CHAPTER 8

WATER AND WATER VAPOR ENVIRONMENT

8.1. INTRODUCTION

Water movement in soil is much more complicated than that of CO_2 because not only is water present in two phases, one liquid and the other gas, but also water movement is related to heat flow. However, in order to simplify the problem and understand the system clearly, it is again assumed that vapor flow in soil is independent of heat flow, as we assumed in the chapter on heat flow analysis. Furthermore, we will focus only on vapor movement in the present chapter, because in most cases water flow is assumed to occur in parallel with water vapor flow and they are combined. This can be condensed into what is the diffusion coefficient for both.

When soil is covered by vegetation, as is usual in agricultural fields, water is transported from the soil via roots, stems and leaves. This transport system in the form of a soil-plant-atmosphere continuum (SPAC) was introduced using water potential (Slatyer, 1963). It is convenient to use water potential to describe the water flow in SPAC. The concept of SPAC is clear, and sophisticated models for open fields have also been developed; the power of CSMP has also been demonstrated. Since evaporation from bare soil is the most important part of these rather complicated systems, a system without plants is considered in this chapter. In Chapter 10, the relationship between transpiration and environmental conditions is discussed in a physiological model of plant leaves.

Water potential, **SS** (J/kg), is proportional to the difference in chemical potential found by Gibb's free energy law and defined as

$$\mathbf{SS} = (\mathbf{MYU} - \mathbf{MYU0}) / \mathbf{VOL} = \mathbf{RC} * \mathbf{AT} / \mathbf{VOL} * \mathbf{log}(\mathbf{P} / \mathbf{P0}) \qquad (8.1)$$

$$= \mathbf{RC} * \mathbf{AT} / \mathbf{GRV} * \mathbf{log}(\mathbf{P} / \mathbf{P0}) \qquad (8.2)$$

where **MYU** and **MYU0** are chemical potentials of the water used in the study and pure water, respectively, **P** and **P0** are water vapor pressure and saturated water vapor pressure, respectively (Pa), **RC** is the gas constant (461.5 J/kg/K or 8.314 J/mole/K), **AT** is absolute temperature (T+273, K), **VOL** is mole volume of water (18.0 cm^3/mole), and **GRV** is acceleration of gravity (9.8 m/s^2) (*e.g.*, Koorevaar *et al.*, 1987). The unit of water potential is J/cm^3. This is dimensionally equivalent to pressure units such as N/cm^2, Pa and bar. It is also equivalent to the unit J/g because water density is 1 g/cm^3. As a practical unit, J/kg is used and is calculated by using 0.018 kg/mole for **VOL**. It is also shown that 1 J/kg equals 1 kPa. The bar is the most popular unit for pressure, and 1 bar is equal to 100 kPa. In eq. 8.1, the unit of water potential (**SS)** is in J/kg. In eq. 8.2, as the unit of water potential is kPa, **SS** is expressed in meters since one atmospheric pressure is approximately 10 m Aq and is equal to 100 kPa, and 1 kPa is equal to 0.1 m.

8.2. WATER AND WATER VAPOR MOVEMENT IN SOIL

Water movement in liquid form is considered first. Vertical water flow in soil is expressed as the following equation:

$$\mathbf{FLR} = -\,\mathbf{KT} * d\mathbf{SS}/d\mathbf{z} - \mathbf{KT} \qquad (8.3)$$

where **FLR** is water flow rate ($m^3/m^2/hr$), **KT** is hydraulic conductivity (m/hr), **SS** is water potential (m), and **z** is soil depth (m). The typical units for water potential are J/kg, kPa and m, as indicated in the introduction. The conversion from the unit $m \cdot m/s^2$ to kPa is as follows: 1 $m \cdot m/s^2$ is equal to 0.1 m of pressure head of water, and 1 m of pressure head of water is 10 kPa. Therefore, the unit $m \cdot m/s^2$ is equivalent to the unit J/kg.

Hydraulic conductivity is complicated and is known to be a function of the volumetric water content (**WW**, m^3/m^3). In order to simplify the situation to show the general behavior of the model, some functional relationships from van Keulen (1975) are introduced. Hydraulic conductivity is expressed as

$$\mathbf{KT} = \mathbf{AFGEN\_KTB}(\mathbf{WW}) \qquad (8.4)$$

and this relationship is depicted by a smooth curve in Fig. 8.1.

