.852\ln(I) - 7.259\ln(E_p)$	$b_1: 40.310 \text{ to } 49.904$ $b_2: 11.506 \text{ to } 14.199$ $b_3: -9.872 \text{ to } -4.645$	0.890
(2) For 2.0 < VZ ≤ 2.5m:		
$GR(\%) = 12.983 + 17.658\ln(I) - 5.294\ln(E_p)$	$b_1: 5.919 \text{ to } 20.047$ $b_2: 16.124 \text{ to } 19.192$ $b_3: -8.229 \text{ to } -2.358$	0.944
(3) For 2.5 < VZ ≤ 3.0m:		
$GR(\%) = 6.564 + 17.827\ln(I) - 6.764\ln(E_p)$	$b_1: -16.291 \text{ to } 29.419$ $b_2: 14.176 \text{ to } 21.477$ $b_3: -14.815 \text{ to } 1.286$	0.880
(4) For 3.0 < VZ ≤ 4.0m:		
$GR(\%) = -13.292 + 21.408\ln(I) - 6.306\ln(E_p)$	$b_1: -27.326 \text{ to } 2.743$ $b_2: 18.536 \text{ to } 24.280$ $b_3: -10.260 \text{ to } -2.352$	0.954

Notes

$GR(\%) = b_1 + b_2\ln(I) + b_3\ln(E_p)$; where b_1 , b_2 and b_3 are regressed coefficients; R^2 is coefficient of determination of the regression; E_p is average daily potential evaporation in mm/day; VZ is vadose zone thickness; GR is gross recharge; I is rainfall intensity; and (1), (2), (3), (4) are numbers representing the ranges of vadose zone.

7.2.2 Recharge estimation method

The developed GR-I and Extended GR-I equations could be applied directly to estimate gross recharge percentage for an isolated rainfall event. Nevertheless, rainfall recharge characteristics at unconfined sandy aquifers were found to be significantly different between isolated rainfall events and continuous rainfall clusters. Compared to isolated rainfall events, rainwater from a continuous

cluster of intense rainfall events was found to percolate more rapidly from the ground surface to the water table, resulting in a significantly higher groundwater recharge percentages. This was discussed in Chapter 5. In order to apply the developed equations to continuous rainfall events, procedures are developed to incorporate the effects of continuous rainfall events into the estimation.

Suppose a daily rainfall event, within a continuous cluster of rainfall events, has rainfall intensity I_i , where i is the index for the day when this particular rainfall event occurs. To incorporate the effect of continuous rainfall events into the estimation, a coefficient k_i is introduced to adjust the gross recharge percentage estimated from the regression equations:

$$GR_{i,cluster}(\%) = k_i GR(I_i) \quad (7.1)$$

where $GR_{i,cluster}$ is the adjusted gross recharge percentage considering the continuous rainfall cluster effect; and $GR(I_i)$ is the gross recharge percentage estimated using the regression equation for a single daily rainfall I_i . The values of k_i are as follows:

$$k_i = \begin{cases} 1.36; & \sum_{j=i-1}^{i-4} I_j \geq 25mm; \sum_{j=i+1}^{i+4} I_j \geq 25mm \\ 1.11; & 15 \leq \sum_{j=i-1}^{i-4} I_j < 25mm; 15 \leq \sum_{j=i+1}^{i+4} I_j < 25mm; \\ 1.00; & 15mm < \sum_{j=i-1}^{i-4} I_j; 15mm < \sum_{j=i+1}^{i+4} I_j; \end{cases} \quad (7.2)$$

where j is the index for day. From earlier simulation results, soil evaporation rate was observed to become almost negligible on the forth day after a rainfall event, signifying that the soil moisture profile within the vadose zone re-attains its initial condition 4 days from a rainfall event. In other words, only those rainfalls occurring within a period of 4 days before and after a rainfall event have impacts on its recharge. This explains the 4-days limit in Equation (7.2).

25mm was set as the upper bound for Equation (7.2), as gross recharge percentage was found to be relatively less sensitive to daily rainfall intensity once the daily rainfall depth is larger than 25mm/day (Section 6.4.2). The lower bound value of 15mm was obtained through a “trial and error” approach, as values lower and higher than 15mm were observed to overestimate and underestimate respectively the gross recharge percentage of the continuous rainfall events. The rationale for the values of coefficient k_i is discussed later in Section 7.3.1. The procedures for obtaining $GR_{icluster}(\%)$ could be understood more easily through illustrations in Figure 7.1.

Figure 7.1 Procedures for obtaining $GR_{icluster}(\%)$ for a daily rainfall event I_i

The gross recharge depth for the daily rainfall event $GR_{icluster}(\text{mm})$ could be obtained through:

$$GR_{icluster}(\text{mm}) = \frac{GR_{icluster}(\%)}{100} \times I_i \quad (7.3)$$

The total gross recharge depth $GR_{Total}(\text{mm})$ and the total gross recharge percentage $GR_{Total}(\%)$ of all rainfall events within a continuous period could then be estimated using Equations (7.4) and (7.5) respectively:

$$GR_{Total}(mm) = \sum_{j=i-n}^{i+m} GR_{jcluster}(mm) \tag{7.4}$$

$$GR_{Total}(\%) = \frac{GR_{Total}(mm)}{\sum_{j=i-n}^{i+m} I_j} \times 100\% \tag{7.5}$$

where n is the day at the beginning of the period; and m is the day at the end of the period as in Figure 7.1. The above procedures for obtaining the $GR_{Total}(\%)$ could be executed using a Microsoft’s Excel® spreadsheet.

An example on formulating a Microsoft’s Excel® spreadsheet to obtain $GR_{Total}(\%)$ using the GR-I method is illustrated in Figure 7.2.

Figure 7.2 An example on formulating a Microsoft’s Excel® spreadsheet to compute $GR_{Total}(\%)$ using the GR-I method: The “default” sand texture

The spreadsheet was formulated for soil hydraulic parameters: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day, which were used for generating the database of gross recharge percentage (herein

named as the “default” values). Rows 19 to 32 in the spreadsheet were hidden to reduce the size of the figure for illustration purpose. For the Extended GR-I method, additional columns were added in the spreadsheet to compute the average daily potential evaporation E_p , which is used as input to the equations. Other steps for formulating the Extended GR-I method are similar to those shown in Figure 7.2. The average daily potential evaporation for a particular rainfall event occurring on i -th day $(E_p)_i$ was approximated by:

$$(E_p)_i = 0.70PEV_{i+1} + 0.20PEV_{i+2} + 0.05PEV_{i+3} + 0.025PEV_{i+4} + 0.025PEV_{i+5} \quad (7.6)$$

where PEV_{i+m} are the measured daily pan evaporation (mm) on $i+m$ day. Instead of using a simple average, a weighted average was applied to estimate the $(E_p)_i$, as actual soil evaporation rate was commonly observed to fully meet the atmospheric demand on the first day after the rainfall event, but decline rapidly below this rate there after (Wallace and Holwill, 1997).

For a “non-default” sand texture, an example of spreadsheet formulation is shown in Figure 7.3. The values of soil hydraulic parameters used in the example are: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.861$; and $K_s = 32.5$ m/day.

Similarly, rows 19 to 32 in the spreadsheet were hidden to reduce the size of the figure for illustration purpose. The spreadsheet formulations are generally similar to those in Figure 7.2, except that the adjusted daily rainfall intensity $(I_{adj})_i$ was used as input to the GR-I equations, instead of I_i in Figure 7.2. To obtain $\bar{U}_z$, $\sum \Delta \bar{U}_z$, $(\bar{U}_z)_{adj}$ and $(I_{adj})_i$, the approach proposed in 6.6 was followed, where $\bar{U}_z$ is the average vertical flow velocity within the vadose zone (mm/day); $\sum \Delta \bar{U}_z$ is the total change (%) in $\bar{U}_z$ attributed to the different values of soil hydraulic parameters from the “default” values; $(\bar{U}_z)_{adj}$ is the adjusted $\bar{U}_z$ (mm/day); and $(I_{adj})_i$ is the adjusted daily rainfall intensity (mm/day).

	G	H	I	J	K	L	M	N	O	P	Q	R	S	T			
3	VZ(m)	Class	Rainfall(mm)	$\bar{U}z$ (mm/day)	$(\bar{U}z)_{adj}$	I_{adj}	GR(%)	CGR(1)	CGR(2)	GR(mm)							
4	1.881	1	0.0	0	0	0	0	0	0	0	Computation of $(Uz)_{adj}$: $(Uz)_{adj} = 1.36 \times Uz$; 1.36 was used, as Change in $\bar{U}z$ (attributed to the different values of soil hydraulic parameters from the "default" values) was estimated to be 36%.						
5	1.896	1	0.0	0	0	0	0	0	0	0							
6	1.916	1	0.0	0	0	0	0	0	0	0							
7	1.933	1	0.4	1.605	2.183	0.544	35.3	35.3	35.3	0.1							
8	1.949	1	14.8	59.401	80.786	20.128	74.9	74.9	74.9	11.1							
9	1.953	1	0.2	0.803	1.092	0.272	26.1	26.1	26.1	0.1							
10	1.971	1	0.0	0	0	0	0	0	0	0							
11	1.987	1	0.0	0	0	0	0	0	0	0							
12	1.994	1	1.4	5.61904	7.64189	1.904	63.6	63.6	63.6	0.9	Computation of $(I)_{adj}$: $(I)_{adj} = (\bar{U}z)/c$; where c is the coefficient of $\bar{U}z = c(I)$ equation.						
13	2.015	2	0.0	0	0	0	0	0	0	0							
14	2.031	2	28.8	108.360	147.370	39.168	70.2	70.2	70.2	20.2							
15	2.037	2	3.6	13.545	18.421	4.896	44.8	44.8	44.8	1.6							
16	2.026	2	0.0	0	0	0	0	0	0	0							
17	2.018	2	0.4	1.505	2.047	0.544	-8.749	0	0	0	Computation of GR(%) $GR_{cluster}(\%) = k_i GR(I_{adj})_i$						
18	2.023	2	1.4	5.268	7.164	1.904	21.8	21.8	21.8	0.3							
33	0.714	1	0.6	2.408	3.275	0.816	40.6	40.6	40.6	0.2							
34	0.603	1	0.0	0	0	0	0	0	0	0							
35			374.2														
36				Computation of $\bar{U}z$: (1) $\bar{U}z = 4.0136(I)$; (2) $\bar{U}z = 3.7625(I)$; (3) $\bar{U}z = 4.6946(I)$; (4) $\bar{U}z = 4.7878(I)$							355.1	Step 8: $GR_{Total} (mm)$ $= \text{sum}(P4:P34)$ Step 9: $GR_{Total} (\%)$ $= P35/I35$					
37																	94.9
38																	
39																	
40																	
41																	

Figure 7.3 An example on formulating a Microsoft's Excel® spreadsheet to compute $GR_{Total}(\%)$ using the GR-I method: A "non-default" sand texture

7.3 Application of the developed method

7.3.1 Estimations of monthly gross recharge percentage

Using RBF as a solution algorithm, the effective K_s and β parameters for the Changi reclaimed land were found to fall within the range of 13.5 to 32.5m/day and 2.247 to 2.861 respectively, as discussed in Chapter 4. To obtain the probable range of monthly gross recharge percentage for the study site, recharge estimations were carried out for the lower and upper bounds of $K_s - \beta$ using the developed methods.

Figure 7.4 Comparison of the GR-I method (ignoring continuous rainfalls effect) with the water-level fluctuation method and the VS2DI simulation

Figure 7.5 Comparison of the GR-I method (integrating continuous rainfalls effect) with the water-level fluctuation method and the VS2DI simulation

Figure 7.4 and Figure 7.5 show the estimated monthly gross recharge percentages for the water-level fluctuation method (named as “WLF”), the VS2DI simulation (named as “VS2DI”), and the GR-I method. Notations “(UP)” and “(L)” represent the monthly gross recharge percentages corresponding to S_{upper} and S_{lower} respectively. Notation “(LB)” represents

monthly gross recharge percentages for the sand texture with the lower bound of $K_s - \beta$ (i.e. the “default” values of soil hydraulic parameters): $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day. Likewise, notation “(UB)” represents monthly gross recharge percentages for the sand texture with the upper bound of $K_s - \beta$: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.861$; and $K_s = 32.5$ m/day.

When the effect of rainfall clusters is ignored (i.e. k_i was set equal to 1 for all rainfall events), the GR-I method (named as “GR-I (Isolated)” in Figure 7.4 appears to underestimate significantly the monthly gross recharge percentages for those months (i.e. October 2003, December 2003 and January 2004) with high monthly rainfall depths (refer Figure 7.6). For these months, recharge events was contributed mainly by intense continuous rainfall events. This further suggests that the effect of continuous rainfall event clusters needs to be incorporated in long term recharge estimations to yield reliable estimates.

Figure 7.6 Daily rainfall depths and daily mean vadose zone thickness

The monthly gross recharge percentage should be at least equal to the monthly net recharge percentage. Gross recharge percentage is the portion of rainwater reaching the water table after losses through soil evaporation within the vadose zone, but the rainwater from the vadose zone is still subjected to the potential of being lost through groundwater evaporation. On the other hand, net recharge percentage refers to rainwater finally recharging to the groundwater system after taking into consideration groundwater evaporation. In other words, gross recharge percentage would approximate to net recharge percentage for deep water table condition (more than 3m, as shown in Figure 7.7), as groundwater evaporation is general insignificant for deep water table at the Changi reclaimed site.

The 95% confidence interval of $GR_{(Isolated)}/R_n$ was found to fall between 1.11 and 1.36, where $GR_{(Isolated)}$ is the monthly gross recharge percentage estimated from the “GR-I (Isolated)” method; and R_n is the monthly net recharge percentage estimated from the water-level fluctuation method. The lower and upper bounds of 95%CI of the ratio were thus set as the k_i values (Equation 7.2) for incorporating the effects of moderate and intense continuous rainfall cluster events into the estimation. Incorporating the effect of continuous rainfall cluster events by applying Equation 7.2, the GR-I method (named as “GR-I (Cluster)” in Figure 7.5) was found to yield reliable estimates for those months with high monthly rainfall depths.

For the period from October 2003 to January 2004, the monthly gross recharge percentages were found to be close to the monthly net recharge percentages, as groundwater evaporation in these months were generally not significant. Water tables during this period (Figure 7.6) were generally more than 2.0m below the ground surface, and groundwater evaporation was found to decrease rapidly beyond this depth, as shown in Figure 7.7. Results in Figure 7.7 were obtained through VS2DI simulations of groundwater evaporation, using both the lower and upper bounds of soil hydraulic parameters as model parameters.

For February 2004, the monthly gross recharge percentages were observed to be much higher compared to the monthly net recharge percentages. This observation could be attributed to high groundwater evaporation loss in the early part of February 2004, where water table rose to a very shallow depth (less than 1.0m below ground surface, Figure 7.6), after heavy rainfall events in January 2004. The difference between gross and net recharge percentages becomes more pronounced, as rainfalls occurred only in the early few days in February 2004. For September 2003, the GR-I method seems to overestimate the monthly gross recharge percentages, as groundwater evaporation in the month was generally negligible due to the large depths to water table (more than 3.0m, Figure 7.6). This indicates that the GR-I method could have overestimated the monthly gross recharge percentage for months with a low monthly rainfall depth (<100mm/month).

Figure 7.7 Response of direct groundwater evaporation to depth to water table

Including the daily potential evaporation as an additional input variable in the Extended GR-I method (shown as “Extended GR-I(Cluster)” in Figure 7.8) was found to be not superior to the GR-I method. No significant

improvement in accuracy of estimations was observed, except for those locations (M2-07 and M2-08) with vadose zone thickness larger than 3.5m.

This suggests that including daily potential evaporation in the estimations does not lead to an improvement in estimating monthly gross recharge percentage. This could be because soil moisture availability is the major governing factor for actual soil evaporation in a highly porous sand medium, instead of atmospheric demand represented by the potential evaporation rate. Therefore, the monthly gross recharge percentage could generally be estimated reliably based solely on daily rainfall intensity, which was found to govern the soil moisture availability for soil evaporation in the highly porous sand medium, as discussed previously in Chapter 6.

Figure 7.8 Comparison of the Extended GR-I method with the water-level fluctuation method and the VS2DI simulation

7.3.2 Estimation of mean annual net recharge percentage

Although the GR-I method could have overestimated the monthly gross recharge percentage for months with a low monthly rainfall depth (<100mm/month), this does not restrict the applicability of the method in

estimating the annual recharge percentages at the Changi reclaimed land. A 20 to 30% overestimation (Figure 7.5) of monthly recharge percentage for drier months (<100mm/month) does not lead to a significant overestimation in the annual recharge percentage. This is because the total rainfall depths contributed by the drier months are just about 3 to 15% of the total annual rainfall depths, as shown in Table 7.2. As a result, the overall overestimation in the annual recharge percentage using GR-I method, was about 0.9 to 4.5%, which is not very significant.

As groundwater discharge was found to be insignificant at the Changi reclaimed land, except for those areas adjacent to the open sea and the unlined drain (as shown in 5.3.4), Equation (5.8) could be simplified to:

$$R_n = GR - ET^{gw} \quad (7.7)$$

As shown in Figure 7.7, groundwater evaporation was found to be not very significant when depths to water table are larger than 3.0m. The net groundwater recharge percentage could therefore be approximated using the (4) GR-I equation in Table 6.3. Using the GR-I method, the annual net recharge percentages at the Changi reclaimed land were estimated using the time series of daily rainfalls (1 Jan 1994 to 31 Dec 2003) from the Changi Meteorological Station. The estimated results are shown in Figures 7.9 and 7.10 for the lower and upper bounds of soil hydraulic parameters, respectively.

Compared to a daily time-scale (Table 6.3), significantly lower values of R^2 (Figure 7.11) were observed between the monthly rainfall depths and the monthly net recharge percentage, implying that the monthly net recharge percentage is not a simple linear function of the monthly rainfall depths, but is influenced strongly by the rainfall distribution patterns during month. This result is consistent with, and provides an additional proof to the observations discussed in Chapter 5.

