J. Jpn. Soc. Soil Phys.
土壌の物理性
No. 95, p. 75～90（2003）

Current and Prospective Applications of Zero Flux Plane (ZFP) Method

Magdi KHALIL*, Masaru SAKAI*, Masaru MIZOGUCHI* and Tsuyoshi MIYAZAKI*

* University of Tokyo, Graduate School of Agricultural and Life Sciences, Department of Biological and Environmental Engineering, Yayoi 1-1-1, Bunkyo-ku, Tokyo 113-8657, Japan

Abstract

Zero flux plane (ZFP) method has been used to measure and estimate the evaporation, evapotranspiration, some hydrological process etc. However, no systematic discussion has been made concerning the ZFP method itself or its application to monitor and control the salt and contamination movement. In this study, comprehensive analysis on existing data sets have been performed to examine ZFP method applications and to give comments for further applications in future. First, ZFP method definition and its mathematical derivation were stated. Second, the application of ZFP to evaporation, evapotranspiration and ground water recharge process were discussed and analyzed. The difficulties that affect the application of ZFP method such as depth of soil, preciseness of measurements etc. have been listed and compared. Finally the potentialities of ZFP method were discussed. The discussion showed that, the development of new techniques related to measurement instruments, required experiments and simulations to implement ZFP in effective way is very important to monitor and control salt transportation and accumulation control.

Key words : zero flux plane, unsaturated soil, Hydrus-2D, salt accumulation, soil contamination

1. Introduction

The importance of the soil-water system in nature and in the life of man has been realized since the dawn of civilization and man's awakening awareness of his relationship to his environment (Hillel, 1971). The liquid phase of a soil is never just pure water. There are always mineral salts and organic substances dissolved in the water. Generally, in spite of the importance of its solutes, the liquid phase of soil is called soil water. (Kutilek and Nielsen, 1994). Most of the process involving soil-water interaction in the field occurs while the soil is in an unsaturated condition (Hillel, 1998), or in other words, in vadose zone, (Miyazaki, 1993). Therefore the movement of water in unsaturated soil is of a great importance where there are many applications especially related to the hydrological cycle and plant growth and stress. Such knowledge allows an estimate of the influence of soil conditions on plant growth, determination of the schedule of irrigation and drainage.

Prior to the recent application of soil physics techniques in water balance studies, the difference between the rainfall and the evapotranspiration was often used to determine the moisture balances and deficit, e.g. Gardiner (1986). Errors arise in both measurements and estimates, and give rise to considerable uncertainty (Cooper *et al.,* 1990). Measurements or estimation of water flux in unsaturated soil is impractical because of the wide range of hydraulic conductivity values found in soils, their spatial variation and hysteresis (Cooper *et al.,* 1990). One of the prospective and promising techniques used to determine the moisture balances in unsaturated soil is ZFP method.

The purposes of this review paper are to make clear the ZFP concept physically and mathematically, to compare the published data of the ZFP, and to discuss the accuracies, difficulties and potentialities of this method.

2. ZFP Method

2. 1 Definition

ZFP is defined as a plane, which separates two zones of upward and downward movement of water in a thoroughly wetted soil with evaporation and drainage occurring simultaneously. Water moves in an upward direction above this plane, and downward below it, i.e., there is no flow across the boundary separating the two zones. With negligible lateral soil variation, the "zero flux" boundary may be assumed to be planar. As the soil dries the plane of "zero flux" moves downward (Arya *et al.,* 1975). In other words, when evaporation exceeds rainfall, it is expected that water in the upper part of the soil profile moves upwards towards crop roots or the soil surface as exemplified in Fig. 1. Water in the lower part continues to drain water table. The point where water is neither flowing up nor down is called the ZFP.