Water potential (**SS**) is a function of volumetric water content (**WW**) in the following way:

$$\mathbf{SS} = \mathbf{AFGEN\_STB}(\mathbf{WW}) \qquad (8.5)$$

Fig. 8.2 also shows the relationship between water potential and volumetric water content. In a similar way, vapor diffusivity (**DWV**, m^2/hr) is a function of volumetric water content (**WW**, m^3/m^3),

$$\mathbf{DWV} = \mathbf{AFGEN\_WVDT}(\mathbf{WW}) \qquad (8.6)$$

where **WW** is given in Fig. 8.1.

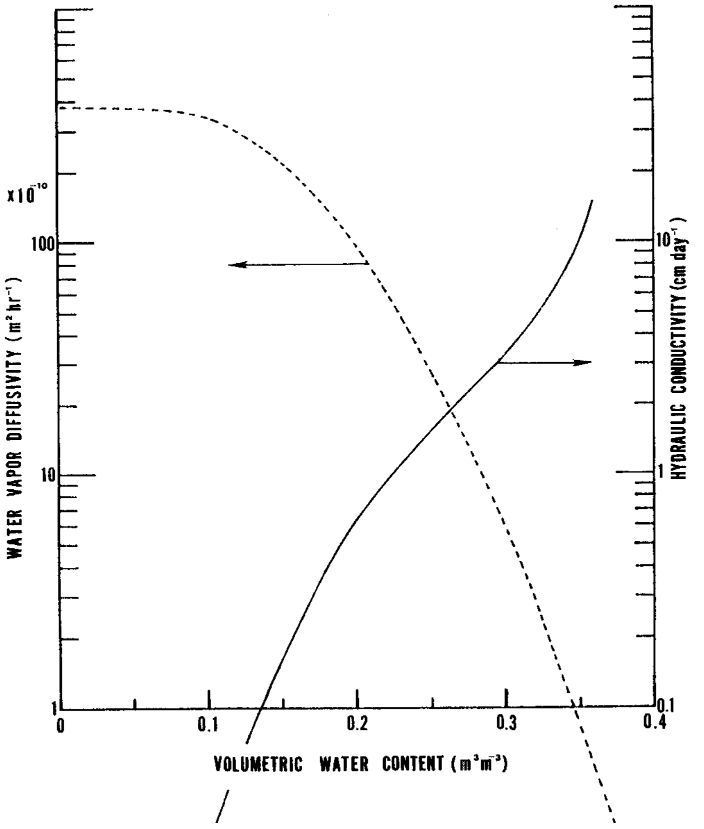

Figure 8.1. Hydraulic conductivity and water vapor diffusivity are given as functions of volumetric water content (after van Keulen, 1975).

Vapor flow is expressed as

$$\mathbf{WVF} = \mathbf{DWV} * d\mathbf{VPC} \,/\, d\mathbf{z} \qquad (8.7)$$

where **VPC** is vapor concentration (m^3/m^3).

Saturated water vapor pressure (**PWS**) was already given in the previous models as a function of temperature, and is expressed in a separate function definition:

$$[\mathbf{PWS}, \mathbf{WWW}] = \mathbf{FWSP(TTT)} \qquad (8.8)$$

Actual vapor pressure (**VPM**, mbar) is given as the product of **PWS** and **DF** (depression factor); furthermore, it is converted to vapor concentration (**VPC**, m^3/m^3).