Table 7.2 Annual Rainfall Depths from Changi Meteorological Station (1994 to 2003)

(Year: 1994 to 1998)					
Annual Rainfall Depth (mm)					
	(1994)	(1995)	(1996)	(1997)	(1998)
January	56.9	349.4	173.2	15.4	268.8
February	133.5	334.0	180.2	105.4	32.5
March	288.2	67.7	129.7	34.3	58.8
April	154	242.3	178.2	118.4	187.7
May	169.6	84.4	107.5	41.6	370.8
June	184.7	63.7	265.8	78.9	198.8
July	53.8	173.6	162.3	18.6	259.2
August	45.1	211.6	258.4	86.6	195.0
September	23.7	29.5	297.0	31.1	258.2
October	84.7	101.1	300.0	78.4	222.7
November	322.2	372.8	180.2	158.3	107.2
December	425.4	303.5	185.5	351.9	463.4
Total	1941.8	2333.6	2418.0	1118.9	2623.1
(Annual)					
Ratio	0.136	0.105	0.000	0.344	0.035

(Year: 1999 to 2003)					
Annual Rainfall Depth (mm)					
	(1999)	(2000)	(2001)	(2002)	(2003)
January	193.9	275.2	425.8	221.2	400.5
February	67.4	237.8	86.6	50.8	176.6
March	181.4	238.3	297.3	55.6	154.6
April	88.5	311.6	203.3	116.5	159.9
May	157.1	96.8	164.9	236.6	81.8
June	103.4	157.5	137.1	83.1	50.3
July	225.4	1116.1	111.3	233.7	170.4
August	204.0	113.5	158.3	54.2	193.6
September	125.9	81.1	162.0	124.2	205.3
October	205.0	120.9	252.2	10.8	333.6
November	241.5	385.7	175.3	307.2	151.6
December	340.5	236.0	609.0	255.0	272.9
Total	2134.0	2370.5	2783.1	1748.1	2391.1
(Annual)					
Ratio	0.073	0.075	0.031	0.146	0.055

Note:

Ratio = Total monthly rainfall depths (<100mm/month)/Total (Annual)

Figure 7.9 Estimation of annual net recharge percentage using the GR-I method: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.247$; and $K_s = 13.5\text{m/day}$

Figure 7.10 Estimation of annual net recharge percentage using the GR-I method: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.00224$ 1/mm; $\beta = 2.861$; and $K_s = 32.5\text{m/day}$

Figure 7.11 Correlation between monthly rainfall depths and monthly net recharge percentage

The annual net recharge percentages could generally be assumed as random events, as daily rainfall process, the major factor controlling the recharge percentage, were random events (Lee and Lee, 2000). The Central Limit Theorem (Montgomery and Runger, 2007, Chapter 7) is valid for independent or uncorrelated processes. Using Central Limit Theorem, the 95%confidence intervals of the mean annual net recharge percentage were inferred from the estimated annual net recharge percentages for both the lower and upper bounds of soil hydraulic parameter values (Chapter 4). These results are summarized in Table 7.3. An almost straight line (Figure 7.12) in the probability plot of the annual net recharge estimates justifies the normal distribution assumption of the Central Limit Theorem. The mean annual net recharge percentage at the Changi Reclaimed Land falls between 56.9 and 69.9%, which correspondents to a mean recharge depth of 1073.8 to 1745.8mm.

Table 7.3 95% Confidence Interval of Mean Annual Net Recharge Percentage and Net Recharge for the Changi Reclaimed Land

	Mean Annual Net Recharge Percentage (%)	Mean Annual Net Recharge (mm)
Lower bound of soil hydraulic parameters	56.9 to 62.5	1073.8 to 1563.4
Upper bound of soil hydraulic parameters	64.4 to 69.6	1209.2 to 1745.8

Figure 7.12 Probability plot of the estimated annual net recharge percentage

7.4 Limitations of the developed method

Although the GR-I method has been shown to be an efficient tool for estimating long term rainfall recharge, it has certain limitations that are attributed to the assumptions inherent in the development of the method. The limitations are:

1. The application of the developed method should be restricted to unconfined sandy aquifers with an equatorial climate, as the method has not been tested for other soil textures and climates;

2. The sand texture was assumed to be lithologically homogeneous in the vertical direction, and the developed method is thus not applicable to layered profiles comprising silty or clayey soils;
3. Soil evaporation was assumed to be the only form of gross recharge loss, and the developed method is thus applicable only for rainfall recharge processes through a bare soil surface. Hortonian overland flow (Chow et al., 1988, Section 5.1) was assumed to be negligible during the entire recharge processes. This assumption is generally valid for most sand textures, as their K_S values are a few orders larger than the rainfall intensity.

CHAPTER 8

CONCLUSIONS

8.1 Achievements of this research work

Existing literature and knowledge on rainfall recharge characteristics, recharge threshold values and rainfall-recharge relationships are not directly applicable to unconfined sandy aquifers of present reclaimed land, as discussed in 1.1. This research program has therefore been executed to accomplish the five (5) objectives as stated in 1.2. It is hoped that the potential groundwater yields from the reclaimed lands in Singapore could be estimated using the knowledge gained from this research work. To accomplish the objectives of this research work, the Changi reclaimed land has been selected as the study site.

The major findings of the present research are summarized below.

- (1) The rainfall recharge characteristics for unconfined sandy aquifers under the equatorial rainfall patterns have been successfully elucidated. The main findings are summarized as follows.
 - (i) Through empirical studies, the percolation rate of rainwater from ground surface to the water table was found to be a combined function of rainfall pattern and vadose zone thickness. For an intermediate vadose zone thickness ($>2.0\text{m}$), rainfall pattern appears to have a noticeable effect on the rainwater percolation rate within the vadose zone. Rainfalls contributed by a series of intense rainfall events appear to percolate more rapidly towards the water table compared to rainfall contributed by an isolated intense rainfall event. However, for shallow water table conditions (less than 2m), no significant difference was observed in the rainwater percolation rate for different rainfall patterns.

The percolation rate of rainwater within the vadose zone was further found to have a significant influence on the rainfall recharge percentage and the correlation between rainfall and water table-fluctuation at the Changi reclaimed land. A higher percolation rate was found to lead to a higher recharge percentage and higher correlation between rainfall and water table-fluctuation.

- (ii) Through deterministic modeling, rainfall intensity was found to have the most significant influence on the recharge percentage for a wide range of vadose zone thickness. The effects of potential evaporation rate, relative humidity and air temperature on recharge percentage were observed to become noticeable when the vadose zone thickness is larger than 2.5m. This implies that the impact of soil evaporation on gross recharge percentage becomes significant only when the vadose zone is larger than 2.5m.

The rainfall intensity–recharge percentage relationships at the unconfined sandy aquifer were found to be well defined by a normal-log relationship. The recharge percentage was observed to increase as rainfall intensity increases. The sensitivity of gross recharge percentage to rainfall intensity was generally higher for low intensity rainfalls (<25mm/day), but decreased as the rainfall intensity increased. Rainfall intensity-recharge percentage relationships for different ranges of vadose zone thicknesses were derived for the Changi reclaimed land.

The recharge threshold values were estimated for the Changi reclaimed. Vadose zone thickness was found to have a pronounced effect on the recharge threshold value at the Changi reclaimed land. For shallow vadose zone thickness (<2.0m), almost all rainfall intensities are capable of producing gross recharge at the Changi reclaimed land. The recharge threshold value increases as the vadose zone thickness increases. The probable range of rainfall recharge threshold values for

different ranges of vadose zone thicknesses has been obtained for the Changi reclaimed land (Table 6.4).

Physical explanations were provided for the observed recharge characteristics in the empirical studies and deterministic modeling. The concept of residence time of rainwater within the vadose zone was found to provide physical explanations for the observations in correlation studies, the rainfall-recharge relationships and the recharge threshold values for the unconfined sandy aquifers. The residence time of the percolating rainwater within the vadose zone, t_R is a combined function of rainfall intensity and vadose zone thickness (Equation 6.2). The residence time was found to directly determine the potential for the percolating rainwater within the vadose zone to be transported to the surface to meet the demands of soil evaporation (i.e. the SE ratio). The residence time of the percolating rainwater within the vadose zone indicates the percolation rate of rainfall recharge from the ground surface to the water table. This was observed to be a combined function of rainfall intensity and the vadose zone thickness in the empirical studies.

- (2) Empirical relationships are efficient for estimating long term rainfall recharge at unconfined aquifers.

Two empirical methods were successfully developed for estimating long term rainfall recharge percentage at the Changi reclaimed land. The reliability of the empirical methods (herein referred to as the GR-I and the Extended GR-I methods) were evaluated against estimates from the VS2DI unsaturated zone model simulations and the water table-fluctuation method. Both the GR-I and Extended GR-I methods were found to provide reliable estimate of monthly rainfall recharge percentages. Using daily potential evaporation rate as an additional input variable, the Extended GR-I method does not seem to perform better than the GR-I method, which uses daily rainfall intensity as the sole input variable. Therefore, the monthly gross

recharge percentage could generally be estimated reliably based solely on daily rainfall intensity, which was found to govern the soil moisture availability for soil evaporation in a highly porous sand medium, as discussed in Chapter 6.

Applying the GR-I method, annual rainfall recharge percentages were successfully estimated for the Changi reclaimed land based on ten years of daily rainfall data (1994 to 2003). The mean annual net recharge percentage at the Changi Reclaimed Land was found to fall between 56.9 and 69.9%, which corresponds to a mean net recharge depth of 1073.8 to 1745.8mm.

An approach was developed and tested for extending the application of the derived GR-I equations (Table 6.3) and GR-I method (Chapter 7) to sand textures other than the “default” sand texture of the Changi reclaimed land. The approach was found to be capable of providing unbiased and reliable estimates of gross recharge percentages, which agree closely with the VS2DI simulations.

- (3) Innovative approaches were successfully developed for calibrating the parameters in the water table-fluctuation method and the unsaturated zone model. The approaches developed include a procedure for obtaining a representative value of specific yield for the reclaimed land, and a solution algorithm for calibrating and verifying the unsaturated zone model. Simplified evaporation models and artificial neural networks were successfully tested for their applicability in estimating open water evaporation rates in the equatorial region.
 - (i) Compared to field pumping test and laboratory test methods, the new estimation method for specific yield involves much lower computational efforts and uses readily obtainable data from sieve analysis, which is a common component in site investigation reports. More importantly, the new estimation method was found to be capable of providing reliable estimate of specific yield by taking into

consideration the effect of capillary fringe and the variations in grains sizes inherent in natural soils. Using the new estimation method, the areal specific yield for the Changi reclaimed land was found to be 0.27 to 0.31. The estimated values agree well with field measurements. This new estimation method is very useful for obtaining representative values of specific yield for other reclaimed lands in Singapore.

- (ii) A Radial Basis Function (RBF) neural network was successfully developed for calibrating the VS2DI unsaturated zone model. The RBF neural network was capable of producing a realistic combination of $K_s - \beta$ values for the calibration event, when the input variables were carefully selected and an appropriate SPREAD value used. . The upper and the lower bounds of $K_s - \beta$ were found to be 0.376mm/sec (32.5m/day) - 2.861 and 0.156mm/sec (13.5m/day) - 2.247, respectively, implying that the effective K_s for the sandy soils of the Changi reclaimed land lie within the range of 0.156 to 0.376mm/sec (13.5 to 32.5m/day). This range was in a close agreement with values from laboratory and field measurements. This study demonstrates the potential of the RBF neural network as an alternative to manual and auto-calibration when the model calibration process requires user intervention.
- (iii) Among the simplified evaporation models, only radiation-based models were found to be applicable for estimating hourly evaporation rates for the Changi reclaimed land. Hourly estimates from all the four radiation-based models show close agreement with those from the Penman's model. With the same input variables, properly trained feed forward ANN models were found to perform better than radiation-based models in term of accuracy.

However, only two of the radiation-based models are acceptable for modeling the daily evaporation rates at the Changi reclaimed land, i.e. Model A_R and Model B_R. The accuracy of the daily radiation-based models is low compared to the hourly radiation-based models, as the significance of relative humidity in affecting evaporation rates increases on a daily time-scale. ANN model was found to be superior to both the radiation-based and the mass transfer models when relative humidity was included as an input variable.

Unlike in temperate regions, energy driven evaporation was found to be the predominant evaporation mechanism at the Changi reclaimed land. In the temperate regions, previous studies have shown that aerodynamic driven evaporation is the predominant evaporation mechanism. The difference in the predominant evaporation mechanism between the equatorial and the temperate region could explain the applicability of radiation-based models and mass transfer models in the equatorial and the temperate region respectively. This study has successfully demonstrated that radiation-based models and ANNs could be an effective alternative to the comprehensive Penman's model, when limited meteorological data are available.

8.2 Limitations of the present findings

Although the present research work has provided good insights for a better understanding of groundwater recharge characteristics for unconfined sandy aquifers, the results and findings presented in this thesis are applicable only to the specific study site, which is an unconfined aquifers with the following characteristics:

- (1) a fairly homogeneous sand textures with a bare soil surface.
- (2) a plane land surface, with negligible Hortonian overland flow.

- (3) soil evaporation is the only form of gross recharge loss.
- (4) a predominantly one-dimensional vertical flow situation through the vadose zone, with negligible horizontal flow components.

8.3 Recommendations for future work

In view of the limitations of the present research findings, further works are recommended in the following aspects.

- (1) The present research findings are restricted to unconfined sandy aquifers with a bare soil surface. The understanding gained from the present research work may not be applicable to unconfined sandy aquifers covered with vegetations. The influences of vegetation on the rainfall-recharge relationships, net recharge percentage and rainfall recharge threshold values require further studies. The understanding of the impact of vegetation on the rainfall recharge characteristics is useful to predict the rainfall recharge percentage at the reclaimed lands when they would be covered by natural grass bushes in the future.
- (2) The potential yield of the unconfined sandy aquifer at the Changi reclaimed land can be estimated using the tools developed in this study. Artificial recharge systems can also be designed for the Changi reclaimed land if natural rainfall recharge alone is found to be not adequate as a viable water source.
- (3) The empirical results from this research work are only applicable for unconfined sandy aquifers with a bare soil surface. The applicability of the empirical methods developed (Chapter 7) could not be applied directly to unconfined sandy aquifers covered with vegetations. Empirical

equations including vegetation parameters as input variables in addition to daily rainfall intensity should be developed. This would provide a useful tool for estimating long term recharge percentage at the reclaimed lands covered by natural grass bushes.

- (4) Further studies are recommended to test the applicability of the new estimation method in Chapter 2 in providing specific yield estimate for soil textures such as clayey or loamy soils.

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APPENDIX A

Daily rainfall & water table elevation data

Note:

- 1.The daily rainfall depths were obtained through integration of the measured 15-minute rainfalls within a day.
- 2. Location: M2-12, Changi Reclaimed Land Site
- 3. Application: Chapters 6 & 9

Date	Daily Rainfall Depth (mm)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	0	0	7.8	4.2	0	0
2	22.6	0	0.2	0.2	0	21
3	0	8.2	1.6	0	0	0.6
4	3.6	25.0	0.4	0.4	0.4	0
5	0.6	2.6	46.4	0	14.8	0
6	0	9.0	0.4	0	0.2	4.4
7	0	0	0	0	0	0.2
8	1.4	18.8	1.0	4.8	0	0
9	8.8	0.4	4.6	0	1.4	0
10	0	0	3.4	45.0	0	0
11	0.4	38.4	6.0	0	28.8	0
12	0.6	44.8	0	18.0	3.6	0
13	0	0.2	0.8	3.2	0	0
14	0	8.8	1.4	2.2	0.4	0
15	0	42.0	0.2	0.2	1.4	0
16	0.2	0.2	1.4	18.8	0	0
17	4.2	11.0	0	12.2	0	0
18	25.0	0	0	10.6	0	0
19	0	0	4.20	1.4	104.2	0
20	3.0	18.6	2.0	67.2	0	0
21	1.2	0.2	2.8	25.2	0	0
22	0	0	1.6	0.2	0	0
23	0	0	0	0	27.2	0
24	6.8	0	0	0	144	0
25	17.0	0.2	1.4	0	24.4	0
26	0	0.6	0	0	5.8	0
27	0	13.4	0	0	11.8	0
28	0	5.4	5.4	0.4	4.6	0
29	0	1.0	0.4	0.2	0.6	0
30	3.6	35.4	0	0	0.6	
31		5.8		0	0	
Total	99.0	290.0	93.4	214.4	374.2	26.2

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **C1 ID100-1**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.897m
4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	1.076	1.105	1.833	1.738	2.034	3.146
2	1.075	1.115	1.854	1.734	2.016	3.163
3	1.081	1.121	1.862	1.724	1.984	3.177
4	1.083	1.128	1.867	1.713	1.957	3.131
5	1.091	1.125	1.876	1.700	1.942	3.087
6	1.103	1.133	1.918	1.690	1.928	3.048
7	1.110	1.138	1.969	1.678	1.915	3.008
8	1.118	1.139	1.982	1.662	1.904	2.968
9	1.118	1.158	1.978	1.649	1.891	2.937
10	1.120	1.175	1.969	1.630	1.880	2.904
11	1.115	1.197	1.952	1.623	1.868	2.870
12	1.112	1.230	1.947	1.618	1.853	2.839
13	1.117	1.344	1.946	1.613	1.861	2.808
14	1.115	1.430	1.942	1.625	1.869	2.778
15	1.111	1.469	1.933	1.633	1.867	2.744
16	1.105	1.542	1.924	1.652	1.852	2.713
17	1.101	1.596	1.914	1.660	1.837	2.691
18	1.085	1.628	1.906	1.674	1.828	2.664
19	1.089	1.655	1.895	1.705	1.832	2.631
20	1.091	1.674	1.885	1.720	2.067	2.601
21	1.089	1.691	1.868	1.841	2.128	2.573
22	1.092	1.708	1.853	1.998	2.121	2.547
23	1.089	1.724	1.840	2.029	2.099	2.511
24	1.084	1.739	1.829	2.037	2.129	2.484
25	1.087	1.744	1.810	2.038	2.736	2.461
26	1.092	1.748	1.798	2.044	2.838	2.427
27	1.096	1.749	1.781	2.049	2.891	2.393
28	1.099	1.744	1.774	2.049	2.950	2.367
29	1.097	1.750	1.756	2.048	3.126	2.342
30	1.101	1.747	1.747	2.046	3.126	
31		1.783		2.042	3.165	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **C3 ID100-3**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.895m
4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	0.949	0.999	1.685	1.530	1.902	3.094
2	0.953	1.008	1.711	1.521	1.904	3.084
3	0.960	1.018	1.727	1.509	1.904	3.078
4	0.963	1.026	1.732	1.498	1.887	3.026
5	0.969	1.030	1.733	1.486	1.871	2.984
6	0.977	1.036	1.767	1.473	1.853	2.941
7	0.989	1.040	1.832	1.461	1.834	2.902
8	0.998	1.043	1.850	1.450	1.813	2.864
9	1.000	1.058	1.858	1.441	1.798	2.826
10	1.003	1.077	1.853	1.430	1.787	2.789
11	1.005	1.098	1.837	1.424	1.770	2.753
12	1.004	1.137	1.818	1.416	1.761	2.717
13	1.006	1.265	1.794	1.413	1.764	2.683
14	1.002	1.370	1.771	1.424	1.777	2.650
15	1.001	1.428	1.757	1.440	1.778	2.614
16	1.000	1.531	1.741	1.456	1.770	2.581
17	0.996	1.596	1.725	1.473	1.756	2.547
18	0.987	1.622	1.713	1.511	1.746	2.511
19	0.982	1.637	1.697	1.559	1.742	2.477
20	0.974	1.639	1.680	1.589	1.969	2.444
21	0.969	1.639	1.664	1.733	2.063	2.412
22	0.962	1.634	1.647	1.931	2.075	2.382
23	0.955	1.634	1.637	1.988	2.067	2.351
24	0.954	1.634	1.621	2.006	2.105	2.319
25	0.950	1.629	1.606	2.010	2.766	2.290
26	0.960	1.627	1.592	2.004	2.837	2.261
27	0.967	1.620	1.581	1.990	2.837	2.232
28	0.974	1.609	1.566	1.969	2.837	2.202
29	0.980	1.606	1.555	1.951	2.837	2.174
30	0.986	1.596	1.542	1.932	3.027	
31		1.632		1.916	3.138	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **C4 ID100-8**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.809m
4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	1.100	1.198	1.920	-	2.156	3.344
2	1.111	1.222	1.940	-	2.117	3.406
3	1.123	1.222	1.949	-	2.139	3.380
4	1.129	1.222	1.979	-	2.122	3.292
5	1.134	1.222	2.014	-	2.104	3.222
6	1.149	1.222	2.082	-	2.085	3.167
7	1.160	1.222	2.126	-	2.066	3.131
8	1.169	1.222	2.143	-	2.045	3.091
9	1.181	1.222	2.149	-	2.028	3.053
10	1.193	1.222	2.142	-	2.010	3.017
11	1.193	1.222	2.127	-	1.995	2.981
12	1.193	1.222	2.108	-	1.988	2.942
13	1.197	1.349	2.088	-	1.983	2.909
14	1.193	1.600	2.063	-	1.981	2.875
15	1.193	1.696	2.043	-	1.979	2.842
16	1.192	1.827	2.024	-	1.969	2.812
17	1.178	1.857	2.009	-	1.961	2.787
18	1.173	1.857	1.994	-	1.948	2.759
19	1.171	1.857	1.981	-	1.951	2.727
20	1.155	1.894	1.968	-	2.181	2.696
21	1.154	1.927	1.951	-	2.276	2.667
22	1.153	1.925	1.938	-	2.293	2.640
23	1.148	1.922	1.929	-	2.289	2.612
24	1.145	1.916	1.912	-	2.352	2.583
25	1.135	1.905	1.897	-	3.114	2.555
26	1.140	1.895	1.885	-	3.229	2.529
27	1.148	1.883	1.872	-	3.236	2.501
28	1.154	1.872	1.856	-	3.242	2.472
29	1.154	1.860	1.842	-	3.359	2.446
30	1.164	1.850	1.832	-	3.540	
31		1.885		-	3.439	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **M1-04**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 4.055m
4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	0.932	1.162	1.888	1.786	2.189	2.985
2	0.941	1.167	1.904	1.770	2.088	2.994
3	0.952	1.169	1.911	1.763	1.990	3.019
4	0.973	1.176	1.916	1.748	1.973	2.977
5	0.987	1.185	1.920	1.735	1.956	2.938
6	1.004	1.200	1.986	1.723	1.943	2.902
7	1.014	1.207	2.037	1.708	1.924	2.869
8	1.024	1.221	2.048	1.692	1.908	2.837
9	1.033	1.234	2.048	1.682	1.890	2.804
10	1.044	1.241	2.046	1.695	1.873	2.772
11	1.045	1.282	2.042	1.750	1.856	2.742
12	1.045	1.387	2.037	1.780	1.839	2.711
13	1.050	1.519	2.024	1.799	1.826	2.680
14	1.056	1.581	2.013	1.821	1.816	2.651
15	1.061	1.629	2.003	1.829	1.801	2.618
16	1.064	1.692	1.989	1.829	1.791	2.586
17	1.064	1.739	1.979	1.826	1.779	2.562
18	1.068	1.767	1.962	1.850	1.763	2.536
19	1.076	1.789	1.949	1.872	1.764	2.503
20	1.083	1.804	1.936	1.887	1.980	2.471
21	1.084	1.819	1.921	2.048	2.042	2.439
22	1.092	1.834	1.906	2.195	2.035	2.410
23	1.102	1.847	1.895	2.221	2.015	2.379
24	1.106	1.853	1.881	2.225	2.070	2.348
25	1.106	1.852	1.867	2.235	2.761	2.318
26	1.116	1.853	1.853	2.240	2.827	2.289
27	1.123	1.848	1.842	2.233	2.849	2.260
28	1.133	1.844	1.826	2.223	2.885	2.229
29	1.143	1.841	1.812	2.220	2.955	2.202
30	1.148	1.835	1.801	2.212	3.060	
31		1.859		2.201	3.010	

