Jurnal
Teknologi

Full Paper

SIMULATION OF LINEAR AND NON-LINEAR SOIL WATER DEFICIT DUE TO TREE WATER UPTAKE

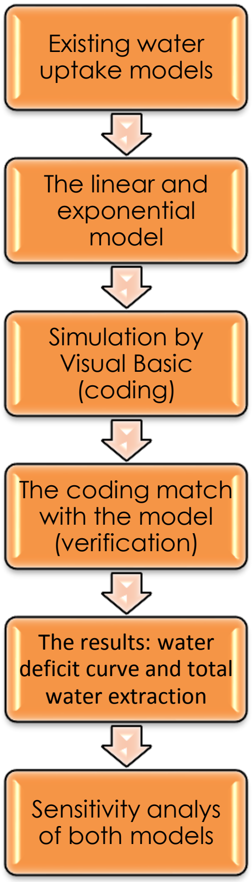
Ong Choon Kian*, Nazri Ali

Geoengineering and Geohazard Research Group, Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

Article history
Received
6 July 2015
Received in revised form
26 July 2015
Accepted
30 July 2015

*Corresponding author
ckong3@live.utm.my

Graphical abstract



Abstract

Simulation of water uptake model is extremely important to anticipate the moisture content changes in the soil. It is very helpful for the development of geotechnical foundation and geo-environmental problem solving. There are several water uptake models that have been developed by previous researchers. However it is difficult to plot and to analyse the model. Hence, this project focuses into the development of coding for linear and non-linear water uptake models. Linear model and exponential model were simulated by using Visual Basic. The results were verified and showed a good match with the models. The sensitivity of the linear and the exponential model was investigated, followed by the comparison between both simulated models. The results show that the total water extraction of the linear model is not affected by rooting depth, but very sensitive to potential transpiration. For the exponential model, the increment of the total water extraction is equal to the increment of potential transpiration. Besides, the extinction coefficient, *b* produces the least affect to the total water extraction. The total water extraction of the linear model is lower than that of the exponential model. For a common potential transpiration of 0.4 cm/day, the rate of the extraction is almost zero at 60% rooting depth and deeper when *b* value is 0.15/cm and higher.

Keywords: Water uptake simulation; linear; exponential; sensitivity analysis; total water extraction.

Abstrak

Simulasi model pengekstrakan air adalah sangat penting untuk menjangkakan perubahan kelembapan di dalam tanah. Ia sangat membantu kepada pembangunan penyelesaian masalah asas geoteknikal dan geo-sekitaran. Terdapat beberapa model pengekstrakan air yang telah dibangunkan oleh penyelidik-penyelidik terdahulu. Walau bagaimanapun, kekurangan program perisian untuk menganalisis model-model tersebut. Oleh itu, kajian ini memberikan tumpuan dalam membangunkan kod untuk model pengekstrakan air linear dan bukan linear. Model linear dan model eksponen telah disimulasi dengan menggunakan kod program "Visual Basic". Hasil simulasi ini telah disahkan dan menunjukkan satu persamaan yang baik dengan model. Kepekaan model linear dan eksponen telah dikaji dan perbandingan juga dibuat antara kedua-dua model tersebut. Keputusan menunjukkan bahawa jumlah pengekstrakan air daripada model linear tidak dipengaruhi oleh kedalaman akar tetapi sangat sensitif kepada potensi transpirasi. Untuk model eksponen pula, pertambahan jumlah pengekstrakan air adalah bersamaan dengan pertambahan transpirasi potensi. Jumlah pengekstrakan air model linear adalah lebih rendah berbanding dengan pengekstrakan air model eksponen. Selain itu, 'extinction coefficient', *b* menunjukkan kesan yang paling rendah kepada jumlah pengekstrakan air. Pada potensi transpirasi 0.4 cm/hari, kadar ekstrak adalah hampir sifar apabila kedalaman akar sama atau lebih dalam daripada 60% kedalaman akarnya apabila *b* melebihi atau sama dengan 0.15/cm.

