Journal of Hydroscience and Hydraulic Engineering
Vol. 22, No.1 May, 2004, 81-98

MEASUREMENT OF WATER AND NUTRIENT CONSUMPTION DURING PLANT GROWTH USING A WEIGHING LYSIMETER AND NUMERICAL MODELING

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SYNOPSIS

This paper describes the consumption of water and nutrients by plants. Water and solute balance measurements were carried out for a crop of corn using a weighing lysimeter. Sap flow was measured by means of the stem heat balance method, and the nutrient absorption rate was determined using a hydroponics culture. The observed results indicate that 192-389kg of water, 13.1-20.8g of nitrogen (N), 1.9-12.3g of phosphorus (P) and 8.0-18.0g of potassium (K) are consumed in producing 1kg of dry corn, and that changes in evapotranspiration and nutrient absorption caused by plant growth are found to be evident. A model of water and nutrient transport in the surface soil layer during plant growth is discussed and proposed. The calculated results of the evapotranspiration, the nitrogen absorption by the plants and the nitrogen concentration in the groundwater runoff are in close agreement with each of the observed results.

INTRODUCTION

Groundwater pollution due to an excess of fertilizers and manure has become a serious problem in many regions, and effective groundwater management is becoming more important. To prevent groundwater pollution, an accurate estimate of the amount of water and nutrient consumption by crops is needed.

Water and nutrient uptake by plant roots is affected by several conditions such as plant growth, meteorology, soil moisture content and solute concentration. Water and nutrient uptake by plants has not been evaluated well, because a direct measurement of nutrient absorption by plants grown in the field is difficult.

In this study, water and solute balance measurements were made for corns using a weighing lysimeter (**Photo 1**) at the location of 135° 47' E, 34° 52' N in southern Kyoto. Consumption of water and nutrients during plant growth is measured under natural weather conditions.

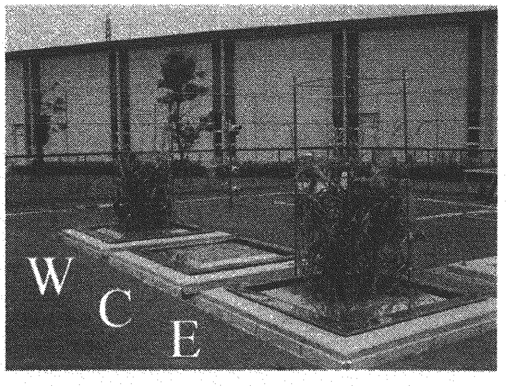

Photo 1 Weighing Lysimeter (July 5, 2001)

To assess evapotranspiration during plant growth, sap flow, which is considered to be equivalent to transpiration, is measured by the stem heat balance method (SHB). A model for estimating evapotranspiration considered plant growth, meteorological conditions and soil moisture content is proposed using the sap flow and the evapotranspiration observed in the lysimeter. The proposed model is applied to the estimation of evapotranspiration during corn growth in the lysimeter.

Measurements of nutrient absorption rate by corn plants grown in hydroponics culture were carried out under the same weather condition as the lysimeter, and changes in the nutrient-absorption characteristics caused by the plant growth are discussed. A numerical simulation model of water and nitrogen transport in soil is constructed using the relationships between the corn growth and the nitrogen absorption rate obtained from the measurement results, and is applied to the lysimeter.

WATER AND SOLUTE BALANCE MEASUREMENTS DURING PLANT GROWTH

Weighing Lysimeter

The weighing lysimeter (**Photo 1**) is composed of three soil tanks, each 1.0 m wide, 1.0 m long and 1.5 m deep (**Fig. 1**). The front, center and back soil tanks shown in **Photo 1** are labeled E, C and W, respectively. Each soil tank was filled with a sandy soil (0.0-1.3m below the ground surface) and gravel (1.3-1.5m). Unsaturated characteristic curves of the sandy soil are shown in **Fig. 2** (8). The weight of each soil tank was measured using an electronic balance with a resolution of 0.1 kg (= 0.1 mm rainfall). The surface runoff and the groundwater runoff were measured utilizing the flow rate gauge of a tipping buckets type. The soil moisture content was measured at depths of 10, 20, 30, 40, 60, and 100 cm below the ground surface in each tank using amplitude domain reflectometry (ADR) probes. Meteorological measurements were made adjacent to the lysimeter. The instruments used for measurement and the performances of each are listed in **Table 1**.

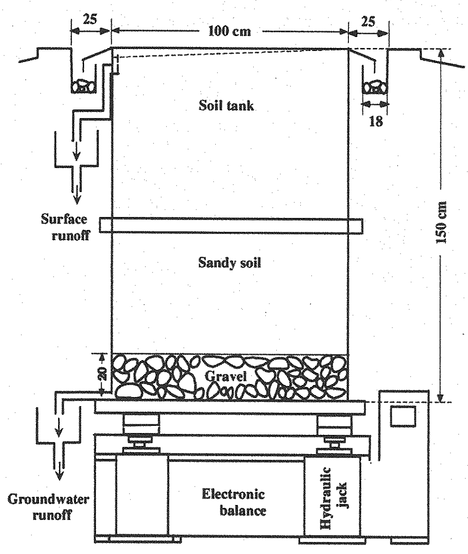

Fig.1 Schematic of soil tank

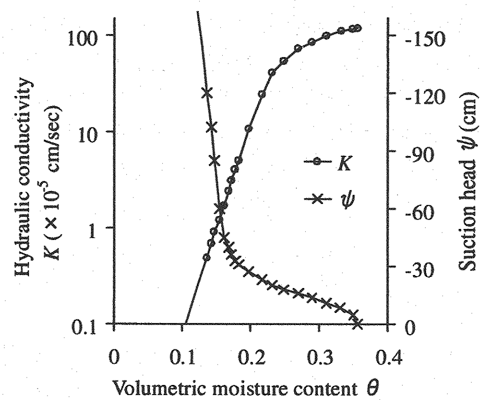

Fig. 2 Unsaturated characteristic curves (8)

Table 1 Meteorological Instruments

Element	Instrument	Resolution / Performance	Notes
Rainfall rate	Tipping bucket rainfall gauge	0.5mm per 1 tipping	
Net radiation	Net radiometer	35mV $kW^{-1} m^{-2}$	
Solar radiation	Pyranometers	7mV $kW^{-1} m^{-2}$	
Air temperature and vapor pressure	Platinum resistance psychrometer	±0 5 K	1.80, 0.90, 0.45m above the ground surface
Wind velocity	Cup anemometer	0〜75m/s	1.85, 0.95, 0.50m above the ground surface
Soil temperature	Platinum resistance thermometer	-10〜70℃	5, 15, 25cm below the ground surface
Soil heat flux	Heat flow sensor	20mV $kW^{-1} m^{-2}$	5, 15, 25cm below the ground surface
Evaporation	Class A pan (Diameter 120cm)	±1 mm	

Water Balance

From May 3 to July 9 in 2001, water and solute balance measurements were carried out with a crop of corn (9 plant/m^2) in tanks E and W, and with tank C remaining barren. Measurement results are given in **Table 2.** Evapotranspiration from the planted tanks was found to be 2.1 to 2.2 times that of the barren tank, demonstrating that the presence of plants significantly affects the water balance.