Note:

- 1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
- 2. Location: **M2-07**,Changi Reclaimed Land Site
- 3. Reduced ground level, MSL: 5.948m
- 4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	1.011	1.145	1.870	-	-	-
2	1.019	1.154	1.871	-	-	-
3	1.028	1.163	1.886	-	-	-
4	1.034	1.165	1.891	-	-	-
5	1.046	1.183	1.901	-	-	-
6	1.052	1.187	1.926	-	-	-
7	1.064	1.198	1.953	-	-	-
8	1.071	1.203	1.984	-	-	-
9	1.079	1.206	2.003	-	-	-
10	1.086	1.220	2.011	-	-	-
11	1.088	1.252	2.018	-	-	-
12	1.098	1.292	2.019	-	-	-
13	1.105	1.370	2.015	-	-	-
14	1.105	1.453	2.007	-	-	-
15	1.105	1.538	2.000	-	-	-
16	1.107	1.595	1.988	-	-	-
17	1.105	1.652	1.985	-	-	-
18	1.107	1.706	1.968	-	-	-
19	1.111	1.740	1.958	-	-	-
20	1.111	1.767	1.947	-	-	-
21	1.111	1.790	1.929	-	-	-
22	1.113	1.809	1.920	-	-	-
23	1.116	1.827	1.909	-	-	-
24	1.121	1.831	1.897	-	-	-
25	1.120	1.838	1.890	-	-	-
26	1.123	1.848	1.872	-	-	-
27	1.125	1.850	1.869	-	-	-
28	1.125	1.850	1.853	-	-	-
29	1.131	1.850	1.847	-	-	-
30	1.142	1.852	1.831	-	-	-
31		1.859		-	-	-

Note:

- 1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
- 2. Location: **M2-08**, Changi Reclaimed Land Site
- 3. Reduced ground level, MSL: 5.773m
- 4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	1.014	1.110	1.796	-	-	-
2	1.015	1.112	1.813	-	-	-
3	1.026	1.115	1.826	-	-	-
4	1.036	1.120	1.838	-	-	-
5	1.048	1.129	1.845	-	-	-
6	1.061	1.145	1.879	-	-	-
7	1.075	1.151	1.924	-	-	-
8	1.083	1.159	1.954	-	-	-
9	1.090	1.170	1.967	-	-	-
10	1.094	1.178	1.970	-	-	-
11	1.096	1.200	1.963	-	-	-
12	1.101	1.265	1.950	-	-	-
13	1.104	1.394	1.932	-	-	-
14	1.101	1.502	1.910	-	-	-
15	1.098	1.599	1.894	-	-	-
16	1.096	1.683	1.882	-	-	-
17	1.091	1.741	1.869	-	-	-
18	1.085	1.767	1.852	-	-	-
19	1.081	1.781	1.840	-	-	-
20	1.075	1.786	1.827	-	-	-
21	1.073	1.788	1.811	-	-	-
22	1.075	1.788	1.798	-	-	-
23	1.075	1.790	1.787	-	-	-
24	1.075	1.791	1.771	-	-	-
25	1.072	1.790	1.756	-	-	-
26	1.077	1.785	1.744	-	-	-
27	1.080	1.776	1.731	-	-	-
28	1.087	1.771	1.717	-	-	-
29	1.092	1.762	1.703	-	-	-
30	1.098	1.755	1.690	-	-	-
31		1.777		-	-	-

Note:

- 1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
- 2. Location: **M2-12**, Changi Reclaimed Land Site
- 3. Reduced ground level, MSL: 3.902m
- 4. Application: Chapters 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	-	-	-	1.715	2.126	3.325
2	-	-	-	1.702	2.110	3.444
3	-	-	-	1.690	2.094	3.333
4	-	-	-	1.682	2.078	3.254
5	-	-	-	1.667	2.060	3.196
6	-	-	-	1.656	2.048	3.146
7	-	-	-	1.643	2.028	3.110
8	-	-	-	1.630	2.007	3.068
9	-	-	-	1.615	1.996	3.029
10	-	-	-	1.609	1.978	2.993
11	-	-	-	1.614	1.961	2.959
12	-	-	-	1.637	1.954	2.925
13	-	-	-	1.658	1.969	2.893
14	-	-	-	1.683	1.976	2.862
15	-	-	-	1.706	1.969	2.829
16	-	-	-	1.713	1.952	2.797
17	-	-	-	1.720	1.942	2.762
18	-	-	-	1.765	1.927	2.742
19	-	-	-	1.804	2.014	2.709
20	-	-	-	1.830	2.280	2.677
21	-	-	-	2.032	2.300	2.647
22	-	-	-	2.223	2.283	2.618
23	-	-	-	2.259	2.264	2.588
24	-	-	-	2.260	2.729	2.557
25	-	-	-	2.250	3.043	2.528
26	-	-	-	2.233	3.043	2.500
27	-	-	-	2.208	3.043	2.471
28	-	-	-	2.186	3.043	2.440
29	-	-	-	2.167	3.043	2.413
30	-	-	-	2.152	3.553	
31	-	-	-	2.137	3.437	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **M2-13**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.904m
4. Application: Chapters 6 & 9

Date	Water table elevation, MSL (m)					
	Year 2003				Year 2004	
	Sept	Oct	Nov	Dec	Jan	Feb
1	1.011	1.051	1.794	1.674	2.023	3.249
2	1.014	1.060	1.815	1.661	2.008	3.278
3	1.019	1.063	1.828	1.651	1.988	3.267
4	1.022	1.066	1.836	1.642	1.971	3.198
5	1.035	1.074	1.837	1.631	1.955	3.144
6	1.049	1.077	1.899	1.622	1.951	3.096
7	1.060	1.081	1.953	1.604	1.933	3.059
8	1.064	1.092	1.960	1.590	1.917	3.020
9	1.064	1.107	1.958	1.583	1.910	2.987
10	1.067	1.127	1.947	1.568	1.889	2.952
11	1.063	1.147	1.932	1.570	1.873	2.917
12	1.062	1.199	1.917	1.571	1.867	2.886
13	1.061	1.342	1.902	1.582	1.878	2.855
14	1.058	1.431	1.879	1.607	1.886	2.823
15	1.057	1.480	1.872	1.626	1.881	2.791
16	1.049	1.566	1.862	1.631	1.870	2.760
17	1.041	1.615	1.856	1.637	1.857	2.731
18	1.038	1.637	1.843	1.669	1.852	2.703
19	1.034	1.646	1.833	1.712	1.851	2.671
20	1.027	1.655	1.821	1.728	2.140	2.637
21	1.022	1.666	1.804	1.892	2.200	2.607
22	1.023	1.677	1.788	2.074	2.181	2.579
23	1.023	1.691	1.777	2.100	2.157	2.547
24	1.023	1.707	1.764	2.094	2.229	2.516
25	1.019	1.707	1.752	2.084	2.962	2.487
26	1.025	1.710	1.741	2.077	2.994	2.459
27	1.027	1.707	1.728	2.070	2.990	2.428
28	1.030	1.704	1.716	2.058	2.994	2.401
29	1.036	1.702	1.697	2.049	2.994	2.373
30	1.041	1.698	1.683	2.039	3.190	
31		1.751		2.031	3.301	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **M2-19**,Changi Reclaimed Land Site
3. Reduced ground level, MSL: 8.778m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	0.601	0.726	1.260
2	0.625	0.736	1.263
3	0.637	0.736	1.263
4	0.635	0.739	1.257
5	0.630	0.744	1.250
6	0.634	0.749	1.260
7	0.638	0.749	1.273
8	0.638	0.749	1.285
9	0.638	0.755	1.285
10	0.638	0.757	1.295
11	0.639	0.768	1.304
12	0.651	0.782	1.316
13	0.657	0.816	1.335
14	0.657	0.844	1.343
15	0.657	0.866	1.348
16	0.657	0.908	1.361
17	0.657	0.943	1.363
18	0.657	0.979	1.361
19	0.657	1.014	1.351
20	0.657	1.044	1.337
21	0.649	1.078	1.317
22	0.646	1.097	1.304
23	0.647	1.120	1.305
24	0.656	1.143	1.304
25	0.657	1.165	1.304
26	0.663	1.185	1.306
27	0.676	1.197	1.310
28	0.687	1.216	1.322
29	0.696	1.233	1.323
30	0.711	1.245	1.323
31	0.601	1.251	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **M2-22**,Changi Reclaimed Land Site
3. Reduced ground level, MSL: 8.995m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	0.661	0.722	1.304
2	0.671	0.732	1.303
3	0.678	0.736	1.302
4	0.677	0.736	1.298
5	0.675	0.739	1.295
6	0.677	0.741	1.303
7	0.680	0.745	1.318
8	0.680	0.744	1.329
9	0.678	0.752	1.344
10	0.677	0.755	1.360
11	0.677	0.760	1.374
12	0.678	0.773	1.393
13	0.682	0.787	1.407
14	0.682	0.810	1.419
15	0.689	0.843	1.422
16	0.688	0.890	1.426
17	0.688	0.947	1.426
18	0.685	1.007	1.420
19	0.683	1.062	1.408
20	0.680	1.113	1.391
21	0.677	1.157	1.372
22	0.677	1.187	1.357
23	0.677	1.216	1.348
24	0.680	1.235	1.344
25	0.682	1.251	1.339
26	0.693	1.264	1.333
27	0.696	1.273	1.335
28	0.700	1.285	1.335
29	0.712	1.291	1.332
30	0.716	1.300	1.326
31		1.304	

Note:

- 1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
- 2. Location: **M3-01**,Changi Reclaimed Land Site
- 3. Reduced ground level, MSL: 4.385m
- 4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	0.398	0.474	0.683
2	0.411	0.464	0.648
3	0.373	0.448	0.622
4	0.339	0.418	0.603
5	0.334	0.412	0.609
6	0.328	0.397	0.636
7	0.325	0.381	0.643
8	0.333	0.398	0.676
9	0.327	0.423	0.694
10	0.327	0.448	0.700
11	0.374	0.469	0.703
12	0.397	0.480	0.703
13	0.403	0.504	0.698
14	0.406	0.553	0.681
15	0.397	0.626	0.677
16	0.379	0.652	0.687
17	0.360	0.648	0.657
18	0.338	0.621	0.622
19	0.312	0.603	0.587
20	0.282	0.581	0.567
21	0.258	0.559	0.572
22	0.253	0.551	0.591
23	0.265	0.585	0.631
24	0.303	0.633	0.669
25	0.351	0.680	0.675
26	0.376	0.686	0.699
27	0.412	0.707	0.739
28	0.446	0.734	0.767
29	0.465	0.736	0.764
30	0.475	0.730	0.723
31		0.718	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P015**,Changi Reclaimed Land Site
3. Reduced ground level, MSL: -
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	-	0.695
2	-	-	0.648
3	-	-	0.634
4	-	-	0.626
5	-	-	0.641
6	-	-	0.670
7	-	-	0.671
8	-	-	0.682
9	-	-	0.670
10	-	-	0.664
11	-	-	0.671
12	-	-	0.678
13	-	-	0.672
14	-	-	0.660
15	-	-	0.654
16	-	-	0.677
17	-	-	0.643
18	-	-	0.645
19	-	-	0.580
20	-	-	0.543
21	-	-	0.529
22	-	-	0.510
23	-	-	0.633
24	-	-	0.659
25	-	-	0.593
26	-	-	0.682
27	-	-	0.794
28	-	-	0.815
29	-	-	0.788
30	-	-	0.763
31	-	-	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P016**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.694m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	1.214	1.436
2	-	1.190	1.460
3	-	1.160	1.441
4	-	1.137	1.450
5	-	1.138	1.478
6	-	1.127	1.501
7	-	1.129	1.552
8	-	1.148	1.560
9	-	1.183	1.542
10	-	1.197	1.521
11	-	1.294	1.509
12	-	1.469	1.499
13	-	1.477	1.488
14	-	1.477	1.473
15	-	1.462	1.468
16	-	1.456	1.471
17	-	1.442	1.449
18	-	1.459	1.437
19	-	1.459	1.421
20	-	1.424	1.413
21	-	1.435	1.414
22	-	1.447	1.417
23	-	1.452	1.430
24	-	1.453	1.429
25	-	1.431	1.418
26	-	1.414	1.437
27	-	1.401	1.451
28	-	1.381	1.450
29	-	1.402	1.428
30	-	1.415	1.393
31	-	1.404	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P017**,Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.735m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	2.769	-
2	-	2.751	-
3	-	2.732	-
4	-	2.730	-
5	-	2.773	-
6	-	2.830	-
7	-	2.830	-
8	-	2.830	-
9	-	2.853	-
10	-	2.869	-
11	-	2.999	-
12	-	3.212	-
13	-	3.298	-
14	-	3.287	-
15	-	3.377	-
16	-	3.366	-
17	-	3.388	-
18	-	3.409	-
19	-	3.380	-
20	-	3.439	-
21	-	3.433	-
22	-	3.403	-
23	-	3.371	-
24	-	3.357	-
25	-	3.338	-
26	-	3.320	-
27	-	3.340	-
28	-	3.452	-
29	-	3.424	-
30	-	3.467	-
31	-	3.556	-

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P018**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.634m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	1.751	2.226
2	-	1.747	2.223
3	-	1.741	2.216
4	-	1.736	2.200
5	-	1.761	2.202
6	-	1.786	2.319
7	-	1.799	2.325
8	-	1.807	2.302
9	-	1.815	2.275
10	-	1.826	2.255
11	-	1.886	2.233
12	-	2.025	2.218
13	-	2.134	2.202
14	-	2.132	2.194
15	-	2.161	2.181
16	-	2.196	2.168
17	-	2.182	2.157
18	-	2.178	2.142
19	-	2.175	2.134
20	-	2.174	2.122
21	-	2.190	2.114
22	-	2.183	2.103
23	-	2.168	2.100
24	-	2.156	2.096
25	-	2.137	2.081
26	-	2.121	2.072
27	-	2.105	2.065
28	-	2.112	2.060
29	-	2.116	2.050
30	-	2.119	2.042
31	-	2.213	

Note:

- 1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
- 2. Location: **P019**,Changi Reclaimed Land Site
- 3. Reduced ground level, MSL: 5.381m
- 4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	2.717	3.475
2	-	2.731	3.496
3	-	2.717	3.496
4	-	2.707	3.483
5	-	2.692	3.461
6	-	2.682	3.457
7	-	2.673	3.465
8	-	2.665	3.479
9	-	2.654	3.476
10	-	2.653	3.461
11	-	2.658	3.436
12	-	2.693	3.413
13	-	2.817	3.390
14	-	2.951	3.366
15	-	3.054	3.353
16	-	3.233	3.335
17	-	3.290	3.317
18	-	3.307	3.300
19	-	3.313	3.285
20	-	3.300	3.272
21	-	3.302	3.261
22	-	3.312	3.245
23	-	3.351	3.226
24	-	3.348	3.211
25	-	3.335	3.198
26	-	3.316	3.182
27	-	3.290	3.169
28	-	3.280	3.159
29	-	3.273	3.143
30	-	3.263	3.133
31	-	3.376	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P020**,Changi Reclaimed Land Site
3. Reduced ground level, MSL: 6.191m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	3.228	4.025
2	-	3.244	4.049
3	-	3.231	4.066
4	-	3.228	4.074
5	-	3.211	4.074
6	-	3.211	4.074
7	-	3.199	4.091
8	-	3.191	4.104
9	-	3.191	4.113
10	-	3.183	4.113
11	-	3.190	4.113
12	-	3.276	4.109
13	-	3.414	4.090
14	-	3.504	4.070
15	-	3.587	4.049
16	-	3.718	4.024
17	-	3.791	4.003
18	-	3.830	3.983
19	-	3.856	3.970
20	-	3.870	3.954
21	-	3.883	3.938
22	-	3.897	3.931
23	-	3.917	3.917
24	-	3.925	3.901
25	-	3.935	3.893
26	-	3.934	3.878
27	-	3.925	3.864
28	-	3.916	3.853
29	-	3.905	3.838
30	-	3.900	3.823
31	-	3.973	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P021**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 6.295m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	2.817	3.666
2	-	2.810	3.684
3	-	2.810	3.697
4	-	2.799	3.712
5	-	2.790	3.712
6	-	2.790	3.753
7	-	2.787	3.814
8	-	2.782	3.841
9	-	2.788	3.861
10	-	2.799	3.869
11	-	2.843	3.862
12	-	3.009	3.844
13	-	3.219	3.822
14	-	3.304	3.793
15	-	3.360	3.770
16	-	3.442	3.748
17	-	3.496	3.729
18	-	3.527	3.712
19	-	3.552	3.693
20	-	3.575	3.682
21	-	3.585	3.670
22	-	3.607	3.650
23	-	3.623	3.634
24	-	3.634	3.616
25	-	3.634	3.600
26	-	3.629	3.589
27	-	3.611	3.575
28	-	3.594	3.556
29	-	3.588	3.535
30	-	3.581	3.520
31	-	3.627	