The old term used for ZFP was static zone. It was first mentioned by Richards (1954), with Fig. 2 where he used a new instrument, multiple unit tensiometer, to measure the hydraulic head and the hydraulic gradient of water in unsaturated field. He used the term static zone in connection with the soil-water system to designate the locus of points, above which water movement is upward, and below which water movement is downward. Due to the influence of the evaporation at the surface of the soil, this static zone passes downward through soil following the wetting. Each curve in Fig. 2 represents the total potential distribution with depth on the days in October indicated by the number on the curve. The curve of Oct. 19 shows the total potential distribution while water was still ponded on the soil surface. Between Oct. 21 and 22 there was a reversal in the hydraulic gradient in the 10–20 cm soil interval. Between Oct. 23 and 24, the flow reversed in the 20–30 cm depth interval. On Oct. 23, there was 1.07 cm rain. This caused a marked shift in the total potential values. By Oct. 27, the static zone has passed below the 20

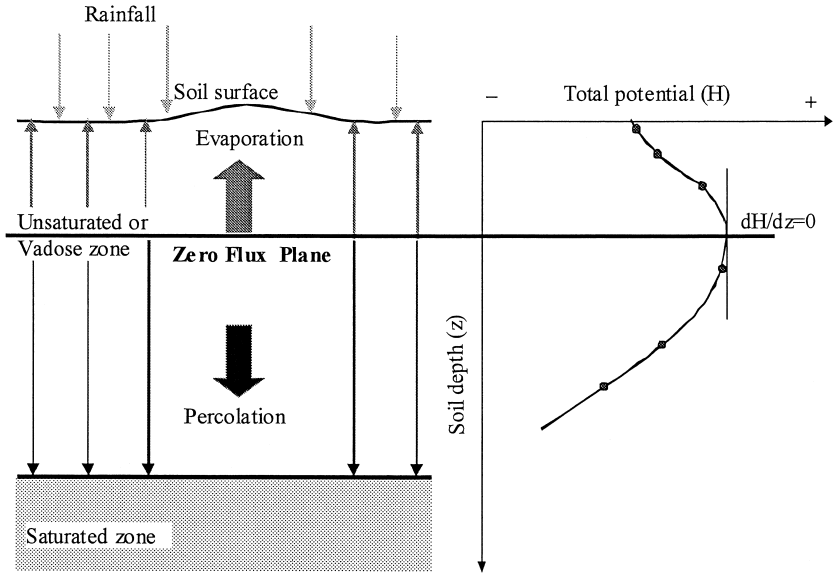


Fig. 1 Zero flux plane concept.

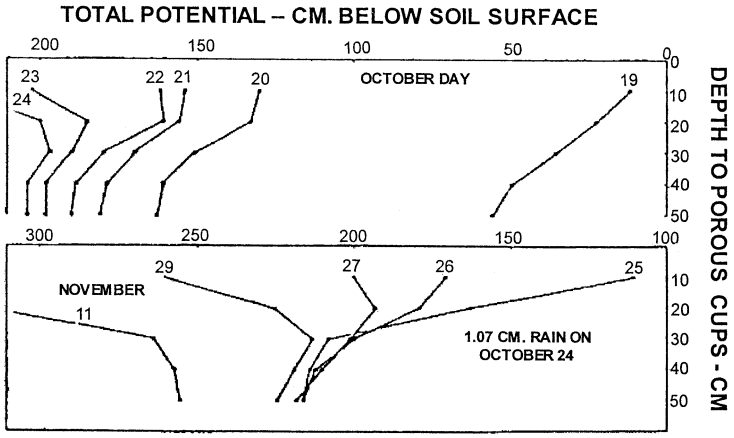


Fig. 2 First use of ZFP method. (from Richards, 1954)

cm depth. By Oct. 29, the static zone has passed below the 30 cm depth. Some time before Nov. 11, upward flow was established from depths greater than 50 cm. Therefore, the static zone corresponds to the depth at which the hydraulic gradient is zero. (Richards et al, 1956). In field studies, the depth within the soil profile at which the water flux density is zero is of major importance and relatively easy to measure (Kutilek and Nielsen, 1994).