Kata kunci: Model pengekstrakan air, linear, eksponen, kepekaan model, jumlah pengekstrakan air.

1.0 INTRODUCTION

The construction technology and development keep improving and geotechnical and foundation problems have become more critical and also the environmental sustainability. There are previous studies on the slope stability [1], embankment, and also dam failure [2] for the investigation of the causes of the failures. The failure or any cases happened become the input for the improvement of the design, concept, method or any maintenance requirements.

Trees can also become the factor that causes the problem. It has the power that can damage the building, direct or indirectly. The direct damage from tree can be avoided by referring to the safe distance guidance given in BS5837: 2005 [3]. Indirectly, the tress can cause the clay soils to shrink by drawing the water along their roots. Shrinkage will result in vertical and horizontal ground movements and the amount of shrinkage depends on the type of clay soil, size of tree and climate. In a typical year, expansive soils cause a greater financial loss to property owners than earthquakes, floods, hurricanes and tornadoes combined [4].

According to Jones and Jefferson [5], the shrinkage and the swelling of clay soil due to tress can cause the foundation movements that could damage the buildings. The prediction of the heave shrinkage can be estimated based on the changes of soil moisture content. The soil suction is a limiting parameter for free water uptake and nutrient uptake. The relationship of the plant-root system and soil water play important roles in agricultural science and geotechnical engineering. Thus, the variation in soil suction that occurs in presence or absence of plant is very important for an analysis. Therefore, a study on changes of moisture content in soil is required to analyse some geotechnical and geo-environmental problems.

The water uptake model and the experimental work had been developed for a period of time with different approaches and factors [6-9]. The equation of the water uptake model had been established and validated with the site measurement. From the results, the water content was investigated and the graph as water deficit curve was plotted in order to present the moisture condition at the site. However, there is lack of software programme to direct plot out and to analyse or perform numerical model, especially for non-linear problem. The estimated moisture content can be obtained easily and faster with the aid of the software. So, this is easier for any researcher to calculate the water deficit. In short, the development of the coding programme on the water deficit curve is very important for geo-environment development.

This paper presents the coding results of the study on simulation of the linear [10] and the exponential [11] soil water deficit due to the tree water uptake. The study produced the relationship between the total water extraction and the governing parameters. The test results are presented and examined in the following sections.

2.0 CODING PROGRAMME

2.1 Programme Flow

The programme was built up by six numbers of forms using software Visual Basic 6.0. Form 1 displays the login page, prior using the programme. For Form 2, two buttons were placed to choose the options which type of model desired. Forms 3 and 4 were fixed for the linear model's guideline and the calculation, respectively. While Forms 5 and 6 were for the guideline and the calculation, respectively, for the exponential model. More information and details are shown in the following section. The programme flow chart is shown in Figure 1.

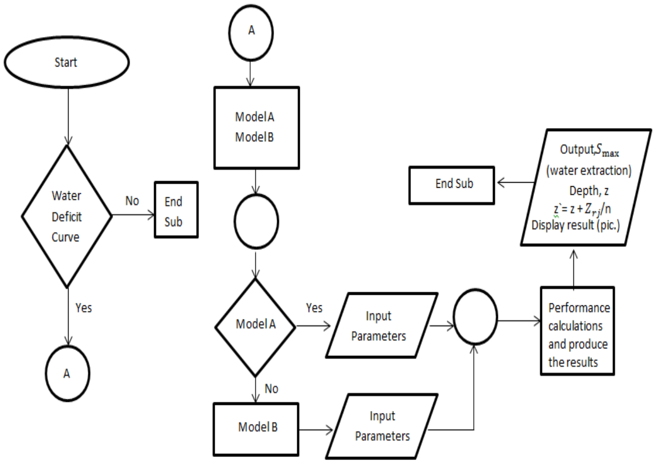


Figure 1 Programming flow chart

2.1.1 Linear Model

Firstly, the linear extraction started with user guideline for the inexperienced user. However, the programme could skip the guideline as desired by the user. This would lead the programme to the next page, Form 4. Next, there are few parameters to be set as the input to calculate the rate of extraction and the total water extraction. Lastly, the results could be obtained, i.e., the total extraction of water estimated and maximum soil water uptake, listed in Equation (1).