Note:

1. The daily water table elevations were computed by averaging the measured 15-minute interval groundwater-elevations of a day.
2. Location: **P022**, Changi Reclaimed Land Site
3. Reduced ground level, MSL: 3.907m
4. Application: Chapters 6

Date	Water table elevation, MSL (m)		
	Year 2003		
	Sept	Oct	Nov
1	-	0.975	1.546
2	-	0.983	1.547
3	-	0.985	1.546
4	-	0.991	1.545
5	-	0.998	1.539
6	-	1.000	1.534
7	-	1.004	1.551
8	-	1.008	1.576
9	-	1.020	1.595
10	-	1.024	1.596
11	-	1.040	1.580
12	-	1.087	1.561
13	-	1.216	1.538
14	-	1.344	1.519
15	-	1.410	1.501
16	-	1.445	1.482
17	-	1.474	1.466
18	-	1.501	1.446
19	-	1.513	1.432
20	-	1.515	1.419
21	-	1.513	1.399
22	-	1.509	1.380
23	-	1.512	1.363
24	-	1.513	1.348
25	-	1.502	1.335
26	-	1.485	1.325
27	-	1.467	1.320
28	-	1.476	1.313
29	-	1.505	1.305
30	-	1.534	1.296
31	-	1.545	

APPENDIX B

15-minute meteorological data

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 14 September 2004 (Calibration event)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_S (kW/m ²)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1815	0	27.47	81.9	0.019	1.957	0	10.32	9.95	8.12	9.52	10.19	10.63	10.77	9.4
1830	15	26.68	85.3	0.006	2.662	2.032	11.48	9.97	8.12	9.52	10.19	10.62	10.77	9.37
1845	30	25.39	88.0	0.001	3.767	5.334	16.34	9.98	8.12	9.51	10.19	10.62	10.78	9.35
1900	45	25.59	83.1	0	3.057	0	14.86	10.13	8.12	9.52	10.19	10.63	10.77	9.33
1915	60	25.23	81.0	0	2.225	0	13.61	11.34	8.12	9.56	10.19	10.63	10.77	9.31
1930	75	25.39	84.0	0	1.632	0	12.85	11.75	8.12	9.56	10.18	10.63	10.77	9.32
1945	90	25.49	83.5	0	0.657	0	12.32	11.66	8.13	9.56	10.18	10.63	10.77	9.31
2000	108	25.69	86.2	0	0	0	11.92	11.50	8.14	9.55	10.18	10.62	10.77	9.30
2015	123	25.79	85.4	0	0	0	11.60	11.36	8.16	9.54	10.18	10.62	10.77	9.29
2030	138	26.05	85.2	0	0.525	0	11.34	11.23	8.25	9.54	10.18	10.62	10.77	9.27
2045	153	26.31	84.6	0	2.84	0	11.13	11.11	8.54	9.53	10.18	10.62	10.76	9.25
2100	168	26.48	85.5	0	1.04	0	10.95	11.00	9.01	9.53	10.18	10.62	10.76	9.24
2115	183	26.51	85.2	0	1.537	0	10.79	10.9	9.67	9.53	10.18	10.61	10.77	9.22

T : Air temperature; RH : Relative humidity; R_S : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 19 September 2004 (Verification event 1)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1500	0	30.42	62.99	0.565	2.920	0	7.76	8.64	8.69	10.48	11.25	11.77	11.58	7.69
1515	15	29.82	66.39	0.156	3.560	0	7.76	8.64	8.68	10.48	11.25	11.77	11.58	7.69
1530	30	26.69	82.0	0.036	6.840	4.572	7.93	8.70	8.69	10.50	11.25	11.78	11.58	7.68
1545	45	24.68	88.5	0.031	8.970	2.286	10.34	8.72	8.70	10.50	11.25	11.77	11.58	7.66
1600	60	24.45	84.5	0.063	2.735	1.270	13.61	8.72	8.70	10.49	11.25	11.77	11.58	7.66
1615	75	25.19	86.5	0.106	1.525	0	13.82	8.72	8.69	10.50	11.25	11.77	11.58	7.65
1630	90	26.81	80.2	0.097	2.522	0	13.12	8.73	8.69	10.50	11.25	11.77	11.57	7.65
1645	108	27.57	74.6	0.174	0.347	0	12.66	8.74	8.69	10.50	11.24	11.77	11.57	7.65
1700	123	26.71	78.6	0.330	3.207	0	12.32	8.78	8.69	10.49	11.24	11.76	11.57	7.65
1715	138	27.01	76.0	0.154	2.697	0	12.03	8.90	8.69	10.49	11.24	11.76	11.57	7.65
1730	153	26.51	81.8	0.125	1.640	0	11.80	9.12	8.69	10.49	11.24	11.76	11.57	7.63

T : Air temperature; RH : Relative humidity; R_S : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 21 September 2004 (Verification event 2)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m ²)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1130	0	29.16	71.7	0.324	3.277	0	8.30	9.11	9.31	11.29	11.66	11.63	11.38	7.19
1145	15	29.39	71.7	0.427	2.352	0	8.28	9.11	9.31	11.29	11.67	11.63	11.38	7.19
1200	30	28.47	78.2	0.202	4.137	0.254	8.28	9.12	9.30	11.29	11.67	11.63	11.38	7.20
1215	45	26.13	81.6	0.091	2.635	3.556	9.30	9.17	9.30	11.29	11.68	11.63	11.38	7.18
1230	60	26.14	77.0	0.262	2.862	0.254	11.93	9.18	9.3	11.29	11.68	11.63	11.38	7.19
1245	75	27.66	75.3	0.360	2.612	0	12.56	9.18	9.29	11.28	11.69	11.63	11.38	7.19
1300	90	28.42	81.3	0.554	4.652	0	12.32	9.17	9.29	11.28	11.69	11.63	11.38	7.20
1315	108	27.70	78.1	0.251	6.825	0	12.05	9.18	9.28	11.28	11.69	11.63	11.38	7.21
1330	123	27.47	76.2	0.239	5.337	0	11.80	9.18	9.28	11.27	11.70	11.63	11.38	7.22

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: **22 October 2004** (Verification event 3)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m ²)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
2130	0	26.88	82.5	0	1.530	0	9.48	7.67	7.78	9.52	10.16	12.11	13.18	37.56
2145	15	26.68	85.5	0	1.787	0	9.47	7.67	7.78	9.52	10.16	12.11	13.16	37.57
2200	30	24.83	90.7	0	3.722	11.18	18.56	7.70	7.78	9.53	10.16	12.13	13.11	37.52
2215	45	24.01	92.1	0	4.892	0.254	16.00	7.94	7.78	9.53	10.16	12.11	13.09	37.60
2230	60	23.94	91.6	0	2.830	0.254	13.98	10.23	7.78	9.56	10.16	12.10	13.09	37.62
2245	75	24.67	92.6	0	2.832	0.508	13.16	11.92	7.78	9.58	10.16	12.09	13.08	37.62
2300	90	24.35	91.2	0	2.330	0.508	12.97	12.03	7.78	9.58	10.16	12.08	13.08	37.61
2315	108	24.06	91.2	0	2.185	0.254	12.90	11.99	7.78	9.57	10.15	12.08	13.07	37.61
2330	123	24.26	91.7	0	1.303	0.508	12.62	11.93	7.78	9.57	10.15	12.07	13.07	37.61
2345	138	24.36	91.6	0	1.688	0.254	12.35	11.85	7.79	9.56	10.15	12.07	13.07	37.61
2400	153	24.29	91.4	0	1.585	0	12.13	11.75	7.79	9.56	10.15	12.07	13.07	37.60

T : Air temperature; RH : Relative humidity; R_S : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: **25 October 2004** (Verification event 4)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m ²)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
815	0	25.82	89.2	0.023	0	0	9.89	9.73	10.03	12.31	12.79	13.62	12.65	36.36
830	15	25.66	89.6	0.004	1.697	0	9.94	9.72	10.02	12.3	12.8	13.62	12.64	36.34
845	30	23.74	87.8	0.004	5.907	6.858	11.81	9.75	10.02	12.3	12.8	13.62	12.63	36.16
900	45	23.48	90.2	0.012	1.042	1.016	15.62	9.75	10.00	12.29	12.8	13.62	12.63	36.20
915	60	23.99	88.0	0.021	1.433	0	14.64	9.91	10.00	12.29	12.8	13.62	12.64	36.22
930	75	23.96	89.1	0.03	0.902	0	13.85	10.50	9.99	12.28	12.8	13.62	12.65	36.23
945	90	24.19	89.1	0.046	0.92	0	13.27	11.05	9.98	12.27	12.8	13.62	12.65	36.25
1000	108	24.82	90.2	0.076	1.555	0	12.83	11.29	9.97	12.27	12.8	13.62	12.65	36.26
1015	123	25.25	89.3	0.128	1.377	0	12.49	11.37	9.96	12.26	12.8	13.62	12.65	36.26
1030	138	25.58	87.7	0.196	1.002	0	12.21	11.37	9.96	12.25	12.8	13.62	12.65	36.26
1045	153	25.96	85.1	0.367	2.012	0	11.97	11.34	9.98	12.24	12.8	13.62	12.65	36.27
1100	168	26.75	83.4	0.564	2.255	0	11.77	11.30	10.06	12.23	12.8	13.62	12.66	36.27

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: **26 October 2004** (Verification event 5)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
545	0	25.27	90.7	0	0.422	0	8.58	9.58	10.01	12.47	13.31	14.28	13.20	36.36
600	15	25.60	90.1	0	2.012	0	8.57	9.57	10.00	12.47	13.30	14.29	13.20	36.36
615	30	25.57	90.7	0	1.280	0.254	8.58	9.57	9.99	12.45	13.29	14.30	13.21	36.36
630	45	25.56	91.5	0	0	0.254	8.59	9.56	9.98	12.43	13.27	14.30	13.21	36.36
645	60	25.49	91.9	0.002	0.712	1.270	8.64	9.56	9.97	12.43	13.26	14.30	13.22	36.35
700	75	25.26	91.9	0.017	1.540	5.080	9.50	9.58	9.96	12.41	13.25	14.31	13.22	36.24
715	90	25.23	92.2	0.069	1.837	0.762	13.98	9.58	9.95	12.40	13.23	14.30	13.22	36.26
730	108	25.30	91.9	0.057	1.337	0	13.85	9.57	9.94	12.39	13.22	14.30	13.23	36.27
745	123	25.46	91.5	0.029	0	0	13.31	9.60	9.93	12.38	13.21	14.30	13.22	36.29
800	138	25.82	91.4	0.037	1.127	0	12.91	9.73	9.92	12.36	13.20	14.30	13.22	36.31
815	153	25.99	91.4	0.025	0.335	0	12.60	9.95	9.91	12.35	13.18	14.30	13.23	36.31
830	168	25.99	91.8	0.055	1.135	0	12.56	10.21	9.90	12.33	13.17	14.30	13.22	36.31
845	183	26.18	91.3	0.081	0	0	12.35	10.41	9.89	12.32	13.16	14.30	13.22	36.32

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 12 November 2004 (1) (Verification event 6)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m ²)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1145	0	29.99	69.0	0.146	3.672	0	6.43	8.00	8.14	9.95	10.59	13.13	17.39	37.41
1200	15	29.16	73.0	0.241	2.845	0	6.43	8.00	8.14	9.95	10.59	13.14	17.41	37.41
1215	30	27.45	85.0	0.194	6.250	0.508	6.43	8.02	8.14	9.95	10.59	13.14	17.4	37.42
1230	45	26.13	85.5	0.161	5.082	1.016	6.51	8.06	8.14	9.97	10.59	13.16	17.41	37.42
1245	60	25.78	80.3	0.097	6.050	1.016	6.58	8.07	8.14	9.97	10.59	13.16	17.39	37.40
1300	75	25.03	86.3	0.080	6.605	1.778	7.29	8.08	8.15	9.98	10.59	13.17	17.42	37.40
1315	90	25.85	81.8	0.118	2.530	0.508	9.04	8.09	8.14	9.98	10.59	13.17	17.46	37.39
1330	108	26.58	78.8	0.181	1.300	0	10.42	8.09	8.14	9.98	10.59	13.18	17.52	37.39
1345	123	27.57	75.5	0.136	0.540	0	11.08	8.09	8.14	9.98	10.59	13.19	17.50	37.40
1400	138	27.54	77.7	0.169	0.550	0	11.25	8.08	8.14	9.98	10.59	13.19	17.51	37.40
1415	153	28.03	75.2	0.193	0.697	0	11.27	8.08	8.14	9.98	10.58	13.20	17.51	37.39
1430	168	28.2	71.8	0.407	0.902	0	11.23	8.08	8.14	9.98	10.59	13.20	17.53	37.40

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 12 November 2004 (2) (Verification event 7)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1445	0	28.59	74	0.315	1.365	0	11.19	8.08	8.14	9.98	10.58	13.20	17.55	37.39
1500	15	27.77	80.2	0.049	3.705	0	11.12	8.08	8.14	9.98	10.58	13.21	17.55	37.39
1515	30	24.73	84.5	0.057	4.792	4.572	15.07	8.10	8.14	9.98	10.59	13.22	17.49	37.34
1530	45	25.79	82.2	0.062	3.745	1.270	15.57	8.11	8.14	9.99	10.58	13.22	17.53	37.39
1545	60	24.96	88.7	0.053	4.955	2.540	16.76	8.17	8.14	9.98	10.58	13.22	17.51	37.39
1600	75	23.58	90.0	0.030	6.467	2.794	17.79	12.81	8.14	10.04	10.58	13.20	17.45	37.35
1615	90	23.52	93.1	0.027	3.017	1.016	16.53	14.47	8.16	10.03	10.58	13.18	17.47	37.34
1630	108	23.83	93.1	0.054	1.122	0	13.77	13.51	8.80	10.03	10.58	13.18	17.55	37.35
1645	123	24.45	92.7	0.064	2.377	0	12.71	12.82	13.13	10.03	10.58	13.20	17.56	37.33
1700	138	24.72	87.3	0.078	3.050	0	12.09	12.30	13.39	10.04	10.58	13.21	17.56	37.31
1715	153	25.15	87.3	0.078	2.992	0	11.67	11.89	13.18	10.05	10.58	13.22	17.52	37.30
1730	168	25.31	88.6	0.074	2.292	0	11.36	11.58	12.94	10.06	10.58	13.23	17.52	37.29
1745	183	25.54	88.8	0.061	1.645	0	11.12	11.34	12.70	10.84	10.58	13.23	17.52	37.30

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 14 November 2004 (Verification event 8)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
1345	0	29.20	69.4	0.077	4.952	0	9.13	9.41	9.53	11.90	13.23	19.46	27.15	37.40
1400	15	26.92	76.9	0.055	6.900	0	9.08	9.42	9.52	11.88	13.22	19.55	27.2	37.41
1415	30	26.00	83.0	0.050	4.870	4.572	9.33	9.46	9.52	11.88	13.21	19.65	27.26	37.37
1430	45	25.21	87.6	0.079	3.032	2.540	13.79	9.48	9.52	11.87	13.20	19.80	27.35	37.32
1445	60	25.55	84.6	0.154	2.285	0	14.03	9.48	9.51	11.86	13.18	19.97	27.42	37.34
1500	75	26.28	81.5	0.292	2.090	0	13.46	9.50	9.50	11.84	13.17	20.13	27.50	37.35
1515	90	27.47	74.3	0.688	2.345	0	12.99	9.59	9.50	11.83	13.16	20.23	27.53	37.36
1530	108	27.21	79.5	0.137	2.775	0	12.63	9.77	9.49	11.82	13.15	20.29	27.56	37.37
1545	123	27.17	79.0	0.165	2.227	0	12.35	9.98	9.49	11.80	13.13	20.43	27.63	37.36
1600	138	27.73	72.1	0.222	1.610	0	12.11	10.18	9.48	11.79	13.12	20.55	27.68	37.36
1615	153	28.62	67.2	0.233	0.785	0	11.91	10.34	9.47	11.78	13.11	20.66	27.72	37.36
1630	168	28.69	70.4	0.278	1.560	0	11.74	10.45	9.47	11.77	13.10	20.73	27.75	37.37
1645	183	28.79	68.7	0.170	2.252	0	11.58	10.52	9.47	11.76	13.09	20.84	27.79	37.37

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: 1 January 2005 (Verification event 9)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
945	0	25.61	85.3	0.226	2.510	0	9.43	9.75	9.95	12.43	13.80	23.69	31.37	37.66
1000	15	25.93	84.3	0.187	2.780	0	9.42	9.75	9.94	12.42	13.78	23.71	31.38	37.66
1015	30	25.44	87.9	0.055	3.920	2.286	9.56	9.76	9.93	12.41	13.77	23.77	31.42	37.63
1030	45	25.33	89.2	0.210	3.610	0.508	9.88	9.75	9.92	12.40	13.75	23.82	31.46	37.63
1045	60	25.86	85.6	0.153	4.467	0	10.20	9.74	9.91	12.38	13.74	23.86	31.50	37.63
1100	75	25.76	86.8	0.038	3.635	0	10.38	9.74	9.91	12.37	13.72	23.90	31.52	37.64
1115	90	25.21	88.6	0.043	3.837	0.762	10.58	9.74	9.9	12.36	13.71	23.96	31.58	37.62
1130	108	25.37	90.1	0.106	3.940	0	11.37	9.74	9.89	12.35	13.70	24.03	31.63	37.61

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Date: **5 January 2005** (Verification event 10)
- 3. Application: Chapters 7