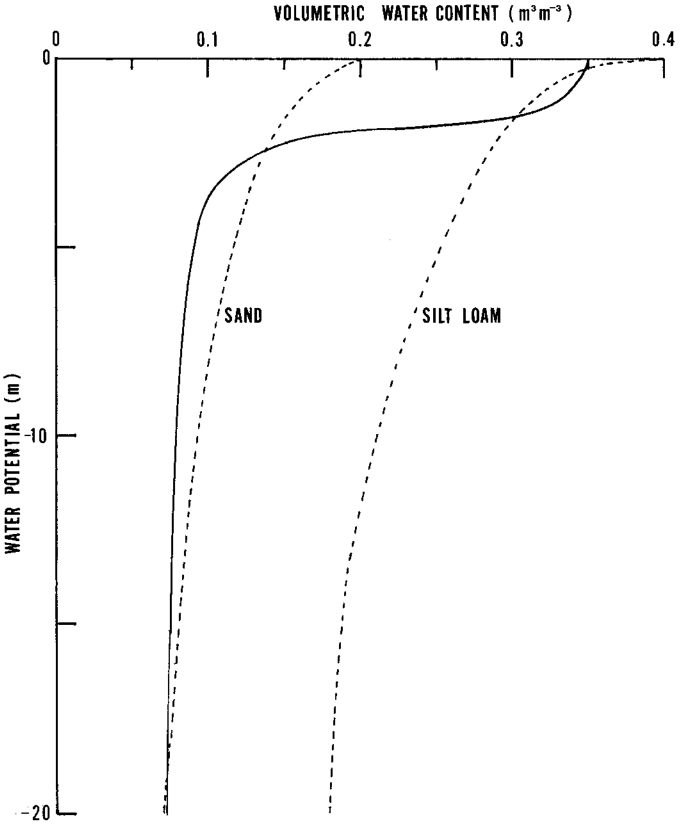

Figure 8.2. The relationship between water potential and volumetric water content; (Solid line after van Keulen, 1975; and dotted lines from Campbell, 1985).

8.3. WATER AND HEAT BALANCE IN SOIL LAYER (**CUC90**)

The complete model is given in Fig. 8.3, and the simulated results are given in Fig. 8.4. The main structure of the model is the same as that for the heat flow model (**CUC03**) discussed in Chapter 4. The water and water vapor flow model of van Keulen (1975) has been modified and added to the original heat flow model.

Evaporation was already taken into account in the previous model; conversion from water content to humidity ratio at the soil surface is still needed. First, using eq. 8.2, the depression factor (**DF**) is calculated as

$$\mathbf{DF} = \mathbf{P} / \mathbf{P0} = \mathbf{exp(SS * GRV / (RC * AT))} \quad (8.9)$$

The humidity ratio at the soil surface (**WF**, kg/kg DA) is

$$\mathbf{WF} = 0.622 * \mathbf{VPMF} / (1.0\text{E}5 - \mathbf{VPMF}) \tag{8.10}$$

where **VPMF** is vapor pressure and is calculated by **PWSF*DF**, and **PWSF** is saturated vapor pressure (Pa).

The relationships listed in eqs. 8.1 - 8.10 are introduced into the model of **CUC03.** The basic structure of the model consists of five differential equations for temperature (**TF** – **T4**) and five equations for volumetric water content (**WWF** – **WW4**). Analogous to heat balance, water balance is given as

$$d\mathbf{WW} / d\mathbf{t} = (\mathbf{FLR} + \mathbf{WVF}) / d\mathbf{z} \tag{8.11}$$

The water balance expression for the surface layer is as follows:

$$\mathbf{I\_WW}_{\mathrm{F}} = (\mathbf{FLR_F} - \mathbf{FLR_1} + \mathbf{WVF_F} - \mathbf{WVF_1}) / \mathbf{Z0} \tag{8.12}$$

where **WWF** is the water content in the surface layer, and it is the integration of water flow gradient **($\mathbf{FLR_F}$ - $\mathbf{FLR_1}$) / Z0** and vapor flow gradient **($\mathbf{WVF_F}$ - $\mathbf{WVF_1}$) / Z0**. The suffix **F** is for the surface layer, and the suffix 1 is for the first layer under the surface layer.

Hydraulic conductivity (**KT**) is a function of water content; thus it would be better to take the average of two adjacent layers. For example, $\mathbf{KT_1}$ is calculated as follows :

$$(\mathbf{WW_F} * \mathbf{AFGEN\_KTB}(\mathbf{WW_F}) + \mathbf{WW_1} * \mathbf{AFGEN\_KTB}(\mathbf{WW_1})) / (\mathbf{WW_F} + \mathbf{WW_1}) \tag{8.13}$$

In a similar way, water vapor diffusivity of the first layer ($\mathbf{DWV_1}$) is averaged:

$$(\mathbf{Z0} * \mathbf{AFGEN\_WVDT}(\mathbf{WW_F}) + \mathbf{Z1} * \mathbf{AFGEN\_WVDT}(\mathbf{WW_1})) / (\mathbf{Z0} + \mathbf{Z1}) \tag{8.14}$$

During the execution, a progress report will be displayed in the Command Window showing ‘Progress: xx.xx out of 48 hours’ which means it is now at the xx.xx simulated time out of the total 48 hours simulated times. Due to the complexity of the model (solving 10 simultaneous differential equations) which can involve rapid changes of the values, execution with large calculation intervals may not be able to converge, thus leading to a long execution time for this model. The execution time is the longest among all models in this book.