$$S_{max} = \frac{2T_j}{z_{rj}}\left(1 - \frac{z}{z_{rj}}\right)\alpha(h) \ldots \qquad (1)$$

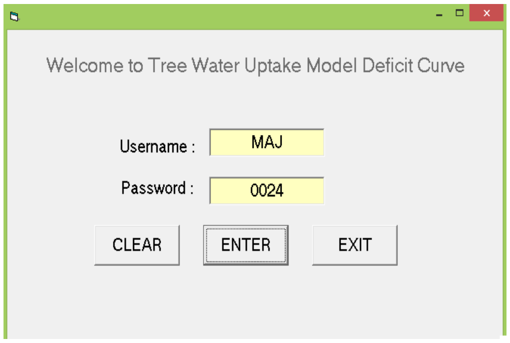
Where PT is rate of potential transpiration, z is depth, z_r is rooting depth, and $\alpha(h)$ is a dimensionless function of pressure head.

2.1.2 Exponential Model

The exponential extraction model is started with Form 5 for the inexperienced user but this could be skipped if desired by the user. This would lead the programme to the next stage in Form 6. Three parameters were fixed as the inputs of model to calculate the rate of water uptake and total water extraction. Lastly, the estimated maximum soil water uptake (Equation 2), total extraction of water and graph could be obtained as the output of the programme.

$$S_{max} = \frac{K_{Z_1-Z_2} PT_j}{|Z_1 - Z_2|} \dots \qquad (2)$$

Where $Z_1$and Z_2 is the depth at point 1 & 2, $K_{Z_1-Z_2}$ is fraction of total root length between depth Z_1- Z_2, and PT is potential transpiration. The important parts of the programme are shown in the Figures 2 to 6.



Welcome to Tree Water Uptake Model Deficit Curve

Username : MAJ

Password : 0024

Figure 2 Login page

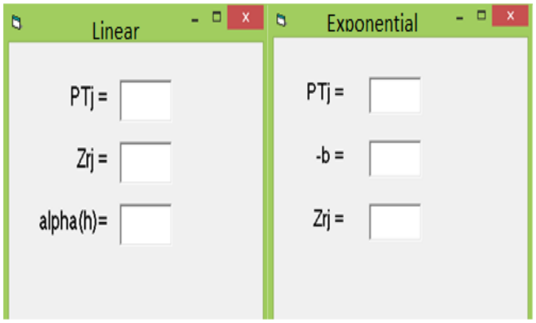


Figure 3 Data input

```
z(cm)        Smax(/day)
0.00         0.00800
5.00         0.00760
10.00        0.00720
15.00        0.00680
20.00        0.00640
25.00        0.00600
30.00        0.00560
35.00        0.00520
40.00        0.00480
45.00        0.00440
50.00        0.00400
55.00        0.00360
60.00        0.00320
65.00        0.00280
70.00        0.00240
75.00        0.00200
80.00        0.00160
85.00        0.00120
90.00        0.00080
95.00        0.00040
100.00       0.00000
Total Water Extraction = 0.40cm per day
```

```
z(cm)        Smax(/day)
3.00         0.03605
8.00         0.01996
13.00        0.01108
18.00        0.00622
23.00        0.00357
28.00        0.00208
33.00        0.00124
38.00        0.00075
43.00        0.00046
48.00        0.00028
53.00        0.00018
58.00        0.00011
63.00        0.00007
68.00        0.00004
73.00        0.00003
78.00        0.00002
83.00        0.00001
88.00        0.00001
93.00        0.00001
98.00        0.00000
100.00       0.00000
Total Water Extraction = 0.57cm per day
```