From June 10 to August 14 in 2002, water and solute balance measurements were made for a crop of corn in soil tank E (9 plant/m^2), C (5 plant/m^2), and W (9 plant/m^2). The growth of the corns in soil tank W was stopped due to shortages in water. The observed results in soil tank E and C are also shown in **Table 2.** These results also indicate that the consumption of water by the corn corresponds to 192 to 389 times the dry weight of the corn, and 988 to 3305 times the dry weight of the caryopses.

Table 2 Water Balance

		May 3～Jul. 9, 2001			Jun.10～Aug. 14, 2002	
Soil tank		E	W	C	E	C
Crop density	(plant / m^2)	9	9	0	9	5
Weight of corns	(kg)	8.60	8.66	-	5.32	3.02
Dry weight of corns	(kg)	1.54	1.54	-	1.27	0.68
Dry weight of caryopses	(kg)	0.30	0.31	-	0.20	0.08
Rainfall	(mm)	295.0	295.0	295.0	269.0	269.0
Irrigation	(mm)	75.0	75.0	75.0	140.0	140.0
Surface runoff	(mm)	51.9	50.8	145.9	47.1	102.8
Groundwater runoff	(mm)	72.4	61.6	86.5	42.3	40.1
Soil storage	(mm)	-50.7	-54.3	-11.6	-55.1	-12.6
Evapotranspiration, etc.	(mm)	296.4	311.9	149.3	374.7	278.7

Solute Balance

Fertilizer including nitrogen (N), phosphorus (P) and potassium (K) was supplied to the soil tanks. Solute concentrations (Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, $H_2PO_4^-$, F^-, Cl^-, NO_3^- and SO_4^{2-}) in the surface and the groundwater runoff were periodically measured by ion chromatography (PIA-1000, Shimazu Co., Kyoto, Japan). Storage of total N and total P in the corn plants grown in the lysimeter were determined by means of the moist decomposition method (3), and that of K was measured by diluted acid extraction. Storage of nutrients in the soil was determined from the difference between the amount of nutrient in the soil before fertilizing and after harvest. The amount of nutrient was measured by the following method. Ten soil samples at each 10cm depth interval to 100cm below the ground surface were taken. Cations and anions included in the soil samples were

Table 3 Solute Balance

	May 3-Jul. 9, 2001			Jun. 10-Aug. 14, 2002					
	W			E			C		
Crop density (plant / m^2)	9			9			5		
Dry weight of corns (kg)	1.54			1.27			0.68		
	N	P	K	N	P	K	N	P	K
Supplied fertilizer (g)	30.0	63.9	30.0	13.6	10.0	11.2	13.6	10.0	11.2
Absorption by corns (g)	32.0	19.0	28.9	16.7	2.4	10.1	9.0	2.8	5.8
Storage in soil (g)	-	-	-	0.7	11.1	2.0	4.4	2.7	11.7
Solute drawn with groundwater runoff (g)	-	-	-	0.4	0.4	0.1	0.2	0.1	0.1
Residual, etc. (g)	-	-	-	-4.2	-3.9	-1.0	0.0	4.5	-6.4

extracted with 0.1mol/liter HCl and 0.001mol/liter NaOH solution (4). Cation and anion concentrations in each extract solution were measured by the ion chromatography.

Measurements of the solute balance in the soil tanks are given in **Table 3**. The solute discharge with surface runoff is not shown in **Table 3** due to fact that it is negligible. The corn plants absorbed most of N and K, but more than 76% of P remained in soil tank E in 2002. **Table 3** indicates that 13.1-20.8g of N, 1.9-12.3g of P and 8.0-18.0g of K are consumed in producing 1kg of dry weight of the corns.

Plant Growth Measurement

Plant growth was measured to determine evapotranspiration and nutrient absorption. In this study, 120 corn plants were grown in a field located adjacent to the lysimeter. Two or three crops of similar scales in terms of height, number of leaves and ears of corn, were periodically sampled. Leaf area, height, dry weight, stem diameter and root depth were measured.

Measurements of (a) dry weight, (b) crop height and (c) leaf area for the periods May 3 to July 9 in 2001 and June 10 to August 14 in 2002 are given in **Fig. 3**. Here the time is set to 0 days on May 3 in 2001 / June 10 in 2002. The results observed by Kimball in 1965 (5) are also shown in **Fig. 3** (a). The dry weight measured in 2001 and 2002 agree with the results observed by Kimball. The height and the leaf area measured in 2001 are similar to each other in 2002.

The increase of the dry weight, the crop height and the leaf area can be expressed by a logistic growth curve (5), given as

$$\frac{M}{M_e}=\left\{1+\left(\frac{M_e}{M_0}-1\right)\exp(-rt)\right\}^{-1} \qquad (1)$$

where M = the index of plant growth such as dry weight (w), the crop height (h), the leaf area (A); M_e = the maximum value of M; t = the time; r = the growth rate; and M_0 = the value of M at t = 0. The results calculated using **Eq. 1** are also shown in **Fig 3**(a) (b) (c). The optimum values of r and M_0 determined by the least square error method are found to be 0.12 day^{-1} and 0.02M_e for the dry weight, 0.12 day^{-1} and 0.08M_e for the crop height, 0.12day^{-1} and 0.06M_e for the leaf area, respectively.