An improvement was made in the program to accelerate the execution of the program by using options= **odeset**('**RelTol**',0.005) and **ode15s**(….., options) functions. The **odeset** function allows users to create/alter the **ode** options structure and the ‘**RelTol**’ stands for relative error tolerance. The estimated error in each integration step satisfies e(i) <= max(**RelTol*abs**(**y**(i)), **AbsTol**(i)), where, ‘**y**(i)’ is the i th unknown variable involved in solving the **ode** function, and ‘**AbsTol**’ stands for absolute error tolerance and defaults to 1e-6. The default value of ‘**RelTol**’ of the **ode** function in **MATLAB** is 0.001. The larger the ‘**RelTol**’ value, the shorter the execution time required. The current value of 0.005 was decided based on trial and error. The model will not converge if the value is increased to 0.01.

Two figures will be generated by the **CUC90** model. The first figure (not shown) displays the temperature regimes in the soil layers and is similar to the output of the **CUC03** model. The second figure, shown in Fig. 8.4, is the water content in the soil layers. As shown in the figure, the effect of the initial condition remains at first, but soon the water content drops in all soil layers. Water content begins to increase in the early part of the morning because the humidity ratio of the air is greater than that in the soil surface layer and water vapor flows from the air to the soil surface. After sunrise, the water content in all soil layers drops rapidly, and most dramatically in the upper layers. Water content is recovered in the nighttime mainly due to condensation at the soil surface, as indicated in Fig. 8.4. Dew-point temperature at night is higher than the soil surface temperature, and this causes condensation. The soil surface does not recover to the original water content level, however, and the water content in each soil layer gradually decreases with the passage of time.

```
% Program to calculate temperature                                  CUC90.m
%          and water regimes in the soil layer
% function required: soil90.m
%
clear all; clc
t0=0;tfinal=48;
y0=[10;10;10;10;10;0.3;0.31;0.33;0.34;0.35];
%  TF T1 T2 T3 T4 WWF  WW1  WW2  WW3  WW4
options = odeset('RelTol',0.005);
[t,y]=ode15s('soil90',[t0 tfinal],y0,options);
%--------------------------------------------------------------------------
h1=findobj('tag','cuc90_part1');   close(h1);
figure('tag','cuc90_part1','Resize','on','MenuBar','none',...
  'Name','CUC90.m (Figure 1: Soil temperature regimes in soil layers)',...
  'NumberTitle','off','Position',[160,80,520,420]);
plot (t,y(:,1),'r+-',t,y(:,2),'b^:',t,y(:,3),'k*-',t,y(:,4),'ko-',...
   t,y(:,5),'k-','linewidth',2);
grid on;
xlabel('time  elapsed, hr');   ylabel('Temperature, ^oC');
legend('T_f','T_1','T_2','T_3','T_4',2);
%--------------------------------------------------------------------------
h1=findobj('tag','cuc90_part2');   close(h1);
figure('tag','cuc90_part2','Resize','on','MenuBar','none',...
  'Name','CUC90.m (Figure 2: Water contents regimes in soil layers)',...
  'NumberTitle','off','Position',[200,40,520,420]);
plot (t,y(:,6),'r+-',t,y(:,7),'b^:',t,y(:,8),'k*-',t,y(:,9),'ko-',...
   t,y(:,10),'k-','linewidth',2);
grid on;
legend('WWF','WW1','WW2','WW3','WW4',1);
xlabel('time  elapsed, hr');  ylabel('Water content, m^3/m^3');
fprintf('\n\n');
disp('  You can enter ''close all'' to close figure windows.');
```