Figure 4 Rate and the total water extraction

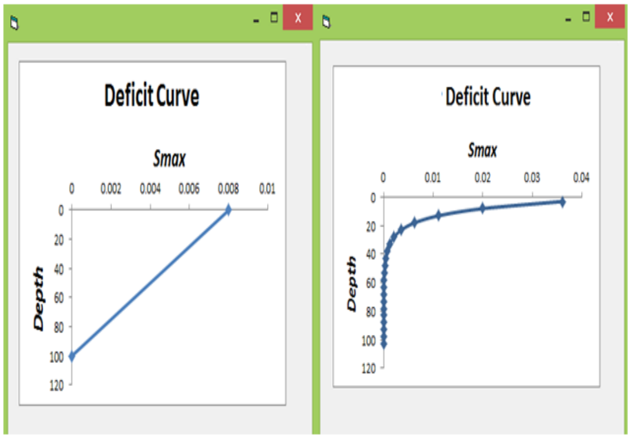
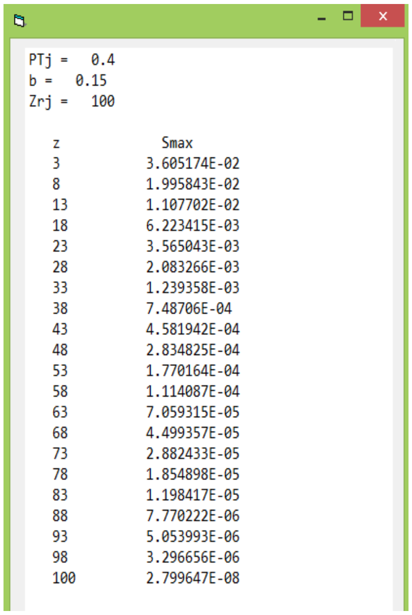


Figure 5 Water deficit curve imported from Excel



```
PTj =   0.4
b =   0.15
Zrj =   100

   z             Smax
   3          3.605174E-02
   8          1.995843E-02
   13         1.107702E-02
   18         6.223415E-03
   23         3.565043E-03
   28         2.083266E-03
   33         1.239358E-03
   38         7.48706E-04
   43         4.581942E-04
   48         2.834825E-04
   53         1.770164E-04
   58         1.114087E-04
   63         7.059315E-05
   68         4.499357E-05
   73         2.882433E-05
   78         1.854898E-05
   83         1.198417E-05
   88         7.770222E-06
   93         5.053993E-06
   98         3.296656E-06
   100        2.799647E-08
```

Figure 6 The data saved in text document

2.2 Verification of Coding

The codings were checked with a test plan, or called verification with the linear and exponential model from Prasad [10] and Li *et al.* [11], respectively. Besides that, the linear and the exponential model had been validated by the researcher with the site measurement results.

2.2.1 *Linear Model*

For the linear model simulation, the model of Prasad [10] and the created coding were put into verification. The result shows the data obtained from Prasad and the simulation with fixed potential transpiration, PT equal to 0.4 cm/day, rooting depth of 100 cm, and constant prescribed function, 1.0. This showed that the coding matched with the model.

2.2.2 *Exponential Model*

For the exponential model simulation, the model of Li *et al.* [11] and the simulated coding were put into verification. The difference between the results of the model and VB coding are as shown in Table 1. In order to make sure the simulated coding is same with the model referred was with fixed potential transpiration, PT is equal to 0.4 cm/day, rooting depth of 100 cm, and extinction coefficient, b. The maximum of difference was 0.00034 and this value is very small compared to the exact value of 0.004 obtained directly from the graph. Three graphs were plotted according to the data obtained to show that they matched with the model of Li *et al.* [11] as shown in Figures 7, 8, and 9.