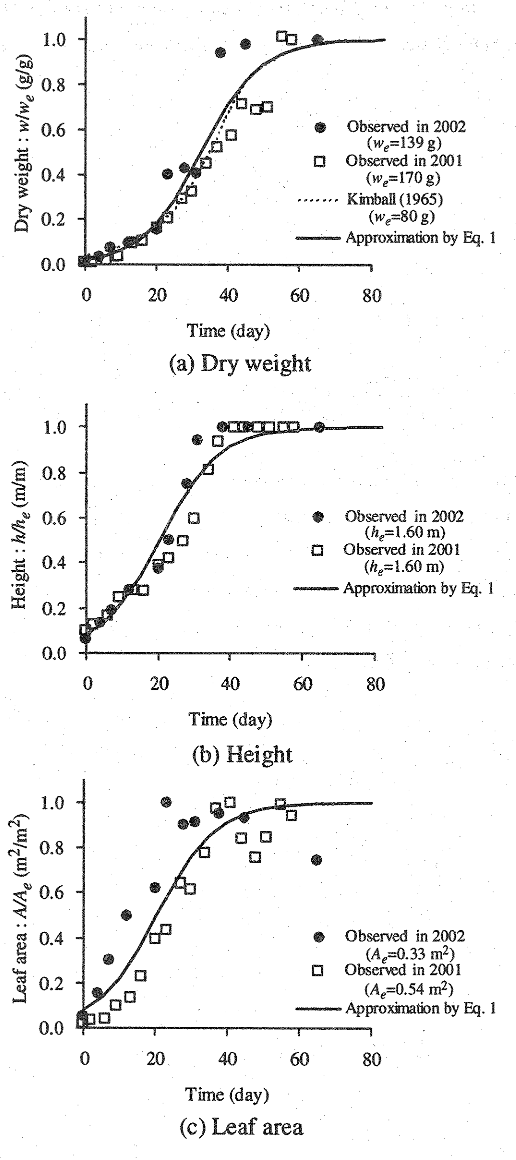

Fig. 3 Growth curves of a corn

Sap Flow Measurement

Sap flow provides useful information regarding transpiration. In this study, the stem heat balance (SHB) method (11) was employed for measuring sap flow thorough intact plant stems. The measurement apparatus for the SHB system (**Photo 2**) consists of a heater and 6 thermisters (**Fig. 4**).

In performing the measurement, a constant heat flux Q was applied to a segment of a plant stem by using an external annular heater. Under steady state conditions, the heat balance for the segment is expressed as

$$Q = q_f + q_u + q_d + q_r \tag{2}$$

$$q_f = c_w F(T_b - T_c) \tag{3}$$

$$q_u = \lambda A_s \frac{T_b - T_a}{\Delta x} \tag{4}$$

$$q_d = \lambda A_s \frac{T_c - T_d}{\Delta x} \tag{5}$$

$$q_r = \frac{2\pi\lambda_s L(T_e - T_f)}{\ln(r_2 / r_1)} = k(T_e - T_f) \tag{6}$$

where q_f = the energy transported by sap flow from the heated segment; q_u, q_d = the upward and downward energy transfer rates due to thermal conduction along the stem; q_r = the rate of radial energy loss; F = the sap flow rate; c_w = the specific heat capacity of water; $T_{a\sim f}$ = the temperatures at the points indicated in **Fig. 4**; A_s = the stem cross-sectional area; λ, λ_s = the thermal conductivities of the stem and the sheath material; L = the length of the heat segment; and Δx, r_1, r_2 = the distances given in **Fig. 4**, $k = 2\pi\lambda_s L/\ln(r_2/r_1)$ = the constant. The equation for the sap flow rate F in the plant stem obtained from **Eqs.2-6** is

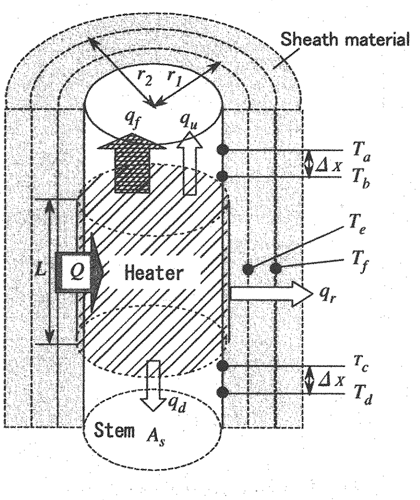

Fig. 4 Schematic of the apparatus used for SHB

Photo 2 Sap flow measurement by SHB

$$F = \frac{Q - \lambda A_s (T_b - T_a + T_c - T_d)/\Delta x - k(T_e - T_f)}{c_w (T_b - T_c)} \qquad (7)$$

Sap flow measurements were carried out during the periods, June 2-3, June 16-18 in 2001, June 26-28 and July 20-25 in 2002. **Table 4** shows the measurement results of sap flow and evapotranspiration from the soil tank under cultivation conditions of 9 plant/m^2. The sap flow, considered to be equivalent to transpiration, is smaller than the evapotranspiration that consists of the transpiration and the evaporation from the soil surface. Evaporation ($E_{s\ obs.}$) from the soil surface determined from the difference between the evapotranspiration and the sap flow, the ratio of evaporation to evapotranspiration ($E_{s\ obs.}/ET_{obs.}$), and daily average of soil moisture content at 10cm deep in the soil tank are also shows in **Table 4.** The ratio ($E_{s\ obs.}/ET_{obs.}$) decreases with the decrease in the soil moisture content at 10cm deep, indicating that the influence of soil moisture content on the evaporation from the soil surface is greater than one on the transpiration.

Table 4 Observed and Calculated Evapotranspiration

		h	LAI	θ_{10}	$ET_{obs.}$	$E_{p\ obs.}$	$E_{s\ obs.}$	$E_{s\ obs.}/ET_{obs.}$	ET	E_p	E_s
2001	Jun. 2	0.90	3.0	0.12	6.8	5.4	1.4	0.20	6.7	5.5	1.2
	Jun. 3			0.10	6.3	6.3	0.0	0.00	5.9	5.6	0.3
	Jun. 16	1.60	4.3	0.14	7.8	6.2	1.6	0.20	7.1	5.7	1.4
	Jun. 17			0.12	8.2	7.2	1.0	0.12	7.9	7.0	0.9
	Jun. 18			0.10	6.1	6.1	0.0	0.00	6.3	6.1	0.2
2002	Jun. 26	0.65	1.7	0.15	3.2	1.6	1.6	0.50	2.6	1.3	1.3
	Jun. 27			0.14	2.6	1.4	1.2	0.46	2.4	1.4	1.0
	Jun. 28			0.12	5.5	4.0	1.5	0.26	4.5	2.7	1.7
	Jul. 20	1.60	2.8	0.15	8.6	6.7	1.9	0.22	9.7	7.4	2.3
	Jul. 21			0.14	10.1	8.0	2.1	0.21	11.1	8.9	2.3
	Jul. 22			0.12	8.9	7.9	1.0	0.11	8.7	7.5	1.2
	Jul. 23			0.11	9.2	8.0	1.2	0.14	7.4	6.6	0.8
	Jul. 24			0.10	9.2	8.3	0.9	0.10	7.7	7.2	0.5
	Jul. 25			0.10	6.2	5.7	0.4	0.07	8.8	8.5	0.3