Figure 8.3a. Main program to calculate water regime in soil **(CUC90.m)**.

```
% Functions used in CUC90 model.                              soil90.m
%  Including:
%    soil90, tabs, solar, WPCH, FWSP, AFGEN_KTB, AFGEN_STB, AFGEN_WVDT
%
function dy = soil90(t,y)
Tavg=10.0; TU=5.0; TBL=10.0; TD=4.5;RP=2000;
KS = 5.5; CS= 2.0E+3; RHO=1.164;QH=36;HS= 25.2;SIG = 20.4;
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.1;
ALF=0.7; EPSF=0.95; HLG=2501.0;LE=0.9;
KM=HS/LE;
[PD,WO]=FWSP(TD);
EPSA=0.711+(TD/100)*(0.56+0.73*(TD/100));
%----------------------------------------------------------------------
%        Brief Description of constants
%----------------------------------------------------------------------
% RHO:   Density of air (kg/m^3)
% TD:    Outside dew point temperature, in degree C
% KS:    in(kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m^3/C)
% QH:    ventilation air flow rate (m^3/m^2/hr), 8 cfm/ft^2 = 146 m/hr
% HS:    Convective heat transfer coefficient
% SIG:   Stefan-Boltzmann constant (kJ/m^2/K^4/hr) = 5.67(W/m^2/K^4)
% Z0-Z4: Depths of soil layer (m)
% ALF:   Absorptivity of solar radiation at soil surface
% EPSF:  Emissivity of soil surface
% HLG:   Latent heat
% EPSA:  Emissivity of air layer
%----------------------------------------------------------------------
%        Brief Description of parameters
%----------------------------------------------------------------------
% DFF,   DF1,...,DF5 :        Depression Factor
% VPMF,  VPM1,..,VPM5:        Vapor Pressure, in Pa
% PWSF,  PWS1,..,PWS5:        Saturated Vapor Pressure, in Pa
% PWSMF, PWSM1,.,PWSM5:       Saturated Vapor Pressure, in mbar
% WWWF,  WWW1,..,WWW5:        Absolute humidity
% SSF,   SS1,...,SS5:         Water potential
% TF,    T1,....,T5:          Temperature, in degree C
% FLRF,  FLR1,..,FLR5:        Water flow rate
% WVFF,  WVF1,..,WVF5:        Vapor flow rate
% WWF,   WW1,...,WW5:         Water content
% VPCF,  VPC1,..,VPC5:        Water vapor concentration
% DWV1,   ,..,DWV5:           Water vapor diffusivity, in m^2/hr
% Function of water content (WW1-5) and is averaged.
%----------------------------------------------------------------------
clc;
fprintf('Progress: %f out of 48 hrs\n',t);   %  Display  the  execution
progress
clk = mod(t,24);                     % Time (hr)
OMEGA=2*pi/24;                       % converter
TO= Tavg+TU*sin(OMEGA*(clk-8));      % TO is outdoor air temperature
RAD=solar(RP,OMEGA,clk);             % Calling function solar()
%-------------------------------------------------[Surface layer]------
TF=y(1);  T1=y(2);  T2=y(3);  T3=y(4);  T4=y(5);
WWF=y(6); WW1=y(7); WW2=y(8); WW3=y(9); WW4=y(10);
[PWSF,WWWF]=FWSP(TF);
TERF=WWF*AFGEN_KTB(WWF)/2400;
TER1=WW1*AFGEN_KTB(WW1)/2400;