Table 1 Difference of results between model and VB coding

Depth (cm)	**S_{max} (per day)**		
	b = 0.05	**b = 0.15**	**b = 0.20**
0	0.0005	0	0.00194
20	0.00016	0.00034	0.00004
40	0.00016	0.00031	0.00027
60	0.00022	0.00001	0
80	0.00004	0	0
100	0.00018	0	0

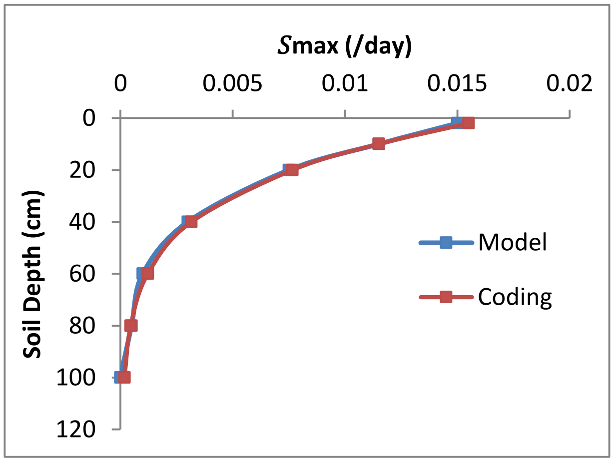


Figure 7 Maximum soil water uptake for b = 0.05

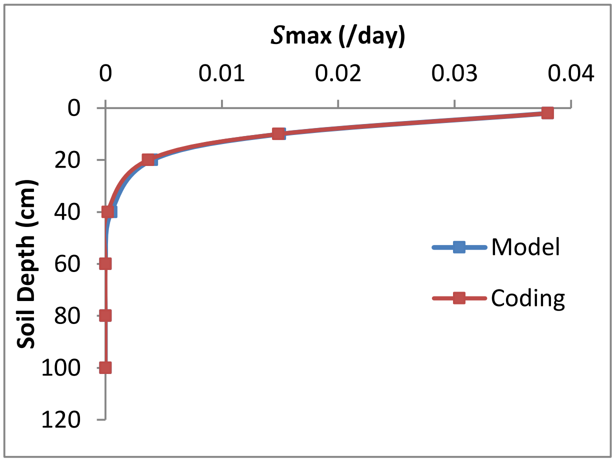


Figure 8 Maximum soil water uptake for b = 0.15

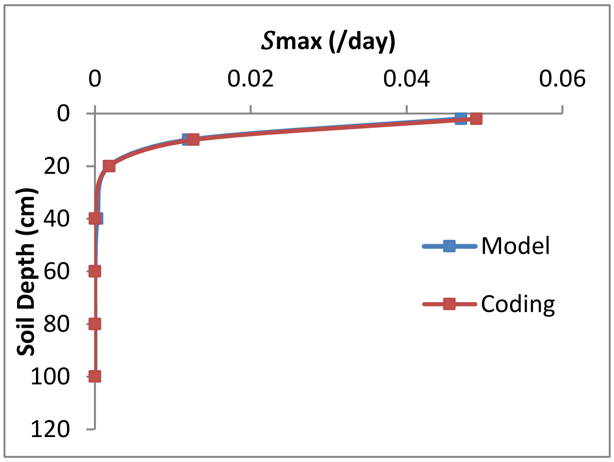


Figure 9 Maximum soil water uptake for b = 0.20

2.3 Sensitivity Analysis

The results of the simulation in this study were for two types of models, linear and exponential. The coding had been verified and matched with the model as shown in Figures 7, 8, and 9. For the linear model, the parameters of the rooting depth (Z_{rj}) and potential transpiration (PT) were tested to get the relationship with total water extraction meanwhile there is one more parameter, extinction coefficient (*b*) was investigated for exponential model. Lastly, the results of the simulation were put for comparison between the linear and the exponential models. The comparison was done with respect to the rate and the total extraction under the same potential transpiration condition.

3.0 RESULTS AND DISCUSSION

3.1 Linear Model

There were two sets of trials had been done for various rooting depth and potential transpiration with constant alpha (*h*) = 1.0 either PT = 0.4 cm/day or Z_{rj} = 100 cm, respectively, to obtain the total water extraction. When the parameter rooting depth goes deeper, the total water extraction remains unchanged.