2. 2 Mathematical derivation of ZFP Method

Stammers *et al.* (1973) described the approximation of mathematical derivation of the correct expression of ZFP depth as shown in Fig. 3. Both evaporation and drainage could be calculated at above and below ZFP.

$$E=R+\int_{0}^{z_0(t_1)}\theta(t_1)dz-\int_{0}^{z_0(t_2)}\theta(t_2)dz+\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\left[\theta(t_1)+\theta(t_2)\right]dz \quad (1)$$

$$D=\int_{z_0(t_1)}^{Z}\theta(t_1)dz-\int_{z_0(t_2)}^{Z}\theta(t_2)dz-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\left[\theta(t_1)+\theta(t_2)\right]dz \quad (2)$$

where :

E is evaporation over the period t_1 to t_2

R is rainfall over the same period

t is time

z is depth measured positively downwards

Z is the depth at which drainage is calculated

D is drainage over the period t_1 to t_2 through depth Z

θ is volumetric water content

$z_o(t)$ is the ZFP depth at time t.

From Fig. 3, it is clear that, by decreases the moisture content in the soil, the ZFP is getting much deeper as well. The procedures to obtain equations (1) and (2) based on Fig. 3 is given in Appendix attached.

3. Application of ZFP to Evaporation and Evapotranspiration

In dry periods, when evapotranspiration exceeds rainfall, the soil water in the upper part of the soil profile moves upwards towards the root zone and the soil surface. At lower depth soil water moves downwards towards the water table due to gravity. Above ZFP, any reduction in the soil moisture content must be due to the moisture loss caused by an excess of evapotranspiration, below the ZFP, and assuming no uptake of moisture content by roots at these depths, reduction in moisture content must be due to drainage out of the soil, i.e. recharge to the ground water table.

The ZFP moves downwards as loss to evapotranspiration increase. In using the ZFP, it is assumed (Cooper *et al.,* 1990) that :

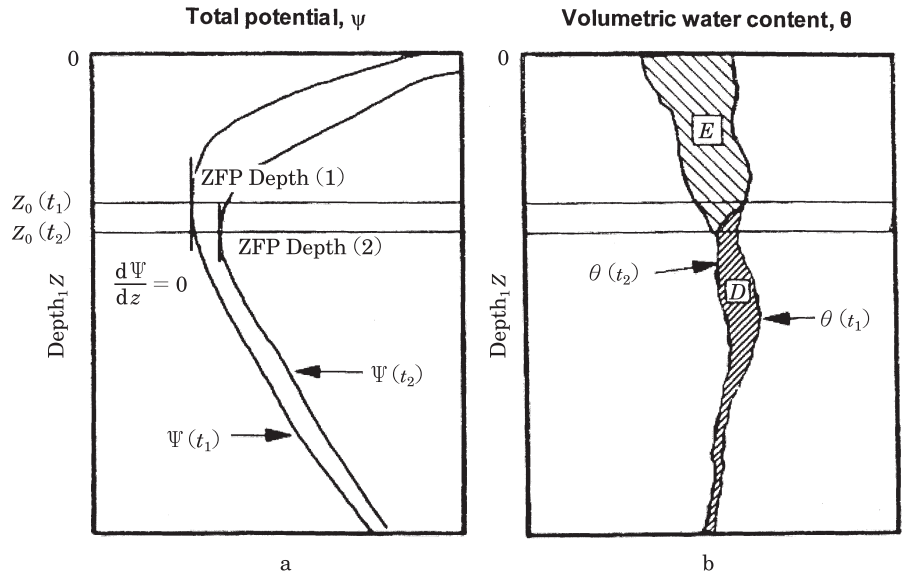


Fig. 3 Principle of the zero flux plane method. (a) Hypothetical pressure potential profiles. (b) The corresponding water content profiles.
The shading represents water that has evaporated or drained between t_1 and t_2. (from Cooper, 1990)

1) Root extraction of soil moisture below the ZFP is negligible, i.e. there is only drainage below the ZFP

2) Water infiltrating the soil surface moves downward through the soil matrix ; if there is percolation through macropores, such as cracks or wormholes, evapotranspiration will be overestimated and drainage will be underestimated

3) There is no surface run-off, if there is, it should be taken into account.