% AFGEN_KTB: Hydraulic conductivity KTB (cm/day)
%   is a function of water content (WWF-5)
%   and is averaged between adjacent two layers.
% Water flow is a function of water potential difference (SSF-5) and gravity.
SSF=-1/100*AFGEN_STB(WWF);
```

```
DFF=WPCH(TF,SSF);
VPMF=PWSF*DFF; % DFF is ratio of vapor pressure and saturated vapor pressure
WF=WWWF*DFF;
% Assuming DFF equals ratio of absolute humidity and saturated absolute
humidity
%WF=0.622*VPMF/(1.e5-VPMF);   another way to calculate WF (this is eq.8.10)
TO4=tabs(TO);  % calling function TABS()
TF4=tabs(TF);
FLRF=0;           % assuming no irrigation
SS1=-1/100*AFGEN_STB(WW1);
FLR1=(TERF+TER1)/(WWF+WW1)*((SSF-SS1)*2/(Z0+Z1)+1);
VPCF=1.3411/1000/(273+TF)*VPMF;
[PWS1,WWW1]=FWSP(T1);
PWSM1=PWS1*0.01;
DF1=WPCH(T1,SS1);
VPM1=PWSM1*DF1;
VPC1=1.3411/1000/(273+T1)*VPM1;
DWV1=(Z0*AFGEN_WVDT(WWF)+Z1*AFGEN_WVDT(WW1))/(Z0+Z1)*3.6;
I_TF=(ALF*RAD+EPSF*SIG*(EPSA*TO4-TF4)+HS*(TO-TF)+HLG*KM*(WO-WF)+...
   KS*(T1-TF)*2/(Z0+Z1))/CS/Z0;                              % 1st eq.
WVFF=-KM*(WF-WO);
WVF1=DWV1*(VPCF-VPC1)*2/(Z0+Z1);
I_WWF=(FLRF-FLR1+WVFF-WVF1)/Z0;                              % 2nd eq.
%------------------------------------------------------[First layer]----
I_T1=(KS*(TF-T1)*2/(Z0+Z1)+KS*(T2-T1)*2/(Z1+Z2))/CS/Z1;      % 3rd eq.
SS2=-1/100*AFGEN_STB(WW2);
TER2=WW2*AFGEN_KTB(WW2)/2400;
FLR2=(TER1+TER2)/(WW1+WW2)*((SS1-SS2)*2/(Z1+Z2)+1);
[PWS2,WWW2]=FWSP(T2);
PWSM2=PWS2/100;
DF2=WPCH(T2,SS2);
VPM2=PWSM2*DF2;
VPC2=1.3411/1000/(273+T2)*VPM2;
DWV2=(Z1*AFGEN_WVDT(WW1)+Z2*AFGEN_WVDT(WW2))/(Z1+Z2)*3.6;
WVF2=DWV2*(VPC1-VPC2)*2/(Z1+Z2);
I_WW1=(FLR1-FLR2+WVF1-WVF2)/Z1;                              % 4th eq.
%----------------------------------------------------[2nd layer]--------
I_T2=(KS*(T1-T2)*2/(Z1+Z2)+KS*(T3-T2)*2/(Z2+Z3))/CS/Z2;      % 5th eq.
SS3=-1/100*AFGEN_STB(WW3);
TER3=WW3*AFGEN_KTB(WW3)/2400;
FLR3=(TER2+TER3)/(WW2+WW3)*((SS2-SS3)*2/(Z2+Z3)+1);
[PWS3,WWW3]=FWSP(T3);
PWSM3=PWS3/100;
DF3=WPCH(T3,SS3);
VPM3=PWSM3*DF3;
VPC3=1.3411/1000/(273+T3)*VPM3;
DWV3=(Z2*AFGEN_WVDT(WW2)+Z3*AFGEN_WVDT(WW3))/(Z2+Z3)*3.6;
WVF3=DWV3*(VPC2-VPC3)*2/(Z2+Z3);
I_WW2=(FLR2-FLR3+WVF2-WVF3)/Z2;                              % 6th eq.
%----------------------------------------------------[3rd layer]--------
I_T3=(KS*(T2-T3)*2/(Z2+Z3)+KS*(T4-T3)*2/(Z3+Z4))/CS/Z3;      % 7th eq.
SS4=-1/100*AFGEN_STB(WW4);
TER4=WW4*AFGEN_KTB(WW4)/2400;
FLR4=(TER3+TER4)/(WW3+WW4)*((SS3-SS4)*2/(Z3+Z4)+1);
[PWS4,WWW4]=FWSP(T4);
PWSM4=PWS4/100;
DF4=WPCH(T4,SS4);
VPM4=PWSM4*DF4;
VPC4=1.3411/1000/(273+T4)*VPM4;
DWV4=(Z3*AFGEN_WVDT(WW3)+Z4*AFGEN_WVDT(WW4))/(Z3+Z4)*3.6;
WVF4=DWV4*(VPC3-VPC4)*2/(Z3+Z4);
```

```
I_WW3=(FLR3-FLR4+WVF3-WVF4)/Z3;                              % 8th eq.