This shows that the total water uptake of linear model is not affected by the rooting depth; the total water extracted for all cases were same for the constant potential transpiration of 0.4 cm/day. However, the rate of extraction ($S_{\max}$) decreased with increasing rooting depth as shown in Figure 10.

In addition, when the potential transpiration increased, the total water extraction also increased linearly. This shows that potential transpiration directly affected the total water uptake for the linear model. The relationship between the total water extraction and the potential transpiration was plotted as shown in Figure 11. This shows that potential transpiration significantly controlled the water uptake by the roots.

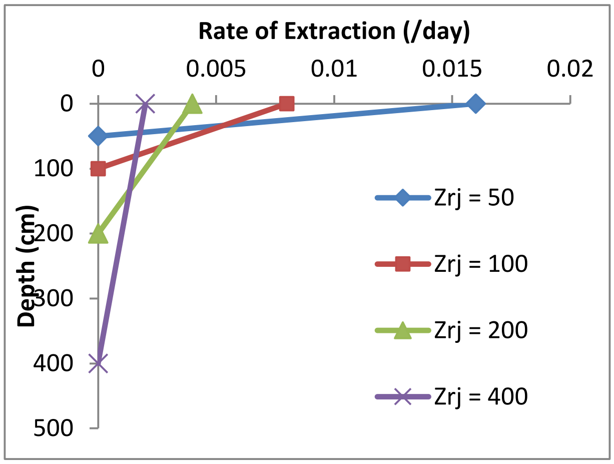


Figure 10 Relationship between the rate of extraction and the rooting depth

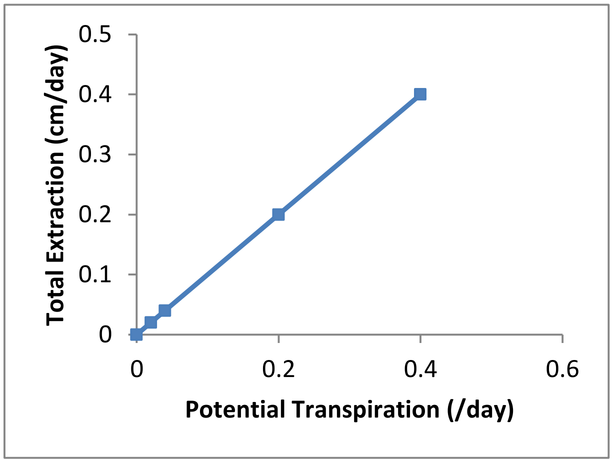


Figure 11 Relationship between the total water extraction and the potential transpiration

3.2 Exponential Model

There were three sets of tests that had been done. First, the variation of rooting depth (Zrj) then followed by potential transpiration (PT) and extinction coefficient (*b*) by fixing the PT at 0.4 cm/day and Z_{rj} at 100 cm or b = 0.05/cm, respectively, to obtain the total water extraction.

For Case 1, potential transpiration was fixed at 0.4 cm/day and the rooting depths were 100 cm, 200 cm and 300 cm. For Case 2, extinction coefficient, *b* was fixed at 0.2/cm and potential transpiration was 0.2, 0.4, and 0.6 cm/day. For Case 3, the rooting depth was fixed at 100 cm and extinction coefficient (*b*) was 0.05, 0.2, and 0.4/cm. The relationship between the total water extraction and the various parameters were plotted as shown in Figures 12, 13, and 14.