h : Crop height (m), LAI : Leaf area index (m^2/m^2), θ_{10} : Soil moisture content at 10cm deep in Soil-tank W in 2001/ E in 2002, (m^3/m^3), $ET_{obs.}$: Observed evapotranspiration at Soil-tank W in 2001/ E in 2002 (mm/day), $E_{p\ obs.}$: Observed transpiration (= sap flow, mm/day), $E_{s\ obs.}$: Observed evaporation from soil surface (=$ET_{obs.}$-$E_{p\ obs.}$, mm/day), ET : Calculated evapotranspiration (=E_p+E_s, mm/day), E_p and E_s : Calculated transpiration and evaporation, respectively (mm/day)

A Model of Evapotranspiration during Plant Growth

Penman-Montieth equation is widely used to quantify evapotranspiration (6), and is given as

$$ET = \phi \left\{ \frac{\Delta}{\Delta + \gamma} \frac{R_n - G}{l} + \frac{\rho c_p (e_s - e)/r_a}{l(\Delta + \gamma)} \right\} \quad ; \quad \phi = \frac{\Delta + \gamma}{\Delta + \gamma(1 + r_c / r_a)} \qquad (8)$$

where Δ = the slope of the saturation vapor pressure curve; γ= the psychometric constant; R_n = the net radiation; G = the soil-heat flux; l = the latent heat of evaporation; e_s = the saturation vapor pressure; e = the vapor pressure; ρ = the density of dry air; c_p = the specific heat capacity of dry air; ϕ= the evapotranspiration coefficient; r_a = the aerodynamic resistance;

and r_c = the stomatal diffusion resistance.

r_a is expressed as

$$\frac{1}{r_a}=\frac{\kappa^2 u(z)}{\left[\ln\{(z-d)/z_0\}\right]^2} \tag{9}$$

where κ = von Karman's constant; u = the wind velocity; z = the height above soil surface; d = the zero plane displacement from soil surface; and z_0 = the roughness length. d and z_0 depend on the planted crops. **Equation 9** can be used only when exchanges of water vapor, heat, and momentum are governed by atmospheric turbulence, and the profiles of temperature, vapor pressure, and wind velocity are uniform above the crops.

r_c is often negligible under well-watered conditions. When $r_c = 0$ ($\phi = 1$), **Eq. 8** becomes

$$ET_0=\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{l}+\frac{\rho c_p(e_s-e)/r_a}{l(\Delta+\gamma)} \tag{10}$$

where ET_0 = evapotranspiration under well-watered conditions.

The second term on the right side of **Eq. 10** is often expressed by using an empirical equation called the wind function $f(u)$.

$$ET_0=\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{l}+\frac{\gamma}{\Delta+\gamma}f(u)(e_s-e) \tag{11}$$

The wind function is generally expressed as

$$f(u)=a+bu \tag{12}$$

or

$$f(u)=au^b \tag{13}$$

where a, b = empirical coefficients. **Equation 14** proposed by Penman (9) is widely used

$$f(u)=0.26(1+0.54u_2) \quad (\mathrm{mm\ day^{-1}\ hPa^{-1}}) \tag{14}$$

where u_2 = wind velocity at 2 m above the soil surface (m/s). Although **Eq. 14** is an empirical equation for estimating evapotranspiration from short grass under well-watered conditions, the results calculated using **Eqs. 11 and 14** agree well with the evapotranspiration from a well-watered field covered by low crops. However, it is well known that the evapotranspiration calculated by **Eqs. 11 and 14** is underestimated for a field covered by high crops because the crop conditions are not taken into consideration in **Eq. 14**.

When exchanges of water vapor, heat, and momentum are governed by atmospheric turbulence, and the profiles of temperature, vapor pressure, and wind velocity are uniform above the crops, **Eq. 15** can be obtained from a comparison of **Eq. 10** with **Eq. 11.**

$$f(u)=\frac{\rho c_p}{\gamma l r_a} \tag{15}$$

Combining **Eqs. 9 and 15** gives

$$f(u)=\frac{\rho c_p \kappa^2}{\gamma l}u(z)\frac{1}{\left[\ln\{(z-d)/z_0\}\right]^2} \tag{16}$$

From **Eq. 16**, plant growth and wind velocity affect the wind function because the crop condition changes in terms of d and z_0. In this study, it is assumed that the wind function is a function of wind velocity and crop height. Evapotranspiration under well-watered conditions (ET_0) can therefore be expressed as

$$ET_0=\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{l}+\frac{\gamma}{\Delta+\gamma}f(u,h)(e_s-e) \tag{17}$$

where h = plant height.

Evapotranspiration is the sum of transpiration and evaporation from the soil surface, is given as

$$ET_0=E_{p0}+E_{s0} \tag{18}$$

where E_{p0}, E_{s0} = the transpiration and evaporation from the soil surface under well-watered conditions. E_{s0} is given by

$$E_{s0}=\frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{l}\exp(-\alpha LAI) \tag{19}$$

where LAI = leaf area index; and α = the empirical coefficient (10). From **Eqs. 17-19**, E_{p0} is expressed as

$$E_{p0}=\frac{\Delta}{\Delta+\gamma}\frac{R-G}{l}\{1-\exp(-\alpha LAI)\}+\frac{\gamma}{\Delta+\gamma}f(u,h)(e_s-e) \tag{20}$$

It is widely recognized that evaporation and transpiration depend on the soil moisture content. The actual transpiration (E_p) and actual evaporation from the soil surface (E_s) are given as

$$E_s=\phi_s(\theta)E_{s0} \tag{21}$$
$$E_p=\phi_p(\theta)E_{p0} \tag{22}$$

where ϕ_s, ϕ_p = the evaporation and the transpiration coefficients (=0.0~1.0), respectively. Therefore, the actual evapotranspiration can be calculated using

$$ET=\phi_p E_{p0}+\phi_s E_{s0} \tag{23}$$

(1) *Relationship between Evaporation and Soil Moisture Content : ϕ_s*

The value of ϕ_s can be calculated by setting *LAI* to 0 in **Eq. 19** and using the resulting E_{s0} together with the value to the evaporation from the barren tank in **Eq. 21**. The relationship between ϕ_s and θ_{10} is shown in **Fig. 5** by means of the following approximation.

$$\phi_s(\theta_{10}) = \left[1+\exp\left\{-35\left(\frac{\theta_{10}-\theta_r}{\theta_s-\theta_r}\right)+11\right\}\right]^{-1} \qquad (24)$$

Here, θ_r = the residual soil moisture content (= 0.01); and θ_s = the saturated soil moisture content (= 0.36).