%---------------------------------------------------[4th layer]--------
I_T4=(KS*(T3-T4)*2/(Z3+Z4)+KS*(TBL-T4)*2/Z4)/CS/Z4;         % 9th eq.
SS5=0;
TER4=WW4*AFGEN_KTB(WW4)/2400;
WSAT=0.35;
KSAT=AFGEN_KTB(WSAT)/2400;
KA5=(WW4*AFGEN_KTB(WW4)/2400+KSAT*WSAT)/(WW4+WSAT);
WTB=-1; % Assumed there is no water table.
% parameter for water table, if positive there is water table
%                      and if negative FLR5=0
if WTB<0;
  FLR5=0;
else
  FLR5=KA5*(SS4-SS5)*2/Z4;
end
WVF5=0;
I_WW4=(FLR4-FLR5+WVF4-WVF5)/Z4;                             % 10th eq.
%---------------------------------------------------------------------
dy=[I_TF;I_T1;I_T2;I_T3;I_T4;I_WWF;I_WW1;I_WW2;I_WW3;I_WW4];
return
%---------------------------------------------------------------------
function ktb_value=AFGEN_KTB(WW)
xtemp=[0.001 0.01 0.05 0.075 0.1 0.125 0.15 0.175 0.2 0.225 0.25 0.275 0.3 0.325
0.35];
ytemp=[1.e-8 1.e-7 2.5e-6 5e-5 5e-3 0.07 0.15 0.26 0.65 1 1.5 2.2 3.2 5
10];
ktb_value=interp1(xtemp,ytemp,WW,'linear');
%---------------------------------------------------------------------
function stb_value=AFGEN_STB(WW)
xtemp=[0.001 0.01 0.025 0.05 0.075 0.1 0.125 0.15 0.175 0.2 0.225 0.25 0.275 0.3 0.325 0.3325 0.35 1.35];
ytemp=[1.e9 1.e7 2.5e6 2.e5 1.475e3 365 265 230 215 190 182 170 158 151 126 60 0
-600];
stb_value=interp1(xtemp,ytemp,WW,'linear');
%---------------------------------------------------------------------
function wvdt_value=AFGEN_WVDT(WW)
xtemp=[0.01 0.05 0.1 0.2 0.35 0.4];
ytemp=[2.89e-8 2.55e-8 2.46e-8 9.84e-9 8.68e-11 1.e-11];
wvdt_value=interp1(xtemp,ytemp,WW,'linear');
%---------------------------------------------------------------------
function DF=WPCH(TTT,SSS)
GRV=9.8;   % Gravity (m/s^2)
RC=461.5;  % Gas constant (J/kg/k) and m^2/s^2=J/kg
AAA=SSS*GRV/(RC*(TTT+273));
DF=exp(AAA);
%---------------------------------------------------------------------
function [PWS, WWW]=FWSP(TTT)
Patm=101325; % Patm: assuming at sea level, in Pa, 1 atmosphere is 0.1
MPa
TQQ=TTT+273.16;
T10=TQQ/100.0;
if TTT>0
A=-5800.2206/TQQ+1.3914993-0.04860239*TQQ;
B=0.41764768*T10*T10-0.014452093*T10*T10*T10;
C=6.5459673*log(TQQ);
else
A=-5674.5359/TQQ+6.3925247-0.9677843*T10;
B=0.62215701E-2*T10*T10+0.20747825E-2*T10*T10*T10;
C=-0.9484024E-4*T10*T10*T10*T10+4.1635019*log(TQQ);
end
BETA=A + B + C;
```

```
PWS=exp(BETA);
WWW=0.622*PWS/(Patm-PWS);
%----------------------------------------------------------------------
function TT4 = tabs(TT)
     TAA = (TT+273.16)/100.0;      TT4 = TAA*TAA*TAA*TAA;
%----------------------------------------------------------------------
function rad = solar(RP,OMEGA,clk)
%    Calculation of solar radiation: RAD
%    Sunrise is 6 o'clock
     rad= RP*sin(OMEGA*(clk-6.0));
     if rad<=0,    rad=0;     end
```