Literature search revealed that most of authors have used ZFP method either to estimate the evaporation, to calculate the drainage, or to differentiate between drainage and evaporation. (Van Bavel *et al.,* 1968 ; Stone *et al.,* 1973 ; Roman *et al.,* 1999). Therefore, we will discuss two examples of estimating the short-term evaporation and long-term evapotranspiration by ZFP method in this section, followed by estimation of drainage in the next section.

Estimation of the evaporation in short term

Thony *et al.* (1979) estimated the evaporation from a 100 m^2 plot of bare soil during a five-day period of intense evaporation following heavy rain, which had saturated the upper soil horizon. They evaluated the daily evaporation rates for five days from 2/08/77 to 7/08/77, (a) by monitoring the moisture movement using ZFP method and soil water balance method and (b) by aerial measurements of the evaporative fluxes into the atmosphere (energy balance method).

ZFP method has been used when ZFP existed. On the other hand, soil water balance method has been implemented during the absence of ZFP. The field experiment is located in Gernoble Mechanical Institute in France. The soil profile was as follows : from 0.0 to 0.25 m muddy silt, from 0.25 to 0.50 m fine sand and from 0.50 to 1.0 m clay soil. They used neutron probe to measure water content and manometer tensiometers to measure the matric potentials. The total potential profile and soil moisture content profile during five days monitoring are shown in Fig. 4. The total potential

profile of Aug. 2 shows that ZFP is blow 20 cm. By Aug. 7, the ZFP has passed below the 60 cm depth. The daily and cumulative evaporation obtained by both ZFP and soil water balance methods, and energy balance method were compared in Table 1.

They also studied the soil water dynamics in the upper layer under natural cyclic evaporation conditions, it being found that the hydraulic head in this horizon is subject to periodic variations. This phenomenon can be attributed principally to the cyclic nature of the evaporative process, which results in drying up of the soil during the day followed by rewetting at night as a result of internal redistribution. They concluded that the moisture movement under these conditions is governed principally by hydrodynamic effects, with thermal effects playing only a very minor role. The results obtained by the two methods being found in good agreement. Other literature concerning short-term evaporation were carried out by Kalms *et al.* (1979) ; McGowan Williams (1980) ; Inoue *et al.* (1985) ; Yamamura *et al.* (1988) ; Villegas and Morries (1990) ; Payne *et al.* (1990) ; Kanamori (1995) ; Diez *et al.* (2000), who all suggested the usefulness of ZFP method to estimate short term evaporation.

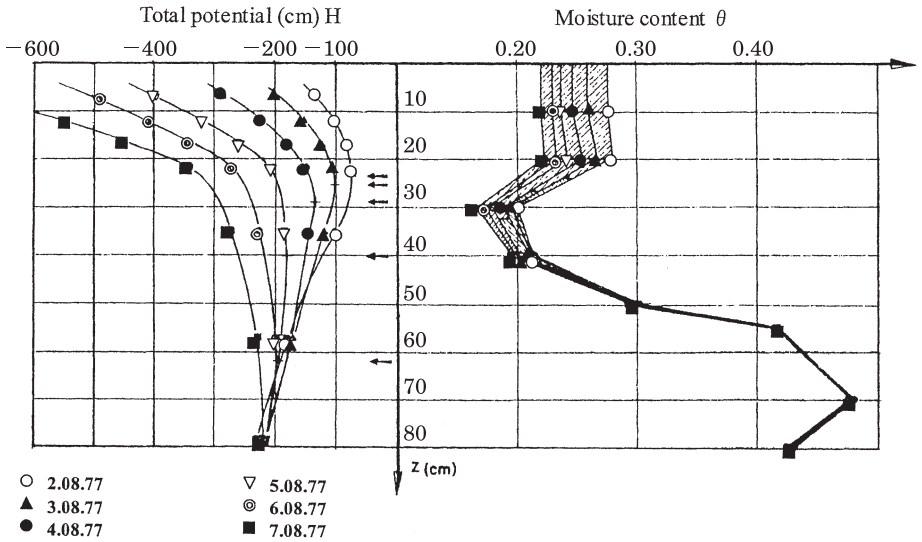


Fig. 4 The hydraulic potential profile and soil moisture content profile during five days monitoring. (from Thony, *et al.*, 1979)