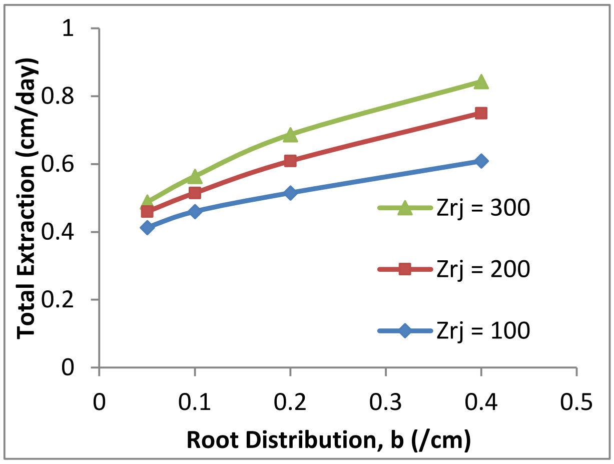


Figure 12 Relationship between the total water extraction and the root fraction

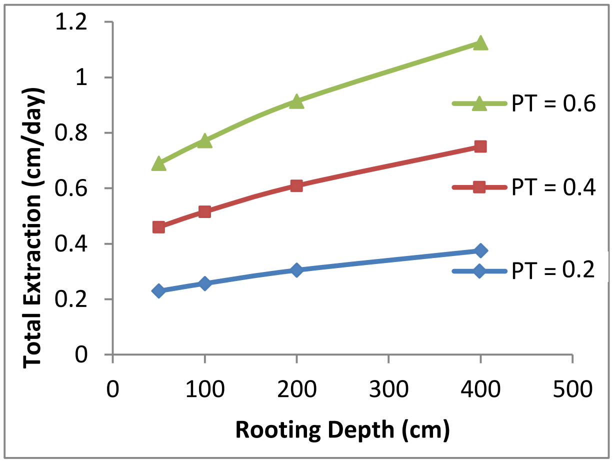


Figure 13 Relationship between the total water extraction and the rooting depth

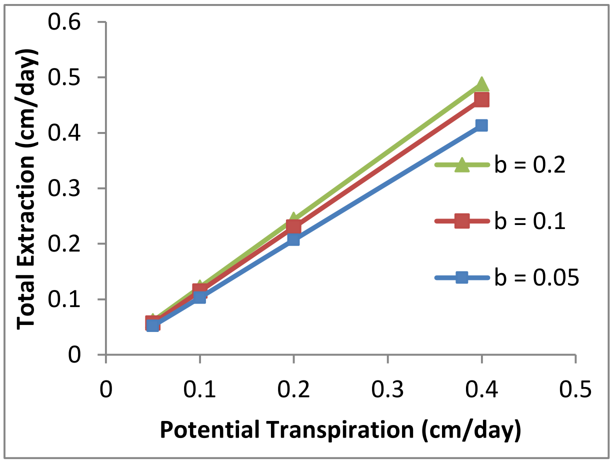


Figure 14 Relationship between the total water extraction and the potential transpiration

Figure 12 shows that the total water extraction was higher when *b* value was higher and the rooting depth was deeper. When the *b* value was 0.05/cm, the total water extraction was increased 0.047 cm/day and 0.028 cm/day when the rooting depth increased from 100 cm to 200 cm and 200 cm to 300 cm. Meanwhile when *b* = 0.4/cm, the total water extraction was increased by 0.141 cm/day and 0.093 cm/day for the same rooting depth change. This proved that the increasing of total water extraction was higher at larger *b* value and the increment became lower when the rooting depth became deeper.

The percentage of the increment and the effect of rooting depth were described in Figure 13. It showed that the total water extraction was higher when the rooting depth was deeper and higher potential transpiration. When the rooting depth was 50 cm and PT was 0.2, the total water extraction was increased by 0.23 cm/day when the potential transpiration increased from 0.2 to 0.4 cm/day and 0.4 to 0.6 cm/day. Meanwhile rooting depth of 100 cm, the total water extraction was 0.257 cm/day and increased to 0.515 cm/day. It showed the same increment when potential transpiration increased from 0.2 to 0.4 cm/day and 0.4 to 0.6 cm/day. This shows that the total water extraction was increased by 100% followed by 50% and 25% and so on as the increasing of potential transpiration fixed to be same. It also showed the increment of total water extraction was constant with respect to the potential transpiration for a fixed rooting depth.