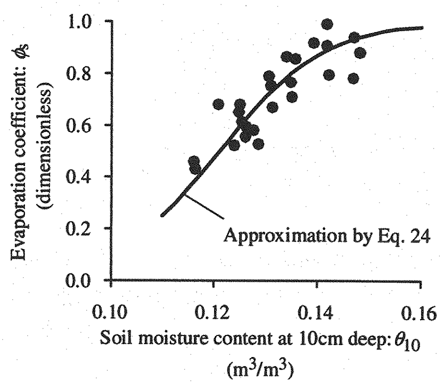

Fig. 5 Relationship between ϕ_s and θ_{10}

(2) *Influence of Leaf Area on Evaporation: α*

Evaporation from the soil surface when a crop is present ($E_{s\,obs.}$) can be calculated by determining the difference between the observed evapotranspiration ($ET_{obs.}$) and the sap flow ($E_{pobs.}$). $E_{s\,obs.}$, $ET_{obs.}$ and $E_{p\,obs.}$ are given in **Table 4.** The optimum value of α is found to be 0.16 from a comparison of $E_{s\,obs.}$ and the calculated evaporation E_s for the period June 16 to 18 using **Eqs. 19, 21 and 24**. The results for the other periods are also shown in **Table 4**. The calculated results for evaporation from the soil surface (E_s) are in close agreement with the observed evapotranspiration ($E_{s\,obs.}$).

(3) *Changes in Wind Function Caused by Plant Growth*

f (*u, h*) is expressed as follows from **Eqs. 20 and 22.**

$$f(u,h) = \frac{\Delta+\gamma}{\gamma(e_s-e)}\left[\frac{E_{p0}}{\phi_p} - \frac{\Delta}{\Delta+\gamma}\frac{R_n-G}{l}\{1-\exp(-\alpha LAI)\}\right] \qquad (25)$$

In this study, the value of ϕ_p on June 16 in 2001 and July 20-21 in 2002 is regarded as 1.0 because θ_{10} for these days are nearly the observed peak value. As a result, f (u, h = 1.60 m) can be calculated using **Eq. 25** and E_{p0} = $E_{p\,obs.}$ The relationship between f (u, h = 1.60 m) and the hourly average wind velocity at 1.85 m above the soil surface $u_{1.85}$ (m/s) when $(R_n - G) > 0$ and $(\Delta+\gamma)/\gamma(e_s - e) \le 1.0$ hPa^{-1} is shown in **Fig. 6**. The relationship between f (u, h = 1.60 m) and $u_{1.85}$ is better approximated by **Eq. 13** than **Eq. 12**. Using the empirical coefficients a and b determined by the least square error method gives

$$f(u,h=1.60m) = 0.13u_{1.85}^{0.59}\Big|_{h=1.60m} \quad (\text{mm hPa}^{-1}\ \text{h}^{-1}) \qquad (26)$$

f (u, h = 0.65 m) for July 20-25 in 2002 and f (u, h = 0.90 m) for June 2-3 in 2001 are investigated using ϕ_p, which is discussed latter.

$$f(u,h=0.90m) = 0.078u_{1.85}^{0.59}\Big|_{h=0.90m} \quad (\text{mm hPa}^{-1}\ \text{h}^{-1}) \qquad (27)$$

$$f(u,h=0.65m) = 0.060u_{1.85}^{0.61}\Big|_{h=0.65m} \quad (\text{mm hPa}^{-1}\ \text{h}^{-1}) \qquad (28)$$

Comparing **Eqs. 26-28**, the change in a is considerable, while b remains almost constant. It is considered that the value of a depends on corn growth. Transpiration must be 0 in the barren tank, (h = 0, LAI = 0), and so $a \rightarrow 0$ when $h \rightarrow 0$. Therefore, $f(u, h)$ is expressed as follows if a is assumed to be proportional to the crop height (h).

$$f(u,h) = 0.083hu_{1.85}^{0.60} \qquad (\text{mm hPa}^{-1}\ \text{h}^{-1}) \qquad (29)$$

(4) *Relationship between ϕ_p and Soil Moisture Content*

The value of ϕ_p was calculated using **Eqs. 20, 22 and 26**, and $E_p = E_{p\,obs.}$ for the periods, June 16-18 in 2001 and July 20-25 in 2002. The relationship between ϕ_p and θ_{10} is shown in **Fig. 7**. The value of ϕ_p can be 1 when θ_{10} ranges from 0.10 to 0.15, which is in agreement with the results reported by (2).

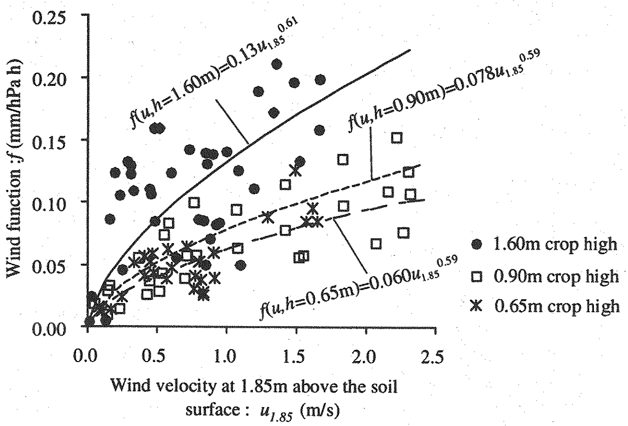

Fig. 6 Relationship between $f(u,h)$ and $u_{1.85}$

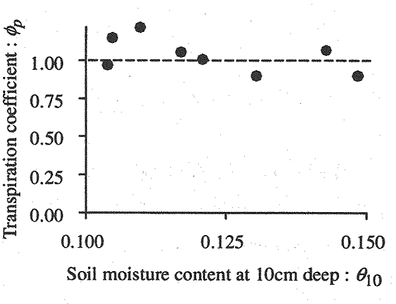

Fig. 7 Relationship between ϕ_p and θ_{10}

NUTRIENT ABSORPTION DURING PLANT GROWTH

Measurement of Nutrient Absorption by Plants

The nutrient absorption rates of corn plants were measured by the following method. Six plants with roots placed in bottles (capacity 1.3 liter, depth 15cm) filled with aerated solution were grown under the natural weather conditions between June 10 to August 14, 2002, in the field located near the lysimeter. The growth of two of the six corns was similar to that of the corns planted in the lysimeter.