Table 1 Cumulative evaporation obtained by both ZFP and energy balance methods (from Thony *et al.*, 1979)

From	to	ZFP method and water balance method	Energy balance method
2/08/77	3/08/77	3.75 mm	4.00 mm
3/08/77	4/08/77	3.25 mm	4.25 mm
4/08/77	5/08/77	3.50 mm	4.50 mm
5/08/77	6/08/77	3.25 mm	3.25 mm
6/08/77	7/08/77	3.25 mm	3.50 mm
		Sum 17.00 mm	19.50 mm

Estimation of the evapotranspiration in long term

Kirsch (1993) used ZFP method for estimating the actual evapotranspiration (ET) in field. The experimental field was located on the grounds of the University of Illinois in U.S.A. The soil at the site is silty clay loam. The vegetation of the field was fescue and red clover. The rooting zone of the growing plants extended to a depth of about 40 cm. He used about 60 tensiometers to monitor the total hydraulic potential, at depths of between 8 and 165 cm. Neutron probe access tubes were used to monitor the water moisture of the soil. He carried out three field experiments. First experiment was conducted for 20 days in July and August 1987. The second experiment was conducted for 12 days in June and July. The last one was conducted for 10 days in October. The movement of ZFP through the time during the three experiments are shown in Fig. 5. It is clear that the ZFP is getting deeper through the summer season and starts to be steady at the beginning of winter. For the three field experiments, the errors ranged between 153% for 1-day ET estimates to 42% for 5 days estimates. It is clear from the result that the improper location of ZFP plays an important role to overestimation or underestimation of water content in the unsaturated area.

Other literature concerning long-term evapo ration were done by Royer and Vachaud (1974) ; Sharma (1985) ; Dolman *et al.* (1988) ; Roman *et al.* (1999), who all obtained reasonable estimations of long-term evaporation by using ZFP method.

4. Application of ZFP to Recharge Processes

For many dry climates, ground water is a major source of water supply for irrigation, industrial, and domestic demands. Estimation of safe yield is an important basis for developing long-term management plans. This requires knowledge of recharge rates beneath various land use conditions, and their expected variability over a long periods.

Furthermore, the efficient management of ground water resources requires knowledge of the quantity of water recharging the aquifer. This allows safe and reliable pumping regimes to be established without over-exploitation of the aquifer or over-reduction of base flows to rivers fed by the aquifer. Ground water recharge can be easily estimated by ZFP method. The reason for that is, below the maximum depth reached by the ZFP, soil water flow is always downward ; hence, the water draining through any depth below this will appear eventually as recharge at the water table. (e.g. Cooper, 1979 ; Sharma, 1985 ; Simmers, 1987 ; Bouwer, 1989).

The ZFP method is considered the most direct method for determining the recharge rate of ground water. Therefore, several authors have used it to estimate the ground water recharge (Royer and Vachaud, 1974 ; Cooper, 1980 ; Wellings, 1984, Dreiss and Anderson, 1985 ; Healy, 1989 ; Cooper *et al.,* 1990 ; Gardner *et al.,* 1990 ; Sharma *et al.,* 1991 ; Tang, 1996 ; Ragab *et al.,* 1997 ; Hosty and Mulqueen, 1996 ; Ab-