Time	Elapse Time (min)	Meteorological factor					Volumetric soil moisture content, θ (%)							
		T (°C)	RH (%)	R_s (kW/m2)	WS (m/s)	I (mm/15min)	θ_{10cm}	θ_{30cm}	θ_{60cm}	θ_{100cm}	θ_{130cm}	θ_{170cm}	θ_{180cm}	θ_{200cm}
545	0	24.19	91.6	0	3.130	0	13.57	9.21	9.29	15.18	34.98	34.27	35.91	37.03
600	15	24.19	91.5	0	3.387	0.508	13.38	9.34	9.29	15.17	34.98	34.27	35.91	37.03
615	30	24.10	91.4	0	3.677	0.762	13.62	9.56	9.28	15.15	34.98	34.27	35.91	37.03
630	45	23.93	91.3	0	3.807	0.508	13.98	9.83	9.28	15.14	34.99	34.28	35.91	37.03
645	60	23.80	91.4	0	3.877	0.508	14.55	10.17	9.27	15.11	34.99	34.27	35.92	37.03
700	75	23.75	91.6	0	4.832	1.016	14.72	10.59	9.27	15.10	34.99	34.28	35.92	37.02
715	90	23.51	91.3	0.001	5.775	1.524	15.36	11.11	9.27	15.08	34.99	34.29	35.92	37.01
730	108	23.54	91.9	0.007	4.175	2.032	17.24	11.75	9.27	15.05	34.99	34.29	35.92	36.99
745	123	23.54	91.6	0.030	3.202	0.254	15.24	12.97	9.26	15.04	34.98	34.28	35.92	37.01
800	138	23.77	91.0	0.097	3.935	0	14.40	12.90	9.27	15.02	34.98	34.28	35.92	37.02
815	153	24.03	90.3	0.129	3.410	0	13.52	12.68	9.33	15.00	34.98	34.28	35.92	37.03

T : Air temperature; RH : Relative humidity; R_s : Solar radiation flux; WS : Wind speed and I : Rainfall Intensity

APPENDIX C

Soil moisture and suction head data

- Note:
- 1. Location: M2-12, Changi Reclaimed Land Site
 - 2. Application: Chapters 7
 - 3. Depth: **10cm** below ground surface

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
4.53	1074.3	5.85	423.1	5.39	570.2	8.24	121.4	6.99	221.0	6.36	312.5	5.96	395.0	5.71	462.7
4.55	1055.5	5.78	442.6	5.38	573.3	8.19	124.1	6.98	222.4	6.34	314.8	5.95	398.0	5.69	467.7
4.56	1047.1	5.69	468.6	5.35	587.5	8.14	126.9	6.97	223.9	6.34	315.9	5.94	400.9	5.68	472.0
4.58	1036.3	5.62	489.6	5.32	597.6	8.09	129.8	6.96	224.7	6.33	317.0	5.93	402.9	5.67	474.7
4.59	1024.0	5.57	506.2	17.32	8.1	8.04	132.8	6.98	222.8	6.33	318.1	5.92	404.4	5.66	478.1
4.60	1015.9	5.53	519.3	13.84	18.3	7.96	137.7	6.99	221.7	6.32	319.8	5.91	406.6	5.65	479.9
4.61	1007.9	5.50	528.3	11.32	38.2	7.86	144.2	6.99	221.7	6.31	320.3	5.91	408.9	5.64	482.4
4.62	1001.5	5.49	533.2	11.24	39.2	7.74	152.5	6.98	222.8	6.33	317.0	5.90	410.4	5.64	484.3
6.68	260.6	5.47	538.9	11.15	40.3	7.62	161.4	6.95	226.3	6.35	313.2	5.90	410.4	5.63	486.2
6.56	278.7	5.46	544.0	10.07	58.5	7.50	171.1	6.90	231.7	6.38	308.2	5.90	410.4	5.62	488.7
6.54	282.1	5.45	547.3	9.54	71.2	7.40	179.6	6.83	240.8	6.40	305.1	5.92	405.9	5.62	489.6
6.48	292.1	5.44	550.2	9.23	80.3	7.31	187.8	6.76	250.1	6.38	309.3	5.94	399.4	5.62	489.6
6.45	296.6	5.43	554.3	9.01	87.7	7.24	194.5	6.68	261.0	6.33	317.6	5.97	393.6	5.62	488.7
6.42	302.3	5.42	559.5	8.85	93.6	7.19	199.5	6.61	271.5	6.30	323.7	5.98	390.7	5.64	484.3
6.38	307.7	5.41	561.8	8.72	98.8	7.15	203.6	6.54	282.1	6.24	333.6	5.96	394.3	5.66	478.1
6.36	312.0	5.41	563.7	8.62	103.0	7.11	207.8	6.49	290.4	6.18	347.4	5.91	408.1	6.08	367.8
6.28	326.1	5.40	566.0	8.53	107.0	7.09	210.0	6.45	296.1	6.12	359.3	5.90	410.4	15.14	13.2
6.15	352.4	5.40	566.7	8.46	110.3	7.06	213.2	6.42	300.8	6.06	371.1	5.87	417.8	12.73	24.9
6.05	374.9	5.40	567.9	8.39	113.7	7.05	214.3	6.41	304.0	6.03	379.7	5.82	432.4	11.62	34.7
5.97	392.9	5.40	567.9	8.34	116.2	7.03	216.6	6.38	307.7	6.00	386.0	5.77	445.9	11.17	40.1
5.92	405.1	5.39	569.0	8.28	119.3	7.01	218.8	6.37	309.8	5.98	391.4	5.73	455.1	14.01	17.5

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **10cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
11.07	41.4	5.84	426.2	5.70	465.1	5.58	503.2	8.78	96.3	8.41	112.7	8.15	126.4	7.62	161.4
10.51	50.0	5.81	434.0	5.69	469.2	5.57	505.2	8.75	97.5	8.48	109.3	8.11	128.6	7.57	165.4
9.89	62.4	5.78	441.2	5.68	472.0	5.56	507.8	8.72	98.8	8.53	107.0	8.07	131.0	7.54	167.8
9.53	71.5	5.76	446.8	5.67	475.3	5.56	508.8	8.71	99.2	8.56	105.7	8.01	134.6	7.51	170.2
5.78	442.0	5.75	450.8	5.66	477.1	5.56	510.8	8.71	99.2	8.49	108.9	7.93	139.6	7.49	171.9
5.77	445.9	5.74	454.2	5.65	479.9	5.55	511.8	8.75	97.5	8.37	114.7	7.87	143.5	7.47	173.6
5.75	450.8	5.73	457.4	5.65	480.5	5.55	512.9	8.75	97.5	8.33	116.7	7.83	146.2	7.45	175.3
5.74	454.2	5.72	459.2	5.64	482.4	5.56	508.8	8.69	100.0	8.29	118.8	7.79	149.0	7.43	177.0
5.73	457.4	5.71	461.8	5.64	483.3	5.59	500.6	8.60	103.9	8.23	121.9	7.76	151.1	7.41	178.8
5.72	459.2	5.71	462.7	5.64	484.3	5.62	488.7	8.52	107.5	8.18	124.7	7.73	153.2	7.39	180.5
5.72	460.0	5.71	463.3	5.63	485.2	5.66	478.1	8.49	108.9	8.13	127.5	7.70	155.4	7.38	181.4
5.71	461.8	5.70	465.1	5.65	479.0	6.37	309.8	8.48	109.3	8.10	129.2	7.68	156.9	7.37	182.3
5.71	462.7	5.70	465.1	5.69	467.7	6.95	225.8	8.46	110.3	8.06	131.6	7.66	158.4	7.35	184.1
5.71	463.3	5.70	465.1	5.74	452.5	7.38	181.4	8.43	111.7	8.04	132.8	7.64	159.9	7.35	184.1
5.71	463.3	5.70	465.1	5.80	437.9	8.25	120.9	8.40	113.2	8.02	134.0	7.63	160.7	7.37	182.3
5.70	464.2	5.71	461.8	5.84	427.0	8.72	98.8	8.39	113.7	7.99	135.8	7.62	161.4	7.42	177.9
5.70	464.2	5.73	456.0	5.86	421.5	8.91	91.3	8.37	114.7	7.97	137.1	7.60	163.0	7.47	173.6
5.71	463.3	5.78	441.2	5.85	423.1	9.02	87.3	8.35	115.7	7.95	138.3	7.60	163.0	7.52	169.4
5.71	462.7	5.83	427.8	5.82	430.8	9.05	86.3	8.34	116.2	7.94	139.0	7.61	162.2	7.57	165.4
5.73	456.5	5.87	418.6	5.80	437.0	9.04	86.6	8.33	116.7	7.92	140.3	7.64	159.9	7.60	163.0
5.75	451.6	5.88	414.7	5.76	447.6	9.02	87.3	8.32	117.2	7.91	140.9	7.68	156.9	7.56	166.2
5.79	440.4	5.90	410.4	5.72	460.0	8.98	88.7	8.31	117.7	7.91	140.9	7.71	154.7	7.48	172.7
5.84	426.2	5.87	418.6	5.67	472.9	8.95	89.8	8.30	118.2	7.94	139.0	7.77	150.4	7.46	174.4
5.87	417.8	5.84	424.6	5.65	480.5	8.93	90.6	8.29	118.8	7.98	136.4	7.79	149.0	7.44	176.1
5.90	409.6	5.82	431.6	5.62	488.7	8.90	91.7	8.28	119.3	8.04	132.8	7.77	150.4	7.39	180.5
5.92	405.9	5.78	441.2	5.61	493.1	8.87	92.8	8.29	118.8	8.10	129.2	7.74	152.5	7.34	185.0
5.90	410.9	5.75	450.8	5.59	498.6	8.84	94.0	8.32	117.2	8.14	126.9	7.72	154.0	7.30	188.8
5.88	415.5	5.72	458.3	5.59	500.6	8.81	95.1	8.36	115.2	8.16	125.8	7.68	156.9	7.27	191.6

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **10cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
7.25	193.6	6.95	225.8	6.68	261.4	11.07	41.4	7.65	159.2	9.18	81.9	12.32	28.0
7.23	195.5	6.94	227.3	6.70	258.3	10.60	48.5	7.62	161.4	9.17	82.2	13.84	18.3
7.21	197.5	6.92	228.9	6.72	254.8	10.23	55.2	7.60	163.0	9.17	82.2	17.93	7.1
7.19	199.5	6.91	230.5	6.75	251.4	10.09	58.0	7.58	164.6	9.15	82.9	13.39	20.7
7.18	200.5	6.90	231.7	6.79	246.3	10.18	56.2	7.57	165.4	9.13	83.5	11.58	35.1
7.16	202.6	6.90	232.0	6.75	251.8	10.37	52.5	7.56	166.2	9.15	82.9	10.87	44.2
7.15	203.6	6.92	229.7	6.73	253.5	14.86	14.2	7.60	163.0	9.11	84.2	10.45	51.1
7.14	204.6	6.96	224.7	6.73	254.4	11.92	31.6	7.65	159.2	9.05	86.3	10.17	56.4
7.12	206.8	7.01	218.8	6.74	252.6	10.95	43.1	7.70	155.4	8.99	88.4	9.97	60.6
7.12	206.8	7.07	212.1	6.76	250.5	10.41	51.8	7.74	152.5	8.89	92.1	9.83	63.8
7.13	205.7	7.09	210.0	6.73	254.4	10.07	58.5	7.77	150.4	8.78	96.3	9.72	66.5
7.17	201.5	7.06	213.2	6.69	259.2	9.83	63.8	7.73	153.2	8.67	100.9	9.61	69.3
7.23	195.5	7.06	213.2	6.66	263.7	9.65	68.3	7.76	151.1	8.58	104.8	9.52	71.7
7.27	191.6	7.08	211.0	6.64	267.4	9.50	72.3	13.61	19.5	8.51	107.9	9.44	74.0
7.30	188.8	7.05	214.3	6.62	270.2	8.11	128.6	12.32	28.0	8.45	110.8	9.37	76.0
7.31	187.8	6.99	221.7	6.60	272.0	8.17	125.2	11.42	37.0	8.41	112.7	9.31	77.8
7.31	187.8	6.92	228.9	6.59	273.9	8.17	125.2	11.10	41.0	8.36	115.2	9.25	79.7
7.30	188.8	6.88	234.4	6.58	275.3	8.15	126.4	10.73	46.4	8.33	116.7	9.21	80.9
7.26	192.6	6.84	238.8	6.57	276.8	8.09	129.8	10.44	51.2	8.30	118.2	9.16	82.5
7.21	197.5	6.81	242.9	6.57	277.3	8.04	132.8	10.21	55.6	8.26	120.3	9.14	83.2
7.15	203.6	6.79	245.4	6.56	278.2	7.99	135.8	10.02	59.5	8.23	121.9	9.15	82.9
7.11	207.8	6.77	247.9	6.56	278.7	7.92	140.3	9.87	62.9	8.21	123.0	9.17	82.2
7.07	212.1	6.76	250.5	6.56	278.7	7.86	144.2	9.74	66.0	8.18	124.7	9.18	81.9
7.05	214.3	6.74	253.0	6.55	279.6	7.82	146.9	9.63	68.8	8.16	125.8	9.18	81.9
7.02	217.7	6.73	254.4	6.56	279.1	7.78	149.7	9.53	71.5	8.15	126.4	9.17	82.2
7.00	220.0	6.71	256.1	6.59	274.4	7.74	152.5	9.44	74.0	8.16	125.8	9.13	83.5
6.98	222.0	6.70	257.9	6.63	268.7	7.72	154.0	9.37	76.0	8.19	124.1	9.05	86.3
6.97	223.9	6.69	259.7	12.98	23.2	7.69	156.2	9.30	78.1	8.27	119.8		

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Application: Chapters 7
- 3. Depth: **30cm** below ground surface

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
7.41	141.7	7.41	141.7	7.44	139.7	9.58	56.2	9.15	66.3	8.92	72.7	8.77	77.3	8.64	81.5
7.41	141.7	7.41	141.7	7.43	140.4	9.54	57.1	9.13	66.8	8.91	73.0	8.76	77.6	8.64	81.5
7.41	141.7	7.41	141.7	7.43	140.4	9.50	57.9	9.12	67.1	8.89	73.6	8.76	77.6	8.64	81.5
7.41	141.7	7.42	141.0	7.43	140.4	9.46	58.8	9.10	67.6	8.88	73.9	8.75	77.9	8.64	81.5
7.41	141.7	7.42	141.0	7.44	139.7	9.42	59.7	9.08	68.2	8.88	73.9	8.74	78.2	8.63	81.9
7.41	141.7	7.43	140.4	12.88	19.4	9.39	60.4	9.06	68.7	8.87	74.2	8.74	78.2	8.63	81.9
7.41	141.7	7.43	140.4	12.63	20.8	9.37	60.9	9.04	69.3	8.85	74.8	8.73	78.5	8.63	81.9
7.41	141.7	7.44	139.7	11.80	26.5	9.34	61.6	9.03	69.6	8.84	75.1	8.72	78.9	8.62	82.2
7.42	141.0	7.44	139.7	11.25	31.5	9.32	62.1	9.01	70.1	8.83	75.4	8.71	79.2	8.61	82.6
7.42	141.0	7.44	139.7	10.91	35.2	9.31	62.3	9.00	70.4	8.82	75.7	8.71	79.2	8.60	82.9
7.41	141.7	7.44	139.7	10.69	37.9	9.29	62.8	8.99	70.7	8.81	76.0	8.70	79.5	8.60	82.9
7.42	141.0	7.45	139.0	10.52	40.1	9.28	63.0	8.98	71.0	8.80	76.3	8.69	79.9	8.59	83.3
7.42	141.0	7.44	139.7	10.36	42.4	9.27	63.3	8.97	71.2	8.79	76.6	8.68	80.2	8.59	83.3
7.41	141.7	7.44	139.7	10.22	44.5	9.26	63.5	8.97	71.2	8.79	76.6	8.67	80.5	8.58	83.6
7.41	141.7	7.45	139.0	10.10	46.5	9.25	63.8	8.96	71.5	8.78	76.9	8.67	80.5	8.57	84.0
7.41	141.7	7.44	139.7	9.99	48.3	9.24	64.0	8.96	71.5	8.78	76.9	8.66	80.9	8.56	84.3
7.41	141.7	7.44	139.7	9.90	49.9	9.23	64.3	8.95	71.8	8.77	77.3	8.66	80.9	8.56	84.3
7.41	141.7	7.44	139.7	9.82	51.4	9.21	64.8	8.95	71.8	8.78	76.9	8.65	81.2	8.55	84.7
7.41	141.7	7.44	139.7	9.75	52.8	9.20	65.0	8.94	72.1	8.77	77.3	8.65	81.2	8.55	84.7
7.41	141.7	7.44	139.7	9.69	54.0	9.18	65.5	8.94	72.1	8.77	77.3	8.65	81.2	8.54	85.0
7.41	141.7	7.44	139.7	9.64	55.0	9.17	65.8	8.93	72.4	8.77	77.3	8.64	81.5	8.54	85.0

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **30cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
8.56	84.3	8.32	93.4	8.25	96.3	8.18	99.3	8.06	104.7	7.98	108.5	8.02	106.6	8.15	100.6
10.52	40.1	8.32	93.4	8.24	96.7	8.17	99.7	8.06	104.7	7.98	108.5	8.02	106.6	8.16	100.2
11.40	30.1	8.32	93.4	8.24	96.7	8.17	99.7	8.05	105.2	7.98	108.5	8.03	106.1	8.17	99.7
11.31	30.9	8.31	93.8	8.23	97.1	8.17	99.7	8.05	105.2	7.98	108.5	8.04	105.6	8.17	99.7
8.42	89.5	8.32	93.4	8.23	97.1	8.16	100.2	8.04	105.6	7.98	108.5	8.05	105.2	8.18	99.3
8.42	89.5	8.31	93.8	8.23	97.1	8.16	100.2	8.04	105.6	7.98	108.5	8.06	104.7	8.18	99.3
8.42	89.5	8.31	93.8	8.23	97.1	8.15	100.6	8.03	106.1	7.99	108.0	8.07	104.2	8.19	98.8
8.41	89.9	8.31	93.8	8.22	97.6	8.15	100.6	8.03	106.1	7.99	108.0	8.08	103.8	8.19	98.8
8.41	89.9	8.30	94.2	8.22	97.6	8.14	101.1	8.03	106.1	7.99	108.0	8.08	103.8	8.19	98.8
8.41	89.9	8.30	94.2	8.21	98.0	8.14	101.1	8.03	106.1	8.00	107.6	8.09	103.3	8.19	98.8
8.40	90.2	8.29	94.6	8.21	98.0	8.14	101.1	8.03	106.1	8.00	107.6	8.09	103.3	8.19	98.8
8.40	90.2	8.29	94.6	8.20	98.4	8.14	101.1	8.03	106.1	8.00	107.6	8.10	102.9	8.19	98.8
8.39	90.6	8.28	95.0	8.20	98.4	8.13	101.5	8.03	106.1	8.01	107.1	8.10	102.9	8.19	98.8
8.38	91.0	8.28	95.0	8.19	98.8	8.13	101.5	8.02	106.6	8.01	107.1	8.10	102.9	8.19	98.8
8.38	91.0	8.27	95.4	8.19	98.8	8.13	101.5	8.02	106.6	8.01	107.1	8.11	102.4	8.19	98.8
8.37	91.4	8.27	95.4	8.18	99.3	8.12	101.9	8.02	106.6	8.01	107.1	8.11	102.4	8.19	98.8
8.37	91.4	8.26	95.9	8.18	99.3	8.12	101.9	8.02	106.6	8.01	107.1	8.11	102.4	8.19	98.8
8.36	91.8	8.26	95.9	8.18	99.3	8.11	102.4	8.02	106.6	8.01	107.1	8.11	102.4	8.19	98.8
8.36	91.8	8.26	95.9	8.18	99.3	8.11	102.4	8.02	106.6	8.00	107.6	8.11	102.4	8.19	98.8
8.35	92.2	8.25	96.3	8.18	99.3	8.10	102.9	8.01	107.1	8.01	107.1	8.11	102.4	8.19	98.8
8.34	92.6	8.25	96.3	8.18	99.3	8.10	102.9	8.01	107.1	8.01	107.1	8.11	102.4	8.20	98.4
8.34	92.6	8.24	96.7	8.18	99.3	8.10	102.9	8.01	107.1	8.00	107.6	8.12	101.9	8.20	98.4
8.33	93.0	8.24	96.7	8.18	99.3	8.09	103.3	8.00	107.6	8.00	107.6	8.12	101.9	8.21	98.0
8.33	93.0	8.24	96.7	8.18	99.3	8.09	103.3	8.00	107.6	8.01	107.1	8.12	101.9	8.21	98.0
8.32	93.4	8.24	96.7	8.18	99.3	8.08	103.8	7.99	108.0	8.01	107.1	8.12	101.9	8.22	97.6
8.32	93.4	8.24	96.7	8.18	99.3	8.08	103.8	7.99	108.0	8.01	107.1	8.13	101.5	8.22	97.6
8.32	93.4	8.24	96.7	8.18	99.3	8.07	104.2	7.99	108.0	8.01	107.1	8.14	101.1	8.23	97.1
8.32	93.4	8.24	96.7	8.18	99.3	8.06	104.7	7.99	108.0	8.01	107.1	8.15	100.6	8.23	97.1