After nutrients were supplied to the solution, transpiration and solute concentrations were measured by

Table 5 Solute concentration just after supplying nutrient

		Solution weight (kg)	Nutrient concentration (g/m^3)			
			Ammoniacal N	Nitrate N	K	P
Bottle 1	Jun. 12-14	1.21	0.755	0.195	1.04	1.28
	Jun. 22	1.17	162	82.0	318	124
	Jul. 11	1.20	29.8	18.2	137	75.4
	Jul. 18	1.18	43.6	21.9	159	86.0
	Jul. 22	1.19	101.6	59.4	300	129
Bottle 2	Jun. 12-14	1.13	39.6	10.3	52.6	16.9
	Jun. 22	1.20	209	92.4	324	141
	Jul. 11	1.16	188	111	210	108
	Jul. 18	1.17	166	78.3	371	177
	Jul. 22	1.15	150	61.3	378	170

weighing the bottles with the plants and sampling the solution on June 12-14, July 11, 18 and 22 in 2002. The solute concentration of N, P, K for the two plants just after supplying nutrient is shown in **Table 5**. Nutrient absorption rates of the plants were calculated from the differences of the nutrient depletion in the solutions measured at intervals of one day (June 12-14) or three hours (July 11, 18 and 22).

Measurement results

Figure 8 shows the relationships between solute concentrations of N and K in solution and the absorption rates. The nutrient absorption in each period tends to increase with each increase of solute concentration. The absorption rate (I) of the ingredients of the nutrient solution can be expressed by Michaelis-Menten kinetics (1) as

$$I = \frac{I_{\max} C}{K_m + C} \qquad (30)$$

where $I_{\max}$ = the maximum absorption rate; K_m = Michaelis-Menten constant; and C = the solute concentration outside roots. Although the value of K_m depends on the ingredients of the nutrient solution, it remains constant during plant growth (1). In this paper, K_m for N and that for K are set to 40 (12) and 390 mg/liter (1), respectively. The values of I_{max} for N and that for K determined by the least square error method are in **Table 6**. The results calculated by using **Eq. 30** are shown in **Fig. 8**. The calculated results for N and K on July 11 are in close agreement with the observed results. On the other days, the validity of **Eq. 30** for the estimate of the nutrient absorption cannot be confirmed as well because the observed nutrient absorption is in a small range. In this study, the nutrient absorption during whole plant growth assumed to be expressed as **Eq. 30**.

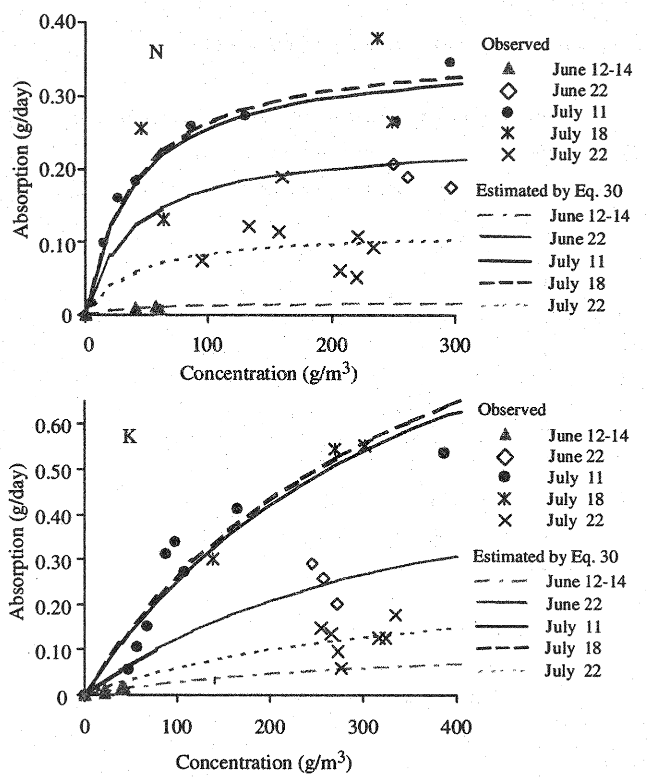

Fig. 8 Relationships between nutrient absorption and solute concentration

Table 6 Values of I_{max}

	Jun. 12-14	Jun. 22	Jul. 11	Jul. 18	Jul. 22
N	0.017	0.240	0.357	0.368	0.116
K	0.104	0.623	1.161	1.279	0.299

(g/day)

Relationship between Nutrient Absorption and Plant Growth

It can be seen that the values of I_{max} for each ingredient increase as the plants grow until July 18, and decrease considerably afterward. **Figure 9** shows the relationships between the values of I_{max} and the increasing dry weight. The values of I_{max} for N and K are found to be proportional to the rate of growth of the dry weight, and are given as

$$I_{\max} = m\frac{dw}{dt} \tag{31}$$

where w = the dry weight; and m = the constant. The optimum value of m for N is 0.096, and that for K is 0.31.