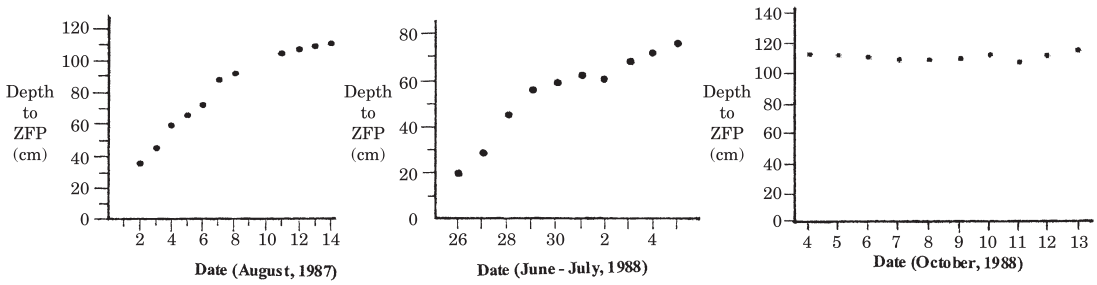


Fig. 5 The movement of ZFP through time during the three experiments. (from Kirsch, 1993)

dallah *et al.,* 2001 ; Tsujimura *et al.,* 2001). Table 2 gives the main features of ground water recharge estimation done by some of these workers.

In the following section, a simple brief and analysis will be mentioned about some of these works.

Sharma *et al.* (1991) used the zero flux plane method and water balance method to estimate the seasonal change in recharge to the underlaying sandy aquifer. They monitored down the soil water dynamic of the unsaturated zone to depth of 20 m of a period for three years. They used neutron probes for moisture content measurements. A simplified schematic of the hydrological cycle for the experiment is shown in Fig. 6. They defined two references Z_1 and Z_2. The depth Z_1 (=10 m) is below the influence of the root water uptake, and is the maximum depth of the ZFP (Cooper, 1979 ; Wellings and

Table 2 The main features of ground water recharge estimation done by some workers

Year	Name & location	Field & soil surface	Purpose	Instruments	Features			Comments
					ZEP Range	Exp. Timing	Soil profile & Analysis	
1980	Cooper England	Forested and clearing sites Sand lying on Chalk	Evaluate ZFP as a tool to measure *R*	N.P. & P.T.	Max. ZFP 3.2 m	34 months		No independent estimate of drainage
1984	Wellings England	Grass & Barely Silty Clay loam lying on Chalk	Estimate *R* and *E*	N.P. & P.T.	3〜6 m	6 years	40 m	ZFP is not valid in winter time
1990	Cooper *et al.* England	6 Grass sites Sand lying on Chalk	Estimate *R*	N.P. & Ts.	Max. ZFP 〜1.6 m	2〜5 years	10–90 m	Effect of soil properties on E & R is not clear
1991	Sharma Australia	Native Woodland & Sandy soil	seasonal change in *R*	N.P.	10 m	3 years	20 m	No matric potential measured Run off is neglected
1996	M. Hosty Ireland	Dry grassland Sandy loam	*E* & *R* to groundwater	N.P. & Ts.	0.85 〜1.5 m W.T. 4 m	5 months	4 m P.M.	Lowering water table has no effec on ZFP
2001	Abdallah M.A. *et al.* Switzerland	Grass land Aquifer Sandy loam	*ET* & *R* to groundwater	N.P. & Ts.	0.55–0.7 W.T. 2.7 〜3.2 m	1 year	Empincal method P.M.	Snow cover problem & Particle size distribution effect

*N.P. Neutron probe *Ts Tensiometers *P.T. Pressures Transducers
**E* Evaporation **ET* Evapotranspiration **R* Recharge *PM. Penman Model