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **30cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
8.24	96.7	8.24	96.7	8.21	98.0	8.13	101.5	8.78	76.9	9.71	53.6	9.38	60.7	9.56	56.6		
8.24	96.7	8.24	96.7	8.20	98.4	8.12	101.9	8.77	77.3	9.78	52.2	9.36	61.1	9.54	57.1		
8.24	96.7	8.23	97.1	8.20	98.4	8.12	101.9	8.77	77.3	9.81	51.6	9.34	61.6	9.52	57.5		
8.24	96.7	8.23	97.1	8.20	98.4	8.12	101.9	8.76	77.6	9.82	51.4	9.32	62.1	9.50	57.9		
8.24	96.7	8.23	97.1	8.19	98.8	8.12	101.9	8.75	77.9	9.81	51.6	9.30	62.6				
8.24	96.7	8.22	97.6	8.19	98.8	8.11	102.4	8.75	77.9	9.80	51.8	9.29	62.8				
8.24	96.7	8.22	97.6	8.18	99.3	8.12	101.9	8.74	78.2	9.79	52.0	9.27	63.3				
8.23	97.1	8.22	97.6	8.18	99.3	8.12	101.9	8.74	78.2	9.77	52.4	16.89	7.3				
8.23	97.1	8.21	98.0	8.18	99.3	8.12	101.9	8.73	78.5	9.74	53.0	13.51	16.3				
8.23	97.1	8.21	98.0	8.18	99.3	8.14	101.1	8.72	78.9	9.72	53.4	11.84	26.2				
8.23	97.1	8.21	98.0	8.18	99.3	9.01	70.1	8.71	79.2	9.70	53.8	11.22	31.8				
8.23	97.1	8.21	98.0	8.18	99.3	11.06	33.5	8.71	79.2	9.68	54.2	10.88	35.6				
8.22	97.6	8.21	98.0	8.18	99.3	11.17	32.3	8.70	79.5	9.66	54.6	10.64	38.5				
8.22	97.6	8.21	98.0	8.17	99.7	11.05	33.6	8.69	79.9	9.64	55.0	10.47	40.8				
8.22	97.6	8.21	98.0	8.18	99.3	10.90	35.3	8.69	79.9	9.63	55.2	10.33	42.9				
8.22	97.6	8.21	98.0	8.17	99.7	10.77	36.9	8.69	79.9	9.62	55.4	10.22	44.5				
8.22	97.6	8.22	97.6	8.17	99.7	8.79	76.6	8.70	79.5	9.61	55.6	10.13	46.0				
8.22	97.6	8.22	97.6	8.17	99.7	8.79	76.6	8.69	79.9	9.59	56.0	10.05	47.3				
8.22	97.6	8.22	97.6	8.17	99.7	8.78	76.9	8.69	79.9	9.58	56.2	9.98	48.5				
8.23	97.1	8.22	97.6	8.16	100.2	8.78	76.9	8.69	79.9	9.57	56.4	9.92	49.6				
8.23	97.1	8.22	97.6	8.16	100.2	8.78	76.9	8.69	79.9	9.55	56.9	9.86	50.7				
8.24	96.7	8.22	97.6	8.15	100.6	8.78	76.9	8.69	79.9	9.53	57.3	9.81	51.6				
8.24	96.7	8.22	97.6	8.15	100.6	8.78	76.9	8.70	79.5	9.51	57.7	9.77	52.4				
8.24	96.7	8.22	97.6	8.15	100.6	8.78	76.9	8.74	78.2	9.49	58.2	9.73	53.2				
8.24	96.7	8.22	97.6	8.14	101.1	8.78	76.9	8.88	73.9	9.47	58.6	9.69	54.0				
8.24	96.7	8.22	97.6	8.14	101.1	8.78	76.9	9.12	67.1	9.45	59.1	9.65	54.8				
8.24	96.7	8.21	98.0	8.13	101.5	8.78	76.9	9.38	60.7	9.42	59.7	9.62	55.4				
8.24	96.7	8.21	98.0	8.13	101.5	8.78	76.9	9.59	56.0	9.40	60.2	9.59	56.0				

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Application: Chapters 7
- 3. Depth: **100cm** below ground surface

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
9.87	93.3	9.78	96.5	9.71	99.1	9.66	101.1	9.61	103.1	9.56	105.1	9.54	105.9	9.52	106.8
9.86	93.6	9.78	96.5	9.71	99.1	9.66	101.1	9.61	103.1	9.56	105.1	9.54	105.9	9.52	106.8
9.86	93.6	9.77	96.9	9.70	99.5	9.65	101.5	9.60	103.5	9.56	105.1	9.54	105.9	9.52	106.8
9.86	93.6	9.77	96.9	9.70	99.5	9.65	101.5	9.60	103.5	9.56	105.1	9.54	105.9	9.52	106.8
9.85	94.0	9.77	96.9	9.70	99.5	9.65	101.5	9.60	103.5	9.56	105.1	9.54	105.9	9.52	106.8
9.85	94.0	9.77	96.9	9.70	99.5	9.65	101.5	9.60	103.5	9.56	105.1	9.54	105.9	9.52	106.8
9.84	94.3	9.77	96.9	9.69	99.9	9.64	101.9	9.60	103.5	9.56	105.1	9.53	106.3	9.52	106.8
9.84	94.3	9.76	97.3	9.69	99.9	9.64	101.9	9.59	103.9	9.56	105.1	9.53	106.3	9.52	106.8
9.83	94.7	9.76	97.3	9.69	99.9	9.64	101.9	9.59	103.9	9.56	105.1	9.53	106.3	9.52	106.8
9.83	94.7	9.75	97.6	9.69	99.9	9.64	101.9	9.58	104.3	9.55	105.5	9.53	106.3	9.52	106.8
9.82	95.1	9.75	97.6	9.69	99.9	9.64	101.9	9.58	104.3	9.55	105.5	9.53	106.3	9.52	106.8
9.82	95.1	9.74	98.0	9.69	99.9	9.63	102.3	9.58	104.3	9.55	105.5	9.53	106.3	9.52	106.8
9.82	95.1	9.74	98.0	9.69	99.9	9.63	102.3	9.58	104.3	9.55	105.5	9.53	106.3	9.51	107.2
9.81	95.4	9.74	98.0	9.68	100.3	9.63	102.3	9.58	104.3	9.54	105.9	9.52	106.8	9.51	107.2
9.81	95.4	9.74	98.0	9.68	100.3	9.62	102.7	9.58	104.3	9.55	105.5	9.52	106.8	9.51	107.2
9.81	95.4	9.74	98.0	9.68	100.3	9.62	102.7	9.58	104.3	9.54	105.9	9.52	106.8	9.51	107.2
9.80	95.8	9.73	98.4	9.67	100.7	9.62	102.7	9.58	104.3	9.54	105.9	9.52	106.8	9.51	107.2
9.80	95.8	9.73	98.4	9.67	100.7	9.62	102.7	9.58	104.3	9.54	105.9	9.52	106.8	9.51	107.2
9.79	96.1	9.73	98.4	9.67	100.7	9.61	103.1	9.57	104.7	9.54	105.9	9.52	106.8	9.51	107.2
9.79	96.1	9.72	98.8	9.66	101.1	9.61	103.1	9.57	104.7	9.54	105.9	9.52	106.8	9.51	107.2
9.79	96.1	9.72	98.8	9.66	101.1	9.61	103.1	9.57	104.7	9.54	105.9	9.52	106.8	9.51	107.2

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **100cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
9.51	107.2	9.52	106.8	10.54	72.9	10.66	69.9	11.39	54.5
9.51	107.2	9.52	106.8	10.53	73.2	10.74	68.0	17.25	11.5
9.50	107.6	9.55	105.5	10.53	73.2	10.80	66.6	15.43	17.5
9.51	107.2	9.53	106.3	10.52	73.4	10.88	64.8	14.45	22.4
9.50	107.6	9.53	106.3	10.51	73.7	10.95	63.2	13.85	26.2
9.50	107.6	9.56	105.1	10.51	73.7	11.01	61.9	13.42	29.5
9.50	107.6	9.97	89.8	10.50	74.0	11.07	60.7	13.11	32.2
9.50	107.6	10.92	63.9	10.49	74.2	11.11	59.9	12.87	34.5
9.50	107.6	11.69	49.5	10.48	74.5	11.15	59.1	12.67	36.6
9.50	107.6	10.68	69.4	10.49	74.2	11.19	58.3	12.52	38.3
9.50	107.6	10.67	69.7	10.49	74.2	11.22	57.7	12.52	38.3
9.50	107.6	10.66	69.9	10.49	74.2	11.25	57.1	12.42	39.4
9.49	108.0	10.65	70.1	10.49	74.2	11.27	56.8	12.32	40.7
9.49	108.0	10.64	70.4	10.48	74.5	11.29	56.4	12.24	41.7
9.49	108.0	10.63	70.6	10.47	74.8	11.31	56.0	12.15	42.8
9.49	108.0	10.63	70.6	10.47	74.8	11.32	55.8	12.08	43.8
9.49	108.0	10.62	70.9	10.46	75.0	11.32	55.8	12.01	44.7
9.49	108.0	10.62	70.9	10.45	75.3	11.33	55.6	11.95	45.6
9.48	108.5	10.61	71.1	10.44	75.6	11.33	55.6	11.89	46.4
9.49	108.0	10.60	71.4	10.44	75.6	11.33	55.6	11.83	47.3
9.49	108.0	10.59	71.6	10.44	75.6	11.33	55.6	11.78	48.1
9.50	107.6	10.59	71.6	10.43	75.9	11.32	55.8	11.74	48.7
9.50	107.6	10.58	71.9	10.44	75.6	11.32	55.8	11.70	49.3
9.51	107.2	10.57	72.2	10.45	75.3	11.31	56.0	11.66	50.0
9.52	106.8	10.57	72.2	10.47	74.8	11.29	56.4	11.61	50.8
9.52	106.8	10.55	72.7	10.50	74.0	11.29	56.4		
9.52	106.8	10.55	72.7	10.54	72.9	11.28	56.6		
9.52	106.8	10.54	72.9	10.60	71.4	11.26	56.9		

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Application: Chapters 7
- 3. Depth: **130cm** below ground surface

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
11.22	41.0	11.11	42.5	11.03	43.6	10.95	44.8	10.88	45.8	10.81	46.9	10.76	47.7	10.71	48.5
11.22	41.0	11.11	42.5	11.02	43.8	10.95	44.8	10.87	46.0	10.80	47.1	10.75	47.9	10.71	48.5
11.22	41.0	11.11	42.5	11.02	43.8	10.94	44.9	10.87	46.0	10.80	47.1	10.75	47.9	10.70	48.7
11.21	41.2	11.10	42.7	11.01	43.9	10.94	44.9	10.87	46.0	10.80	47.1	10.75	47.9	10.70	48.7
11.21	41.2	11.10	42.7	11.01	43.9	10.93	45.1	10.87	46.0	10.80	47.1	10.75	47.9	10.70	48.7
11.20	41.3	11.10	42.7	11.01	43.9	10.93	45.1	10.86	46.1	10.80	47.1	10.74	48.0	10.70	48.7
11.20	41.3	11.10	42.7	11.01	43.9	10.92	45.2	10.86	46.1	10.80	47.1	10.74	48.0	10.69	48.8
11.19	41.4	11.10	42.7	11.00	44.1	10.92	45.2	10.86	46.1	10.79	47.2	10.74	48.0	10.70	48.7
11.19	41.4	11.09	42.8	11.00	44.1	10.92	45.2	10.85	46.3	10.79	47.2	10.74	48.0	10.69	48.8
11.18	41.6	11.09	42.8	11.00	44.1	10.92	45.2	10.85	46.3	10.79	47.2	10.74	48.0	10.69	48.8
11.17	41.7	11.08	42.9	11.00	44.1	10.92	45.2	10.84	46.5	10.78	47.4	10.73	48.2	10.69	48.8
11.17	41.7	11.08	42.9	10.99	44.2	10.91	45.4	10.84	46.5	10.77	47.5	10.73	48.2	10.69	48.8
11.17	41.7	11.07	43.1	10.98	44.4	10.91	45.4	10.84	46.5	10.77	47.5	10.73	48.2	10.68	49.0
11.16	41.8	11.07	43.1	10.98	44.4	10.91	45.4	10.84	46.5	10.77	47.5	10.73	48.2	10.69	48.8
11.16	41.8	11.06	43.2	10.98	44.4	10.90	45.5	10.84	46.5	10.77	47.5	10.72	48.4	10.68	49.0
11.15	42.0	11.06	43.2	10.98	44.4	10.90	45.5	10.83	46.6	10.77	47.5	10.72	48.4	10.68	49.0
11.14	42.1	11.05	43.4	10.97	44.5	10.90	45.5	10.83	46.6	10.77	47.5	10.71	48.5	10.68	49.0
11.14	42.1	11.05	43.4	10.96	44.6	10.89	45.7	10.82	46.8	10.77	47.5	10.72	48.4	10.67	49.2
11.13	42.2	11.05	43.4	10.96	44.6	10.89	45.7	10.82	46.8	10.76	47.7	10.71	48.5	10.67	49.2
11.12	42.4	11.04	43.5	10.96	44.6	10.88	45.8	10.82	46.8	10.76	47.7	10.71	48.5	10.67	49.2
11.12	42.4	11.04	43.5	10.96	44.6	10.88	45.8	10.82	46.8	10.76	47.7	10.71	48.5	10.67	49.2

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **130cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
10.67	49.2	10.63	49.8	11.83	33.9	11.67	35.6	11.67	35.6
10.67	49.2	10.63	49.8	11.82	34.0	11.67	35.6	11.72	35.1
10.67	49.2	10.62	50.0	11.82	34.0	11.66	35.7	18.47	6.8
10.67	49.2	10.62	50.0	11.81	34.1	11.66	35.7	17.96	7.5
10.67	49.2	10.61	50.2	11.80	34.2	11.65	35.8	17.31	8.6
10.67	49.2	10.62	50.0	11.80	34.2	11.65	35.8	16.83	9.5
10.67	49.2	10.63	49.8	11.79	34.3	11.64	35.9	16.46	10.3
10.67	49.2	10.65	49.5	11.78	34.4	11.64	35.9	16.19	11.0
10.66	49.3	10.66	49.3	11.77	34.5	11.64	35.9	16.01	11.4
10.66	49.3	11.96	32.6	11.77	34.5	11.64	35.9	15.96	11.5
10.67	49.2	11.95	32.7	11.76	34.6	11.64	35.9	16.54	10.1
10.66	49.3	11.94	32.8	11.75	34.8	11.64	35.9	16.65	9.9
10.66	49.3	11.93	32.9	11.74	34.9	11.63	36.1	16.78	9.6
10.66	49.3	11.92	33.0	11.74	34.9	11.63	36.1	16.94	9.3
10.66	49.3	11.91	33.1	11.73	35.0	11.63	36.1	17.11	9.0
10.65	49.5	11.90	33.2	11.73	35.0	11.63	36.1	17.27	8.7
10.65	49.5	11.90	33.2	11.72	35.1	11.62	36.2	17.44	8.4
10.65	49.5	11.89	33.3	11.72	35.1	11.62	36.2	17.57	8.2
10.65	49.5	11.89	33.3	11.71	35.2	11.62	36.2	17.72	7.9
10.65	49.5	11.88	33.4	11.71	35.2	11.62	36.2	17.88	7.7
10.65	49.5	11.88	33.4	11.70	35.3	11.62	36.2	18.05	7.4
10.65	49.5	11.87	33.5	11.70	35.3	11.62	36.2	18.27	7.1
10.65	49.5	11.87	33.5	11.69	35.4	11.62	36.2	18.56	6.7
10.65	49.5	11.86	33.6	11.69	35.4	11.63	36.1	18.88	6.3
10.64	49.7	11.85	33.7	11.68	35.5	11.63	36.1	19.28	5.8
10.64	49.7	11.84	33.8	11.68	35.5	11.63	36.1		
10.64	49.7	11.84	33.8	11.68	35.5	11.63	36.1		
10.63	49.8	11.83	33.9	11.68	35.5	11.63	36.1		

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Note:

- 1. Location: M2-12, Changi Reclaimed Land Site
- 2. Application: Chapters 7
- 3. Depth: **200cm** below ground surface