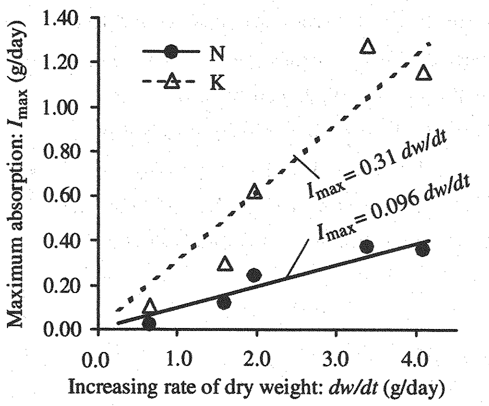

Fig. 9 Relationships between I_{max} and plant growth

NUMERICAL ANALYSIS FOR WATER AND SOLUTE TRANSPORT IN SOIL CONSIDERING PLANT UPTAKE

Numerical Simulation Model

Equations 1, 19-24 and 29-31 are applied to a numerical analysis for water and nitrogen transport in soil considering absorption by plants. Soil moisture movement is analyzed using Rechards' equation (**Eq. 32**).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left\{K(\theta)\left(\frac{\partial \psi}{\partial z}+1\right)\right\} - S \tag{32}$$

Where, $K(\theta)$ = the hydraulic conductivity; ψ = the pressure head; and S = the volumetric plant uptake in the root zone. The unsaturated characteristic curves shown in **Fig. 2** are used.

In this study, it is assumed that ammoniacal N in solute is immediately transformed to nitrate-N (1), and that denitrification and mineralization of organic N are negligible (12). Therefore, nitrate-N transport in a soil can be expressed as

$$\frac{\partial(\theta C)}{\partial t} + \frac{\partial(qC)}{\partial z} = \frac{\partial}{\partial z}\left(\theta D\frac{\partial C}{\partial z}\right) - Q \tag{33}$$

where q = the flux of water calculated by Darcy's law ($= -K(\partial\psi/\partial z) - K$); D = the dispersion coefficient; Q = the volumetric absorption rate by plant roots; and C = N concentration in the soil moisture. The value of D is set to 2.5×10^{-10}m^2/sec obtained from laboratory experiments (7).

If root distribution is assumed to be homogenous in the root zone, S and Q are expressed as **Eqs. 34 and 35**, respectively.

$$S = E_p / l_r \tag{34}$$

$$Q = nI / l_r \tag{35}$$

Where, I = the N absorption rate by a plant; l_r = the root zone length; E_p = the water uptake by the plants considered to be equivalent to transpiration calculated by **Eqs. 20, 22 and 29**; and n = the crop density. The N absorption rate (I) at each depth is estimated by **Eqs. 30 and 31** by using the N concentration (C) calculated by **Eq. 33**. The root zone is set to 0-50cm below the ground surface (l_r = 50cm).

Model Validation

Water and solute transport in soil tank E for the period June 5 to August 14, 2002 is analyzed using the proposed model. **Fig. 10**(a) shows the observed rainfall and irrigation, and (b)-(g) indicate calculated and observed results of changes in the soil tank weight set to 0 kg on June 5, evapotranspiration, groundwater runoff and soil moisture content at 10, 30 and 60cm deep below the soil surface, respectively.

Evapotranspiration calculated by Penman's formula (**Eqs. 11 and 14**) is also shown in **Fig. 10**(c). The evapotranspiration calculated using Penman's formula underestimate the real values for tall corn crops, yet are in close agreement for the shorter crops. The results calculated with the proposed model are in close agreement with the observations over the entire period of corn growth. The observed evapotranspiration, the value calculated by Penman's formula, one by the proposed model are 375, 255 and 360mm, respectively. The proposed method can be applied to estimate evapotranspiration during plant growth.

Figure 10(a) and (h)-(j) show supplied N, calculated and observed solute concentration in the groundwater runoff, calculated results of cumulated N absorption by the plants and N storage at 10, 30 and 60cm deep, respectively. Calculated and observed distributions of N storage in the soil are in **Fig. 11**.

Figure 10(i) shows that the N absorption rate is

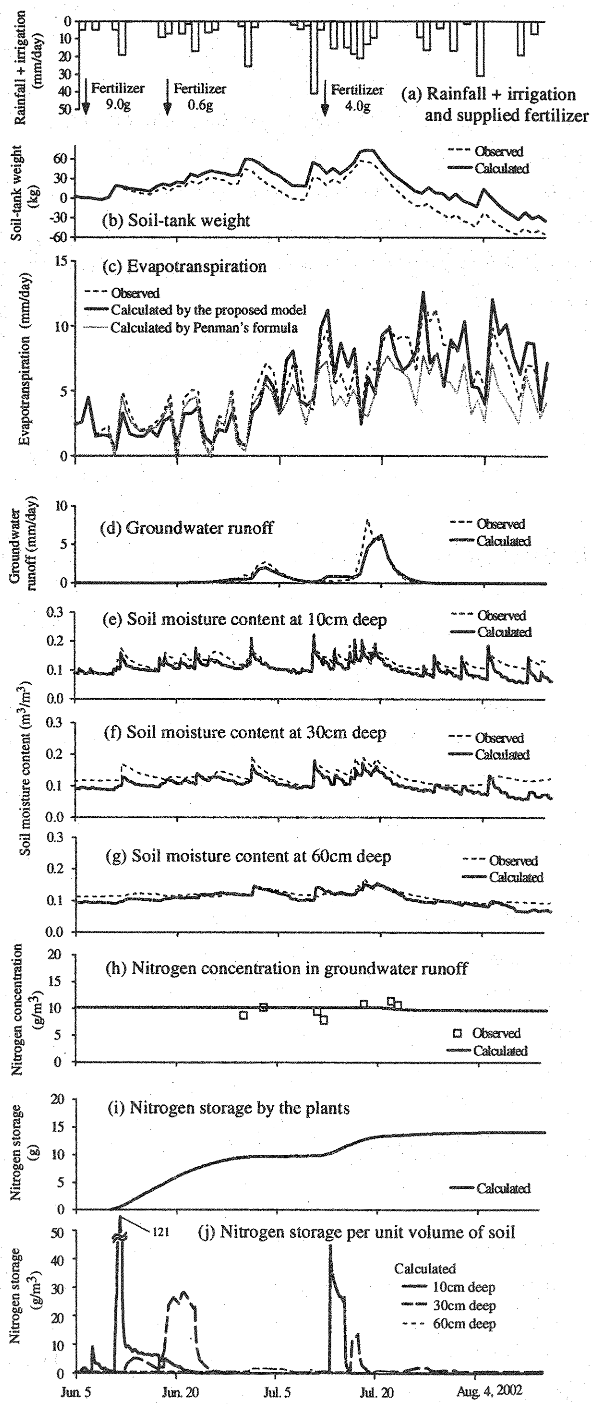

Fig. 10 Comparisons of calculated and observed results

great right after fertilizing, and then decreases slightly. N storage at 10 and 30 cm deep is 0g/m^3 soil in **Fig. 10**(j) when the N absorption rate is small, indicating that N is in short supply for plant growth.