Figure 8.3b. Functions used in ***CUC90*** *model* **(soil90.m)**.

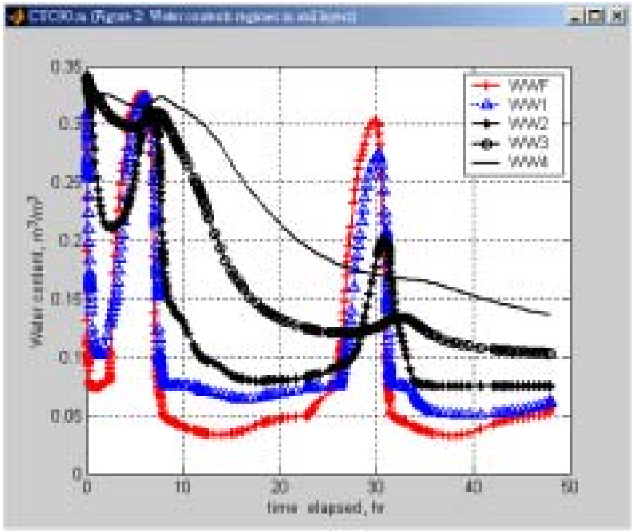

Figure 8.4. Water content in soil layers.

8.4. INTERACTION BETWEEN WATER MOVEMENT AND HEAT FLOW

Interactions of heat and moisture flow have been investigated in many researches. It was concluded that where temperature gradients are important, such as near the soil surface, simultaneous heat and mass transfer analyses gives a better fit with the experimental data than the isothermal diffusion equation (see Hillel, 1980). Simultaneous equations for analyzing non-isothermal transfer of vapor and liquid water under combined temperature and moisture gradients are offered by Philip and de Vries (in Hillel, 1980) in the following way:

$$\mathbf{FLR} + \mathbf{WVF} = -\mathbf{DWD} * d\mathbf{T}/d\mathbf{z} - (\mathbf{KT} + \mathbf{DWV}) * d\mathbf{WW} / d\mathbf{z} - \mathbf{KT} \qquad (8.15)$$

$$\mathbf{HFL} = -\mathbf{KS} * d\mathbf{T}/d\mathbf{z} - \mathbf{HLG} * \mathbf{DWV} * d\mathbf{WW} / d\mathbf{z} \qquad (8.16)$$

where the downward flow is taken as positive in both equations and newly introduced symbols are thermal water diffusivity **DWD**, and heat flow rate **HFL**. The analysis is beyond the scope of the present book.

Another mass flow in the soil layer is salt or ion movement. Ion movement is not covered in the present book, but it would not be difficult to expand the models in this book for these purposes.

MATLAB FUNCTIONS USED

odeset Create/alter ODE OPTIONS structure. With no input arguments, **odeset** displays all property names and their possible values.

OPTIONS = ODESET('NAME1',VALUE1,'NAME2',VALUE2,...) creates an integrator options structure OPTIONS in which the named properties have the specified values. Any unspecified properties have default values. The properties involved in this chapter are as follows:

- RelTol - Relative error tolerance. This scalar applies to all components of the solution vector, and defaults to 1e-3 (0.1% accuracy) in all solvers. The estimated error in each integration step satisfies
  e(i) <= max (RelTol*abs(y(i)),AbsTol(i)).
- AbsTol - Absolute error tolerance. A scalar tolerance applies to all components of the solution vector. Elements of a vector of tolerances apply to corresponding components of the solution vector. AbsTol defaults to 1e-6 in all solvers.

PROBLEMS

1. Calculate the water potential of the air if the relative humidity is 75%, and compare order of the magnitude with that of soil under normal conditions.

2. Explain the physical meaning of the statement for calculating **FLR5** in the program of **CUC90**.

3. Explain why eq. 8.13 uses **WW** (water content) as the weighing factor and eq. 8.14 uses **Z** (depth of the soil layer) as the weighing factor?

4. **INTERP1** is the function of 1-D interpolation of **MATLAB**. There are several methods available in this function, such as 'linear', 'nearest', 'cubic', 'spline' and 'pchip'. Use **function ktb_value=AFGEN_KTB(WW)**, listed in Fig. 8.3b, as an example, and write a **MATLAB** program to plot the differences of these methods.

5. **DFF** is the ratio of vapor pressure to saturated vapor pressure. As listed in Fig. 8.3b, **DFF** is used to calculate **WF** using the scripts of '**WF = WWWF * DFF;**' and assuming **DFF** is also the ratio of absolute humidity (kg/kg DA) of vapor to absolute humidity of saturated vapor. Is there any difference if we change the script to '**WF = 0.622 * VPMF / (1.e5 - VPMF);**'?