Figure 14 shows that the total water extraction was higher when the *b* value was larger and higher potential transpiration which was proved in the above discussion. The water uptake or water extraction did not occur when the potential transpiration was zero at potential transpiration of 0.05/day; the total water extraction increased by 0.05 cm/day and 0.004 cm/day when the b value increased from 0.05 to 0.10/cm and 0.10 to 0.15/cm, respectively. When the potential transpiration was 0.10/day, the total water extraction increased by 11.65% and 6.09%. The result again showed the total water extraction was higher when potential transpiration higher and larger *b* value with the increment of water extraction became lesser as the value of *b* was increased.

3.3 Comparison between Linear and Exponential Models

The results obtained from the simulation of the linear and the exponential model were plotted for the same potential transpiration, PT = 0.4 cm/day, for rooting depth of 100 cm, as shown in Figure 15.

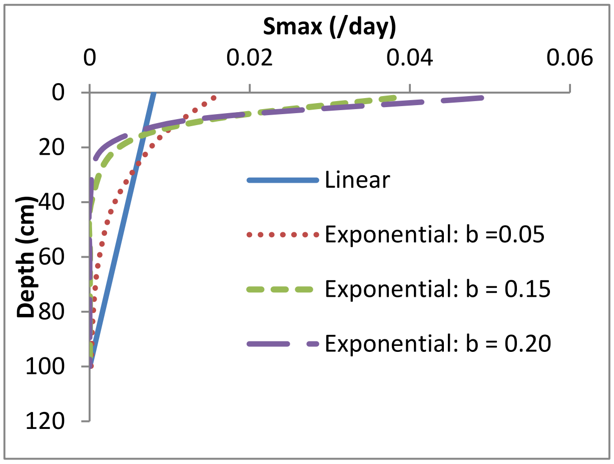


Figure 15 The results of the linear and the exponential simulations

According to the simulation, the total water extraction for linear model was 0.4cm/day while exponential model was 0.45, 0.52 and 0.54 cm/day with *b* value of 0.05, 0.15 and 0.20 respectively. From Figure 15, the linear model produced the maximum rate of extraction at the surface of the soil and decreased linearly to zero extraction at maximum depth. The exponential model also produced the maximum rate at top part of soil but decreased exponentially depending on *b* values. For *b* value of 0.05/cm, the result showed that the rate of extraction decreased from 0.0155/day to 0.00018/day at maximum rooting depth. For *b* value 0.15 and 0.20, it reached almost zero water uptake after 60% of the rooting depth was reached. This showed that the exponential seemed to be more accurate model due to the consideration of root fraction for various depths. When the extinction coefficient, *b* varied, it produced the various rates of extraction. Meanwhile, the linear model did not consider the root fraction, but only depended on potential transpiration and rooting depth. However, the applications of both models need to consider the site condition such as soil and type of plants surrounding, in order to have an efficient and effective result.

4.0 CONCLUSION

This paper describes the simulation of the linear and the exponential soil water deficit due to the tree water uptake. The results obtained from the simulation had been analysed and discussed. Hence, the following conclusion can be done from the study.

1. The total water extraction of linear model is not affected by rooting depth. Besides, the potential transpiration influenced the total water extraction with factor of 1.0. This means that the higher potential transpiration will result in more water uptake and the changes of moisture content is larger.
2. The total water extraction of exponential model is higher when the rooting depth is deeper, b value is larger and potential transpiration is higher. The increment of total water extraction is smaller when the rooting depth becomes deeper. It also shows that the increment of total water extraction is constant with the increment of potential transpiration and the extinction coefficient, b show the least effect to the total water extraction.
3. Both the linear and the exponential model provide the maximum rate of the extraction at the top part of the soil. The linear model shows a linear decreasing of the rate of extraction until the maximum depth. However, the exponential depends on the extinction coefficient, *b*. The total water extraction of the linear model is lower than that of the exponential model. The *b* value of 0.15 and higher shows that the rate of extraction is almost zero when deeper than or equal to 60% of rooting depth for a potential transpiration of 0.4 cm/day.

Acknowledgement

The authors gratefully acknowledged the Faculty of Civil Engineering, Universiti Teknologi Malaysia for the assistance in the undertaking of this research work.

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