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
17.80	18.0	17.28	20.3	16.88	22.3	16.35	25.3	15.48	31.5	13.51	54.1	11.91	89.4	10.98	123.6
17.82	18.0	17.27	20.3	16.82	22.6	16.33	25.4	15.44	31.8	13.34	56.9	11.73	95.0	10.92	126.4
17.80	18.0	17.30	20.2	16.75	23.0	16.31	25.6	15.45	31.7	13.35	56.7	11.56	100.7	10.86	129.2
17.80	18.0	17.32	20.1	16.72	23.1	16.19	26.3	15.43	31.9	13.41	55.7	11.47	103.9	10.77	133.5
17.79	18.1	17.35	20.0	16.72	23.1	16.10	26.9	15.38	32.3	13.37	56.4	11.44	105.0	10.64	140.1
17.75	18.2	17.35	20.0	16.75	23.0	15.97	27.8	15.28	33.1	13.32	57.3	11.43	105.3	10.57	143.9
17.72	18.4	17.34	20.0	16.76	22.9	15.93	28.1	15.12	34.6	13.23	58.8	11.45	104.6	10.49	148.3
17.65	18.7	17.34	20.0	16.80	22.7	15.94	28.0	14.90	36.6	13.14	60.4	11.46	104.3	10.45	150.6
17.62	18.8	17.31	20.2	16.80	22.7	15.98	27.7	14.65	39.2	12.91	64.9	11.44	105.0	10.43	151.7
17.60	18.9	17.26	20.4	16.81	22.7	16.03	27.4	14.52	40.6	12.64	70.6	11.41	106.1	10.44	151.1
17.59	18.9	17.21	20.6	16.78	22.8	16.05	27.2	14.51	40.7	12.44	75.2	11.34	108.7	10.45	150.6
17.59	18.9	17.08	21.3	16.75	23.0	16.05	27.2	14.56	40.2	12.22	80.7	11.26	111.8	10.45	150.6
17.60	18.9	17.03	21.5	16.68	23.4	16.05	27.2	14.63	39.4	12.16	82.3	11.13	117.1	10.44	151.1
17.60	18.9	17.02	21.6	16.65	23.5	16.02	27.4	14.71	38.6	12.16	82.3	11.03	121.4	10.40	153.5
17.58	19.0	17.03	21.5	16.58	23.9	15.95	27.9	14.72	38.5	12.21	81.0	10.97	124.1	10.34	157.1
17.56	19.0	17.03	21.5	16.47	24.6	15.91	28.2	14.63	39.4	12.34	77.6	10.94	125.4	10.28	160.7
17.52	19.2	17.03	21.5	16.42	24.9	15.78	29.1	14.41	41.9	12.38	76.6	10.97	124.1	10.19	166.5
17.47	19.4	17.03	21.5	16.43	24.8	15.64	30.2	14.28	43.4	12.34	77.6	10.96	124.5	10.11	171.8
17.40	19.7	17.01	21.6	16.42	24.9	15.51	31.2	14.13	45.3	12.23	80.5	11.01	122.3	10.05	175.9
17.34	20.0	17.00	21.7	16.41	24.9	15.45	31.7	13.94	47.8	12.12	83.4	11.02	121.9	10.03	177.3
17.29	20.3	16.94	22.0	16.39	25.1	15.46	31.6	13.78	50.0	12.04	85.6	11.02	121.9	10.08	173.8

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

Depth: **200cm** below ground surface (Continue)

θ	ψ	θ	ψ	θ	ψ	θ	ψ	θ	ψ
10.10	172.5	9.33	236.5	7.63	527.2	7.44	582.9	13.72	50.9
10.10	172.5	9.30	239.6	7.60	535.5	7.47	573.7	15.25	33.4
10.13	170.4	9.24	245.9	7.59	538.4	7.49	567.6	16.07	27.1
10.13	170.4	9.18	252.3	7.62	530.0	7.48	570.6	16.64	23.6
10.05	175.9	9.12	259.0	7.64	524.5	7.44	582.9	17.29	20.3
10.00	179.4	9.09	262.4	7.66	519.0	7.40	595.6	19.50	12.5
9.93	184.5	9.11	260.1	7.69	511.0	7.37	605.3	35.63	1.1
9.85	190.6	9.16	254.5	7.66	519.0	7.34	615.2	37.06	1.0
9.78	196.1	7.84	473.2	7.65	521.7	7.30	628.8	37.79	0.9
9.70	202.6	7.89	461.3	7.61	532.8	7.26	642.7	38.07	0.9
9.66	206.0	7.93	452.1	7.57	544.1	7.25	646.2	38.11	0.9
9.67	205.1	7.95	447.6	7.55	549.8	7.27	639.2	38.14	0.9
9.70	202.6	7.94	449.9	7.52	558.6	7.29	632.2	38.16	0.9
9.70	202.6	7.96	445.4	7.49	567.6	7.31	625.3	38.15	0.9
9.69	203.4	7.93	452.1	7.45	579.8	7.31	625.3	38.14	0.9
9.66	206.0	7.90	459.0	7.44	582.9	7.30	628.8	38.13	0.9
9.65	206.8	7.85	470.8	7.44	582.9	7.29	632.2	38.12	0.9
9.59	212.0	7.81	480.4	7.47	573.7	7.27	639.2	38.10	0.9
9.54	216.5	7.76	492.9	7.47	573.7	7.24	649.8	38.05	0.9
9.48	222.0	7.69	511.0	7.47	573.7	7.19	668.0	38.04	0.9
9.45	224.8	7.68	513.7	7.47	573.7	7.17	675.4	38.03	0.9
9.38	231.6	7.68	513.7	7.46	576.7	7.20	664.3		
9.40	229.6	7.69	511.0	7.44	582.9	7.20	664.3		
9.43	226.7	7.72	503.1	7.43	586.1	7.20	664.3		
9.47	222.9	7.72	503.1	7.35	611.9	7.23	653.4		
9.45	224.8	7.72	503.1	7.32	621.9	7.09	706.3		
9.46	223.9	7.71	505.7	7.32	621.9	7.58	541.2		
9.44	225.8	7.68	513.7	7.37	605.3	8.27	382.5		

θ : Volumetric moisture content (%); ψ : Soil suction head (kPa)

APPENDIX D

Database of gross recharge percentage

- Note:
- 1. Application: Chapters 8 & 9
 - 2. Degree of favorability: **Non-favorable**

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_p (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{r=0}^1 O_L$	D_L (mm)	$\bar{U}_z$ (mm/day)
1	4.7	1.7	5.1	30.4	74.0	2.6480	56.3	1.01	2.05	20.2
2	11.2	4.0	8.8	30.4	80.0	1.4194	12.7	0.00	9.80	61.0
3	9.0	1.7	6.0	30.8	83.9	5.8460	64.9	2.23	3.16	39.1
4	8.8	2.9	5.4	28.8	76.4	1.8680	21.2	0.00	6.96	51.0
5	5.8	2.0	9.0	29.6	77.1	2.0480	35.3	0.24	3.76	21.4
6	1.4	2.0	8.7	28.0	83.5	0.2124	15.2	0.02	1.16	51.0
7	1.7	3.6	7.1	30.6	74.9	0.0000	0.0	0.00	-	-
8	14.9	1.6	5.1	28.5	71.4	11.7980	79.2	6.01	3.10	67.1
9	14.0	2.5	6.0	29.3	76.0	5.5140	39.4	0.00	8.46	40.7
10	4.9	1.7	7.2	29.1	81.5	2.6320	53.7	1.06	2.26	21.1
11	0.2	1.5	8.9	29.0	74.9	0.0338	16.9	0.02	0.17	0.796
12	0.5	2.0	4.7	28.0	72.0	0.0280	5.6	0.00	0.47	-
13	1.3	1.6	5.1	28.1	81.9	0.5798	44.6	0.33	0.71	5.94
14	3.2	2.2	5.5	29.0	78.0	0.6248	19.5	0.00	2.58	10.7
15	7.2	1.6	6.3	29.9	82.4	4.8640	67.6	2.55	2.34	33.1

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_p (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{t=0}^1 O_L$	D_L (mm)	$\bar{U}_z$ (mm/day)
16	4.7	2.3	8.0	30.6	78.2	0.9618	20.5	0.00	3.74	15.2
17	1.8	1.8	5.0	29.5	72.0	0.6164	34.3	0.18	1.18	7.46
18	6.2	2.6	5.5	28.0	76.0	1.2200	19.4	0.00	5.00	38.2
19	0.6	2.1	7.1	28.6	80.3	0.0186	3.1	0.00	0.60	4.07
20	8.0	2.8	8.4	30.7	81.0	1.5628	19.5	0.00	2.55	48.3
21	2.8	2.5	6.8	28.9	80.0	0.2478	8.9	0.00	6.46	17.7
22	3.6	2.2	5.0	29.2	78.9	0.7970	22.1	0.01	2.80	12.0
23	11.0	2.2	7.5	29.5	73.0	4.5060	50.0	0.11	5.48	35.8
24	13.1	2.8	9.4	30.7	73.7	3.9020	29.8	0.00	9.18	71.7
25	10.9	2.1	7.5	28.8	77.2	4.8660	44.6	0.30	6.02	37.7
26	2.2	2.7	4.7	30.0	75.0	0.0921	41.9	0.00	1.28	14.9
27	9.6	3.2	5.6	29.9	79.3	1.8120	18.9	0.00	7.77	51.2
28	13.8	2.7	8.8	29.2	71.9	4.5740	33.1	0.00	9.23	74.9
29	7.1	2.6	7.4	28.0	71.6	1.5234	21.5	0.00	5.54	40.8
30	3.8	2.0	5.0	29.9	73.6	1.2670	33.3	0.12	2.53	14.0

Non-favorable (Continue)

I is rainfall intensity ; VZ is vadose zone thickness; E_p is daily potential evaporation rate; T is air temperature; RH is relative humidity ; and GR is gross recharge; $\sum_{t=0}^1 O_L$ (mm) is total rainwater flowing out from the solution domain at the end of rain day; and D_L is total rainfall lost through soil evaporation, generated for “default” sand texture: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.002244$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day.

Note:

- 1. Application: Chapters 8 & 9
- 2. Degree of favorability: Average

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_P (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{t=0}^1 O_L$	D_L (mm)	$\overline{U}_z$ (mm/day)
1	34.8	2.2	3.8	28.8	84.7	26.16	75.2	1.34	8.64	115.0
2	16.5	1.3	2.6	28.4	82.5	15.252	92.4	15.25	1.25	-
3	48.8	2.9	5.6	28.3	83.4	31.9	65.4	0.00	16.87	218.0
4	68.4	1.5	5.0	29.0	89.2	64.58	94.4	44.08	3.83	290.0
5	67.5	3.7	6.5	28.1	79.2	43.7	64.7	0.00	23.83	342.0
6	72.3	3.4	5.2	28.1	84.8	50.82	70.3	0.00	21.47	358.0
7	10.9	1.7	4.7	26.1	89.6	7.7	70.6	2.83	3.22	47.5
8	36.5	3.1	5.8	27.8	81.1	19.818	54.3	0.00	16.67	203.0
9	66.1	2.4	6.3	28.6	78.3	52.16	78.9	1.78	13.95	209.0
10	19.0	2.1	4.1	26.7	79.0	12.322	64.9	0.81	6.67	65.8
11	25.9	2.3	6.2	27.2	84.7	15.608	60.3	0.28	10.29	79.4
12	55.0	2.7	5.7	26.4	82.3	39.18	71.2	0.02	15.84	238.0
13	12.1	3.5	5.7	26.0	81.4	2.648	21.9	0.00	9.45	66.0
14	20.7	2.0	6.0	28.0	86.4	13.664	66.0	13.66	7.03	77.1
15	24.3	2.7	4.1	28.4	84.8	12.758	52.5	0.00	11.53	119.0

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_P (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{i=0}^1 O_L$	D_L (mm)	$\bar{U}_z$ (mm/day)
16	11.1	2.4	5.3	28.3	85.9	4.134	37.2	0.00	6.98	33.4
17	28.5	2.6	6.2	26.7	82.4	13.126	46.1	0.00	15.38	91.2
18	32.3	1.7	6.9	29.0	81.9	26.748	82.8	11.92	5.56	143.0
19	46.0	2.0	5.5	26.1	79.1	37.54	81.6	37.54	8.46	182.0
20	33.2	4.0	2.8	28.1	88.0	14.9	44.9	0.00	18.31	154.0
21	34.2	2.8	6.3	27.4	90.4	19.134	55.9	0.00	15.07	157.0
22	33.1	2.4	2.9	28.7	91.0	23.78	71.8	0.18	9.34	96.3
23	69.2	2.0	4.4	26.5	87.1	61.14	88.4	61.14	8.02	283.0
24	40.3	1.9	2.7	26.1	87.8	35.24	87.4	35.24	5.08	166.0
25	37.7	3.4	3.9	28.9	86.6	20.34	54.0	0.00	17.34	205.0
26	29.8	1.8	4.7	27.3	85.7	24.44	82.0	24.44	5.36	127.0
27	73.4	1.8	4.0	27.4	78.2	67.62	92.1	67.62	5.80	308.0
28	54.0	2.1	4.0	27.4	78.2	45.5	84.3	7.13	8.48	206.0
29	74.4	2.3	3.8	26.1	84.6	63.66	85.6	5.65	10.72	264.0
30	58.0	3.0	3.2	26.6	78.9	42.14	72.7	0.00	15.83	260.0

Average (Continue)

I is rainfall intensity ; VZ is vadose zone thickness; E_P is daily potential evaporation rate; T is air temperature; RH is relative humidity; and GR is gross recharge; $\sum_{i=0}^1 O_L$ (mm) is total rainwater flowing out from the solution domain at the end of rain day; and D_L is total rainfall lost through soil evaporation, generated for “default” sand texture: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.002244$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day.

- Note:
- 1. Application: Chapters 8 & 9
 - 2. Degree of favorability: **Favorable**

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_p (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{i=0}^1 O_L$	D_L (mm)	$\bar{U}_z$ (mm/day)
1	102.1	3.0	3.4	27.9	95.3	84.88	83.1	0.00	17.25	450.0
2	183.4	2.0	3.4	25.2	94.4	175.84	95.9	94.16	7.52	715.0
3	70.7	3.5	4.4	26.6	86.2	49.36	69.8	0.00	21.36	358.0
4	167.0	2.3	3.7	25.6	97.0	155.92	93.4	52.98	11.02	661.0
5	74.2	3.5	1.7	26.8	85.0	57.36	77.3	0.00	16.85	375.0
6	109.8	1.6	1.6	25.6	88.0	107.28	97.7	70.72	2.52	442.0
7	67.0	1.8	3.8	25.5	86.5	61.44	91.7	27.74	5.56	283.0
8	75.8	2.4	2.1	26.3	97.7	66.84	88.2	2.91	8.94	248.0
9	83.8	4.0	0.7	27.1	90.0	68.18	81.4	0.00	15.58	405.0
10	61.0	3.3	0.8	25.0	85.3	49.54	81.2	0.00	11.47	314.0
11	69.5	3.0	3.6	26.6	95.3	52.48	75.5	0.00	17.04	297.0
12	157.3	2.2	1.0	25.3	96.8	152.46	96.9	56.06	4.88	627.0
13	116.2	2.9	4.3	27.2	88.2	98.72	85.0	0.15	17.43	557.0
14	171.2	1.7	1.5	26.7	85.4	168.2	98.2	112.22	3.08	661.0
15	94.8	1.5	0.9	24.9	86.6	93.3	98.4	64.68	1.52	391.0

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_P (mm/day)	T (°C)	RH (%)	GR (mm)	GR (%)	$\sum_{i=0}^1 O_L$	D_L (mm)	$\bar{U}_z$ (mm/day)
16	188.9	2.8	3.3	26.9	97.5	173.28	91.7	1.69	15.67	888.0
17	126.7	3.6	3.5	26.6	86.2	104.78	82.7	0.00	21.92	592.0
18	171.4	2.6	2.6	26.2	90.6	159.12	92.8	26.04	12.34	815.0
19	189.2	2.0	2.5	26.4	84.8	182.86	96.6	98.96	6.43	735.0
20	135.6	3.1	3.1	25.1	93.0	117.9	86.9	0.02	17.76	605.0
21	110.4	1.7	2.4	27.3	95.2	106.54	96.5	63.88	3.86	458.0
22	208.3	2.5	0.6	24.7	86.8	203.2	97.5	60.04	5.21	814.0
23	66.5	2.2	2.6	25.6	94.4	58.6	88.1	7.13	7.92	247.0
24	182.1	3.4	2.1	26.0	90.2	164.2	90.2	0.00	17.85	863.0
25	107.1	2.4	3.9	24.6	91.3	94.9	88.6	11.06	12.21	398.0
26	103.0	1.9	2.6	25.6	94.4	97.52	94.7	44.72	5.46	422.0
27	140.0	3.2	3.8	25.2	86.4	120.6	86.1	0.00	19.46	666.0
28	72.0	3.6	0.6	25.4	94.8	59.78	83.0	0.00	12.24	353.0
29	84.0	2.0	1.5	24.6	87.3	79.44	94.6	25.64	4.54	346.0
30	203.6	3.0	0.8	24.7	93.7	193.98	95.3	7.72	9.57	949.0

Favorable (Continue)

I is rainfall intensity; VZ is vadose zone thickness; E_P is daily potential evaporation rate; T is air temperature; RH is relative humidity; and GR is gross recharge; $\sum_{i=0}^1 O_L$ (mm) is total rainwater flowing out from the solution domain at the end of rain day; and D_L is total rainfall lost through soil evaporation, generated for “default” sand texture: $\theta_s = 0.375$; $\theta_r = 0.052$; $\alpha = 0.002244$ 1/mm; $\beta = 2.247$; and $K_s = 13.5$ m/day.

Note:

- 1. Application: Chapters 8 & 9
- 2. Degree of favorability: **Unknown**

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	<i>I</i> (mm/day)	<i>VZ</i> (m)	<i>E_P</i> (mm/day)	<i>T</i> (°C)	<i>RH</i> (%)	<i>GR</i> (mm)	<i>GR</i> (%)	$\sum_{i=0}^1 O_L$	<i>D_L</i> (mm)	$\overline{U_z}$ (mm/day)
1	98.6	1.8	8.6	28.8	76.4	89.9	91.2	48.80	8.68	405.0
2	79.7	2.1	9.3	28.5	83.7	67	84.1	16.65	12.67	329.0
3	134.0	2.3	7.2	29.4	83.1	119.72	89.3	31.82	14.34	531.0
4	68.0	3.0	7.8	29.5	73.3	48.18	70.9	0.00	19.79	330.0
5	92.0	2.8	9.3	28.2	78.7	72.14	78.4	0.10	19.87	450.0
6	88.0	3.2	8.5	28.2	71.7	65.62	74.6	0.00	22.35	420.0
7	67.1	1.6	8.8	30.9	78.6	61.04	91.0	38.70	6.04	283.0
8	124.5	2.0	6.1	30.2	77.1	114.56	92	51.34	9.96	504.0
9	76.0	2.5	7.8	30.8	73.9	60.1	79.1	1.29	15.88	230.0
10	85.2	1.8	9.5	30.8	80.8	76.16	89.4	39.56	9.03	354.0
11	70.0	2.3	7.9	30.2	73.6	56.16	80.2	4.58	13.86	246.0
12	100.0	2.6	6.9	30.2	72.3	83.24	83.2	1.91	16.80	487.0
13	56.8	1.8	7.5	29.1	74.2	49.18	86.6	21.66	7.61	241.0
14	89.0	2.4	7.6	28.6	71.7	73.88	83	5.48	15.12	305.0
15	120.0	2.5	7.5	29.4	83.3	103.52	86.3	9.91	16.44	429.0
16	0.4	1.6	0.2	24.4	87.0	0.1769	44.2	0.05	0.20	1.72
17	4.2	1.7	1.4	27.5	91.8	2.884	68.7	0.88	1.31	18.0
18	2.3	1.9	0.5	27.4	92.4	1.3914	60.5	0.12	0.91	8.27