Changes in N storage at 10 and 30cm deep are considerable in **Fig. 10**(j), but that at 60cm deep is negligible small. **Figure 11** shows that the supplied N is transported downward due to rainfall and irrigation, but does not move in the region below a depth of 60cm since most N is absorbed by the plants. The distribution of N storage observed at the last stage (on August 14) also shows that there is little residual N. Therefore, the observed and calculated results of N concentrations in the groundwater runoff are very small (almost 10g/m^3, constantly). These findings provide evidence that the affect of N absorption by plants on solute transport in the soil is great.

The observed adsorption during plant growth is 16.7g, and the calculated value is 14.1g. This study has concluded that the proposed model was applicable to the analysis of water and solute transport in the soil.

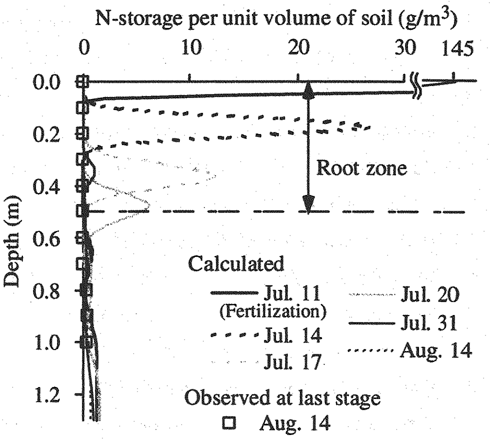

Fig. 11 Distributions of N storage in the soil

CONCLUSION

We describe consumption of water and nutrient during plant growth. Water and solute balance measurements for the corn plants were carried out using a weighing lysimeter. The measurements show that 192-389kg of water, 13.1-20.8g of N, 1.9-12.3g of P and 8.0-18.0g of K are consumed in producing 1kg of dry matter.

A method of calculating evapotranspiration during plant growth is constructed using sap flow measured by the stem heat balance method. The relationship between plant growth and the wind function, and one between evapotranspiration and soil moisture content are considered in the model. Here, **Eq. 13** is used as the wind function and a in Eq. 13 can be expressed as 0.083h and b as 0.60. The validity of the proposed model is confirmed by comparing the calculated and observed results for evapotranspiration during plant growth.

Changes in the characteristics of nutrient absorption during the growth of corn plants are investigated. The absorption rate is clarified to increase with the solute concentration outside the roots, and be proportional to the plant growth rate. The absorption rates for nitrogen and potassium can be expressed as **Eq. 30**. The maximum absorption rate (I_{max}) in **Eq.30** is found to 0.096 and 0.31 times the growth rate of the plant's dry weight.

A numerical model of water and nitrogen transport in a soil is propounded using the relationships between plant growth and nitrogen absorption. Under the assumption that the N absorption characteristics of plants grown in hydroponics culture are identical to those grown in fields, the usefulness of the proposed model is confirmed by comparing observed and calculated results.

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APPENDIX – NOTATION

The following symbols are used in this paper:

a, b	= empirical coefficients defined by **Eq. 13**;
A	= leaf area of a plant;
A_e	= value of A at harvest;
A_s	= stem cross-sectional area;
C	= solute concentration outside roots;
c_p, c_w	= specific heat capacity of dry air and specific heat capacity of water;
d	= zero plane displacement from soil surface;
D	= dispersion coefficient;
ET, E_p, E_s	= evapotranspiration, transpiration and evaporation, respectively;
$ET_{obs.}$, $E_{p\,obs.}$, $E_{s\,obs}$	= observed evapotranspiration, transpiration and evaporation, respectively;
ET_0, E_{p0}, E_{s0}	= evapotranspiration, transpiration and evaporation under well-watered conditions, respectively;
e	= vapor pressure;

e_s	= saturation vapor pressure;
f	= wind function;
F	= sap flow rate;
G	= soil-heat flux;
h	= plant height;
h_e	= value of h at harvest;
I	= nutrient-absorption rate by a plant
I_{max}	= maximum value of I;
K	= hydraulic conductivity;
k	= constant defined by **Eq. 6** ($2\pi\lambda_s L/\ln(r_2/r_1)$);
K_m	= Michaelis-Menten constant;
l	= latent heat of evaporation;
L	= length of the heat segment;
LAI	= leaf area index;
l_r	= root-zone length;
m	= constant defined by **Eq. 31**;
M	= index of plant growth such as dry weight (w), the crop height (h), the leaf area (A);
M_e	= maximum value of M;
M_0	= value of M at planting;
n	= crop density;
q	= flux of water calculated by Darcy's law;
Q	= volumetric nutrient-absorption rate by plant roots;
q_f	= energy transported by sap flow from the heated segment;
q_u, q_d	= upward and downward energy transfer rates due to thermal conduction along the stem;
q_r	= rate of radial energy loss;
R_n	= the net radiation;
r	= growth rate;
r_a	= aerodynamic resistance;
r_c	= stomatal diffusion resistance;
r_1, r_2	= distances given in **Fig. 4**;
S	= volumetric plant uptake in the root zone
t	= time;
u	= wind velocity;
$u_{1.85}$	= wind velocity at 1.85 m above the soil surface;
u_2	= wind velocity at 2 m above the soil surface;
$T_{a\sim f}$	= temperatures at the points indicated in **Fig. 4**;
w	= dry weight of a plant;
w_e	= value of w at harvest;
z	= distance from the soil surface;
z_0	= roughness length;
α	= empirical coefficient defined by **Eq. 19**;
Δ	= slope of the saturation vapor pressure curvel;

Δx	= distance given in **Fig. 4**;
ϕ	= evapotranspiration coefficient defined by **Eq. 8**;
ϕ_p	= transpiration coefficient defined by **Eq. 21**;
ϕ_s	= evaporation coefficient defined by **Eq. 22**;
γ	= psychometric constant;
κ	= von Karman's constant;
λ, λ_s	= thermal conductivity of the stem and one of the sheath material;
θ	= soil moisture content;
θ_{10}	= soil moisture content at 10cm deep from the soil surface;
θ_r	= residual soil moisture content;
θ_s	= saturated soil moisture content;
ρ	= density of dry air; and
ψ	= pressure head.

(Received June 30, 2003 ; revised October 15, 2003)