No.	Randomly Generated Meteorological Factor					VS2DI Simulation Results				
	I (mm/day)	VZ (m)	E_P (mm/day)	T (°C)	RH (%)	GR (mm)	$GR(\%)$	$\sum_{i=0}^1 O_L$	D_L (mm)	$\overline{U_z}$ (mm/day)
19	3.7	1.8	2.5	25.5	89.3	1.9926	53.9	0.49	1.71	15.5
20	0.5	1.6	0.3	27.8	91.2	0.234	46.8	0.08	0.26	2.19
21	11.4	2.2	1.6	24.7	94.5	7.204	63.2	0.21	4.18	37.1
22	5.3	2.0	0.8	24.7	90.7	3.51	66.2	0.12	1.78	19.6
23	6.2	2.1	1.9	26.6	88.0	3.17	51.1	0.08	3.03	19.2
24	2.0	2.3	0.8	27.2	90.7	0.5862	29.3	0.00	1.44	12.8
25	7.8	2.2	2.2	27.6	94.0	3.84	49.2	0.06	3.96	25.7
26	10.7	1.7	1.6	25.6	86.0	8.68	81.1	2.79	2.02	46.7
27	9.5	2.5	2.5	28.2	71.7	3.7	38.9	0.00	5.80	50.4
28	3.4	2.0	0.7	28.5	83.7	2.008	59.1	0.11	1.37	12.6
29	12.2	1.8	1.3	26.4	94.9	9.958	81.6	2.32	2.24	51.4
30	1.8	1.6	1.2	25.7	94.6	1.105	61.4	0.47	0.69	8.06
31	18.0	1.7	8.6	28.8	76.4	13.098	72.8	5.44	4.90	80.1
32	23.6	2.1	9.3	28.5	83.7	14.262	60.4	1.01	9.35	73.0
33	34.9	2.3	7.2	29.4	83.1	23.18	66.4	0.57	11.73	113.0
34	45.3	3.0	7.8	29.5	73.3	27.28	60.2	0.00	18.03	241.0
35	52.0	2.8	9.3	28.2	78.7	33.98	65.3	0.00	18.04	257.0
36	67.0	3.2	8.5	28.2	71.7	45.54	68	0.00	21.44	334.0
37	26.8	1.9	8.8	30.9	78.6	19.016	71	4.40	7.77	109.0
38	15.3	2.0	6.1	30.2	77.1	9.102	59.5	1.06	6.20	56.4
39	20.0	2.5	7.8	30.8	73.9	9.394	47	0.00	10.60	60.7
40	38.3	2.4	9.5	30.8	80.8	24.6	64.2	0.26	13.71	110.0

Unknown (Continue)

APPENDIX E

Porosity & sieve analysis results

Laboratory Measurement of Porosity

Description	Symbol	
Specific gravity of sand	G_s	2.66*
Density of water	ρ_w	1000 kg/m ³
Gravity acceleration	g	9.81m/s ²
Diameter of cylinder	ϕ	0.107m
Height of cylinder	L	0.517m
Weight of sand before oven dry	W_{S1}	8.96kg
Weight of sand after oven dry	W_{S2}	1.52kg
Volume of column	$V_s = (\pi\phi^2 / 4)L$	0.004649m ³
Weight of sand used	$W = W_{S1} - W_{S2}$	7.44kg
Unit weight of water	$\gamma_w = \rho_w g$	9810N/m ³
Density of sand	$\rho_s = G_s \rho_w$	2660kg/m ³
Unit weight of sand	$\gamma_d = (W \times g) / V_s$	15699.79N/m ³
Void ratio	$e = \frac{G_s \gamma_w}{\gamma_d} - 1$	0.6621
Porosity	$n = \frac{e}{1+e}$	0.3984

*Typical values of G_s for sand are from 2.65 to 2.67 (Bowles, 1986). The mean value of 2.66 is used in the calculations. Porosity corresponds to G_s 2.65 and 2.67 for the in-situ soil sample is 0.3961 and 0.4006 respectively.

Bowles, J.E. (1986), "Engineering Properties of Soils and Their Measurement", McGraw-Hill, New York.

Sieve Analysis AASHTO T27 & ASTM D 2487-93

Weight of sand before sieving = 1000.68g

Location: **C1 ID100-1**Sampling depth: **1.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.90	501.51	1.61	1.61	99.84
2.360	394.73	407.51	12.78	14.39	98.56
1.180	385.78	442.00	56.22	70.61	92.94
0.600	350.27	508.32	158.05	228.66	77.15
0.300	304.00	903.75	599.75	828.41	17.22
0.150	284.39	445.56	161.17	989.58	1.11
0.075	271.33	280.78	9.45	999.03	0.16
0.000	512.10	514.06	1.96	1000.99	-0.03

Weight of sand before sieving = 1022.52g

Location: **C1 ID100-1**Sampling depth: **3.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.86	535.81	35.95	35.95	96.48
2.360	394.71	464.65	69.94	105.89	89.64
1.180	386.00	500.07	114.07	219.96	78.49
0.600	350.45	504.30	153.85	373.81	63.44
0.300	304.09	589.11	285.02	658.83	35.57
0.150	284.33	584.37	300.04	958.87	6.22
0.075	271.34	307.76	36.42	995.29	2.66
0.000	512.12	539.76	27.64	1022.93	-0.04

Weight of sand before sieving = 1000.00g

Location: **C1 ID100-1**Sampling depth: **4.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.04	459.11	29.07	29.07	97.09
2.360	425.63	542.47	116.84	145.91	85.41
1.180	390.64	543.89	153.25	299.16	70.08
0.600	348.30	537.06	188.76	487.92	51.21
0.300	319.30	608.83	289.53	777.45	22.26
0.150	301.59	470.00	168.41	945.86	5.41
0.075	292.94	325.24	32.30	978.16	2.18
0.000	271.07	292.68	21.61	999.77	0.02

Weight of sand before sieving = 1000.37g

Location: **C1 ID100-1**

Sampling depth: **6.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.04	438.05	8.01	8.01	99.20
2.360	425.61	470.88	45.27	53.28	94.67
1.180	390.53	472.31	81.78	135.06	86.50
0.600	348.34	478.49	130.15	265.21	73.49
0.300	319.35	703.05	383.70	648.91	35.13
0.150	301.63	609.34	307.71	956.62	4.37
0.075	292.96	325.59	32.63	989.25	1.11
0.000	271.06	282.38	11.32	1000.57	-0.02

Weight of sand before sieving = 1076.00g

Location: **C1 ID100-1**

Sampling depth: **7.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.91	505.11	5.20	5.20	99.52
2.360	395.08	432.30	37.22	42.42	96.06
1.180	386.11	431.48	45.37	87.79	91.84
0.600	350.55	472.52	121.97	209.76	80.51
0.300	304.06	770.71	466.65	676.41	37.14
0.150	284.36	653.99	369.63	1046.04	2.78
0.075	272.46	294.29	21.83	1067.87	0.76
0.000	512.30	520.58	8.28	1076.15	-0.01

Weight of sand before sieving = 1000.96g

Location: **C1 ID100-1**

Sampling depth: **9.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.20	454.11	6.91	6.91	99.31
2.360	420.07	459.93	39.86	46.77	95.33
1.180	388.95	464.04	75.09	121.86	87.83
0.600	348.90	520.63	171.73	293.59	70.67
0.300	323.89	717.43	393.54	687.13	31.35
0.150	307.21	597.28	290.07	977.20	2.37
0.075	293.66	310.04	16.38	993.58	0.74
0.000	272.99	280.71	7.72	1001.30	-0.03

Weight of sand before sieving = 1000.71g

Location: **C2 ID100-6**

Sampling depth: **1.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.88	570.66	70.78	70.78	92.93
2.360	394.78	459.99	65.21	135.99	86.41
1.180	385.97	478.67	92.70	228.69	77.15
0.600	350.41	470.91	120.50	349.19	65.11
0.300	304.05	670.47	366.42	715.61	28.49
0.150	284.36	531.54	247.18	962.79	3.79
0.075	271.63	297.68	26.05	988.84	1.19
0.000	512.11	524.15	12.04	1000.88	-0.02

Weight of sand before sieving = 1000.17g

Location: **C2 ID100-6**

Sampling depth: **3.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.04	445.93	15.89	15.89	98.41
2.360	425.63	461.78	36.15	52.04	94.80
1.180	390.38	435.96	45.58	97.62	90.24
0.600	348.31	427.06	78.75	176.37	82.37
0.300	319.29	578.15	258.86	435.23	56.48
0.150	301.68	751.70	450.02	885.25	11.49
0.075	292.98	370.32	77.34	962.59	3.76
0.000	271.07	309.05	37.98	1000.57	-0.04

Weight of sand before sieving = 1000.83g

Location: **C2 ID100-6**

Sampling depth: **4.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.94	523.37	23.43	23.43	97.66
2.360	394.74	483.80	89.06	112.49	88.76
1.180	386.30	565.18	178.88	291.37	70.89
0.600	350.64	545.02	194.38	485.75	51.47
0.300	304.11	564.96	260.85	746.60	25.40
0.150	284.60	500.22	215.62	962.22	3.86
0.075	271.42	297.55	26.13	988.35	1.25
0.000	512.22	524.71	12.49	1000.84	0.00

Weight of sand before sieving = 1003.08g

Location: **C2 ID100-6**

Sampling depth: **6.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.23	463.08	15.85	15.85	98.42
2.360	420.13	485.88	65.75	81.60	91.87
1.180	388.97	509.16	120.19	201.79	79.88
0.600	349.05	551.09	202.04	403.83	59.74
0.300	324.26	710.08	385.82	789.65	21.28
0.150	307.14	489.44	182.30	971.95	3.10
0.075	294.28	314.08	19.80	991.75	1.13
0.000	273.56	284.99	11.43	1003.18	-0.01

Weight of sand before sieving = 1015.47g

Location: **C2 ID100-6**

Sampling depth: **7.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.03	441.38	11.35	11.35	98.88
2.360	425.62	499.72	74.10	85.45	91.59
1.180	390.38	522.20	131.82	217.27	78.60
0.600	348.28	522.92	174.64	391.91	61.41
0.300	319.33	664.84	345.51	737.42	27.38
0.150	301.64	525.36	223.72	961.14	5.35
0.075	292.96	328.76	35.80	996.94	1.82
0.000	271.06	289.83	18.77	1015.71	-0.02

Weight of sand before sieving = 1001.45g

Location: **C2 ID100-6**

Sampling depth: **9.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.04	443.77	13.73	13.73	98.63
2.360	425.64	474.81	49.17	62.90	93.72
1.180	390.49	487.22	96.73	159.63	84.06
0.600	348.39	531.02	182.63	342.26	65.82
0.300	319.32	675.53	356.21	698.47	30.25
0.150	301.65	557.60	255.95	954.42	4.70
0.075	292.98	327.05	34.07	988.49	1.29
0.000	271.09	284.12	13.03	1001.52	-0.01

Weight of sand before sieving = 1012.80g

Location: **C3 ID100-3**

Sampling depth: **1.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.86	505.00	5.14	5.14	99.49
2.360	394.73	442.19	47.46	52.60	94.81
1.180	386.31	475.73	89.42	142.02	85.98
0.600	351.26	501.81	150.55	292.57	71.11
0.300	304.13	856.29	552.16	844.73	16.59
0.150	284.68	433.37	148.69	993.42	1.91
0.075	271.45	285.72	14.27	1007.69	0.50
0.000	512.13	517.65	5.52	1013.21	-0.04

Weight of sand before sieving = 1006.45g

Location: **C3 ID100-3**

Sampling depth: **3.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.96	505.98	6.02	6.02	99.40
2.360	394.77	424.78	30.01	36.03	96.42
1.180	386.24	449.01	62.77	98.80	90.18
0.600	350.74	484.39	133.65	232.45	76.90
0.300	304.29	849.53	545.24	777.69	22.73
0.150	284.88	493.62	208.74	986.43	1.99
0.075	271.47	286.91	15.44	1001.87	0.46
0.000	512.18	517.05	4.87	1006.74	-0.03

Weight of sand before sieving = 1000.01g

Location: **C3 ID100-3**

Sampling depth: **4.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.01	434.07	4.06	4.06	99.59
2.360	425.02	452.98	27.96	32.02	96.80
1.180	390.37	441.87	51.50	83.52	91.65
0.600	348.35	452.80	104.45	187.97	81.20
0.300	319.24	657.60	338.36	526.33	47.37
0.150	301.61	685.43	383.82	910.15	8.99
0.075	292.99	349.69	56.70	966.85	3.32
0.000	271.07	304.99	33.92	1000.77	-0.08

Weight of sand before sieving = 1000.50g

Location: **C3 ID100-3**

Sampling depth: **7.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.15	546.71	99.56	99.56	90.05
2.360	420.09	488.75	68.66	168.22	83.19
1.180	388.73	495.90	107.17	275.39	72.47
0.600	349.08	511.91	162.83	438.22	56.20
0.300	323.81	634.18	310.37	748.59	25.18
0.150	307.23	530.96	223.73	972.32	2.82
0.075	293.69	311.78	18.09	990.41	1.01
0.000	273.01	284.12	11.11	1001.52	-0.10

Weight of sand before sieving = 1000.26g

Location: **C3 ID100-3**

Sampling depth: **10.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.22	497.55	50.33	50.33	94.97
2.360	420.14	444.39	24.25	74.58	92.54
1.180	388.61	406.85	18.24	92.82	90.72
0.600	349.15	399.76	50.61	143.43	85.66
0.300	323.71	761.77	438.06	581.49	41.87
0.150	307.33	686.62	379.29	960.78	3.95
0.075	293.77	312.30	18.53	979.31	2.09
0.000	273.09	288.81	15.72	995.03	0.52

Weight of sand before sieving = 1000.09g

Location: **C3 ID100-3**

Sampling depth: **11.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.22	454.31	7.09	7.09	99.29
2.360	420.13	450.16	30.03	37.12	96.29
1.180	388.65	468.64	79.99	117.11	88.29
0.600	349.10	478.18	129.08	246.19	75.38
0.300	323.77	673.51	349.74	595.93	40.41
0.150	307.19	664.14	356.95	952.88	4.72
0.075	292.76	323.83	31.07	983.95	1.61
0.000	273.11	290.31	17.20	1001.15	-0.11

Weight of sand before sieving = 1000.02g

Location: **C4 ID100-8**

Sampling depth: **1.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.20	472.18	24.98	24.98	97.50
2.360	420.08	444.51	24.43	49.41	95.06
1.180	388.61	449.22	60.61	110.02	89.00
0.600	348.89	481.17	132.28	242.30	75.77
0.300	323.67	614.90	291.23	533.53	46.65
0.150	307.19	712.57	405.38	938.91	6.11
0.075	282.77	334.74	51.97	990.88	0.91
0.000	273.39	293.93	20.54	1011.42	-1.14

Weight of sand before sieving = 1003.38g

Location: **C4 ID100-8**

Sampling depth: **3.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	430.04	432.34	2.30	2.30	99.77
2.360	425.64	432.88	7.24	9.54	99.05
1.180	390.53	400.06	9.53	19.07	98.10
0.600	348.38	374.54	26.16	45.23	95.49
0.300	319.41	503.18	183.77	229.00	77.18
0.150	301.61	938.88	637.27	866.27	13.66
0.075	292.98	385.06	92.08	958.35	4.49
0.000	271.07	316.19	45.12	1003.47	-0.01

Weight of sand before sieving = 1000.23g

Location: **C4 ID100-8**

Sampling depth: **4.5m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.21	453.77	6.56	6.56	99.34
2.360	420.07	484.06	63.99	70.55	92.95
1.180	388.89	573.85	184.96	255.51	74.45
0.600	348.91	578.30	229.39	484.90	51.52
0.300	323.72	648.72	325.00	809.90	19.03
0.150	307.19	446.43	139.24	949.14	5.11
0.075	293.66	326.83	33.17	982.31	1.79
0.000	273.06	291.08	18.02	1000.33	-0.01

Weight of sand before sieving = 1000.13g

Location: **C4 ID100-8**

Sampling depth: **6.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	499.93	546.85	46.92	46.92	95.31
2.360	394.73	488.17	93.44	140.36	85.97
1.180	386.17	552.44	166.27	306.63	69.34
0.600	350.65	525.22	174.57	481.20	51.89
0.300	304.22	605.20	300.98	782.18	21.79
0.150	284.58	471.54	186.96	969.14	3.10
0.075	271.42	294.67	23.25	992.39	0.77
0.000	512.19	520.15	7.96	1000.35	-0.02

Weight of sand before sieving = 1000.2g

Location: **C4 ID100-8**

Sampling depth: **7.0m**

Sieve Opening (mm)	Wt of empty sieve (g)	Wt of each sieve after shaking (g)	Net wt of sand retained (g)	Cum. Wt of sand retained (g)	% of sand retained by weight
4.750	447.16	470.75	23.59	23.59	97.64
2.360	420.09	459.48	39.39	62.98	93.70
1.180	388.81	500.53	111.72	174.70	82.53
0.600	349.07	546.15	197.08	371.78	62.83
0.300	323.79	781.23	457.44	829.22	17.09
0.150	307.25	453.05	145.80	975.02	2.52
0.075	293.70	310.98	17.28	992.30	0.79
0.000	273.08	281.40	8.32	1000.62	-0.04

APPENDIX F
Specifications of measurement devices

Measurement device	Variable	Specifications
Hydrostatic pressure transducer (Model 6508C, Unidata [®])	Water table elevation	Measurement range: 0 – 5m; Resolution: 20mm; Operation temperature range: -1 to 60°C;
Tipping bucket rain gauge (Model 6506A, Unidata [®])	Rainfall depth	Measurement range: 0 – 200mm/hr; Resolution: 0.2mm/tip
EnviroSMART soil water content probe (Campbell Scientific Inc.)	Volumetric soil moisture content	Measurement range: over dry to saturation; Accuracy: 0.03%; Operational temperature range: -20 to 75°C
229 soil water potential probe (Campbell Scientific Inc.)	Soil suction head	Measurement range: -10 to -1000kPa; Resolution: 1kPa
LI200X Pyranometer (Campbell Scientific Inc.)	Solar radiation flux	Operational temperature range: -40 to 65°C; Operational relative humidity range: 1 – 100%; Sensitivity: 0.2kWm ⁻² mV ⁻¹

Specifications of measurement devices (Continue)

Measurement device	Variable	Specifications
HMP45C temperature and relative humidity probe (Campbell Scientific Inc.)	Relative humidity and air temperature	<u>Relative humidity</u> Measurement range: 0.8 – 100%; Accuracy: 1 – 3% Air temperature Measurement range: -39.2 to 60°C; Accuracy: 0.2 to 0.5°C
03001-5RM Young Wind Monitor (Campbell Scientific Inc.)	Wind speed	Measurement range: 1 to 60m/s Accuracy: 3%

PUBLICATIONS

Peer-Reviewer Journal Papers

1. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., Ngonidzashe, M., “Estimation of Areal Specific Yield in Sands Using Central Limit Theorem”, Accepted in Hydrological Processes, John Wiley and Sons. (Published Online)
2. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., “Modelling Hourly and Daily Open Water Evaporation Rates in Areas with an Equatorial Climate”, Accepted in Hydrological Processes, John Wiley and Sons. (Published Online)
3. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., Yee, W.K., “Studies on Groundwater Recharge Characteristics at a Reclaimed Land Site with an Equatorial Climate Using Time Series and Spectral Analyses”, Accepted in Hydrological Processes, John Wiley and Sons.
4. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., “Effects of Meteorological and Hydrogeological Factors on Gross Recharge Percentage at Unconfined Sandy Aquifers with an Equatorial Climate”, Accepted in Hydrological Processes, John Wiley and Sons.
5. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., “Regression Method for Estimating Rainfall Recharge at Unconfined Sandy Aquifers with an Equatorial Climate”, Accepted in Hydrological Processes, John Wiley and Sons.
6. **Tan, S.B.K.**, Shuy, E.B., Chua, L.H.C., “Radial Basis Function Neural Network as an Inverse Solving Algorithm for Calibrating Soil Moisture Dynamics Model”, Submitted to Hydrological Processes, John Wiley and Sons.