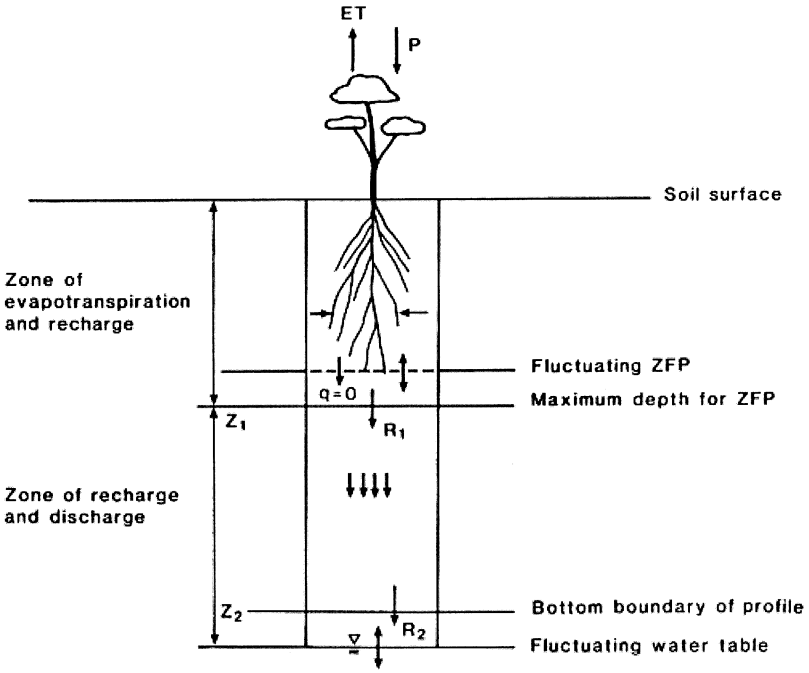


Fig. 6 A simplified schematic representation of the hydrological balance used in the analysis. Here Z_1=10 m and Z_2=18 m are arbitrary depths. Z_1 is the maximum depth for the ZFP and recharge below this depth is termed R_1. Z_2 is an arbitrary depth just above the water table and recharge below this depth is termed R_2. (Sharma, *et al.*, 1991)

Bell, 1980). The depth Z_2 (=18 m) is an arbitrary depth just above the water table. Recharge below Z_1 and Z_2 are termed R_1 and R_2 respectively. Four pore holes were drilled and soil water content down the profile was measured for each.

It is interesting that the authors did not estimate evapotranspiration in computing the recharge and did not use the directly- measured soil matric potentials in the profile. For identifying the location of ZFP in the profile, matric potentials are obtained inversely from measured soil water content. However their scheme could be valid for reasonably deep unsaturated zone exists between the maximum rooting depth and the water table. The changes in soil water storage for this depth interval are used at appropriate times to compute water flux.

There is some uncertainty in the exact location of the ZFP particularly when the matric potential is calculated not measured. However, with the start of the rainy seasons, ZFP develops at the surface and the wetting front moves downward and finally cancels the original ZFP below. The soil water profile for the hole 6 at various time during an annual cycle is shown in Fig. 7.Total water potential profiles for the same hole are shown in Fig. 8. Approximate location of the ZFP is shown for each profile. It is interesting that ZFP could be last to over 10 meters and not for few centimeters below the soil surface as known. Therefore, ZFP is dynamic not static.

Hosty and Mulqueen (1996) studied the soil moisture for a free-draining podzolic soil with a water table at 4 m below ground level. Evaporatranspiration and drainage to ground water were computed using both zero flux plane and water balance methods. They used

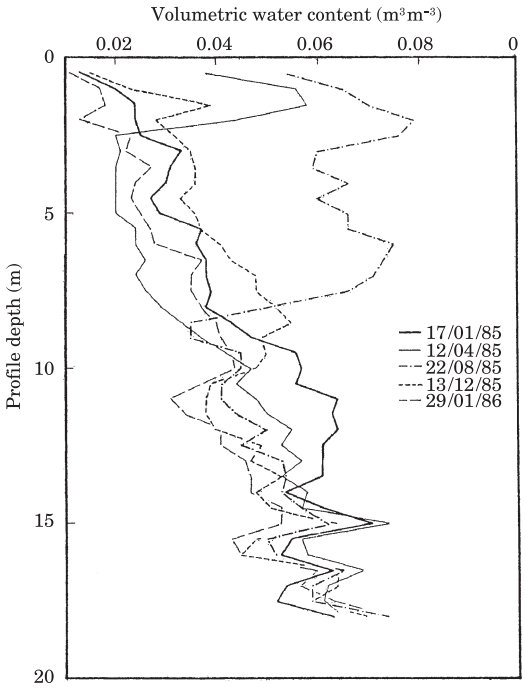


Fig. 7 Total water potential for the same period shown in Figure. (Sharma *et al.*, 1991)

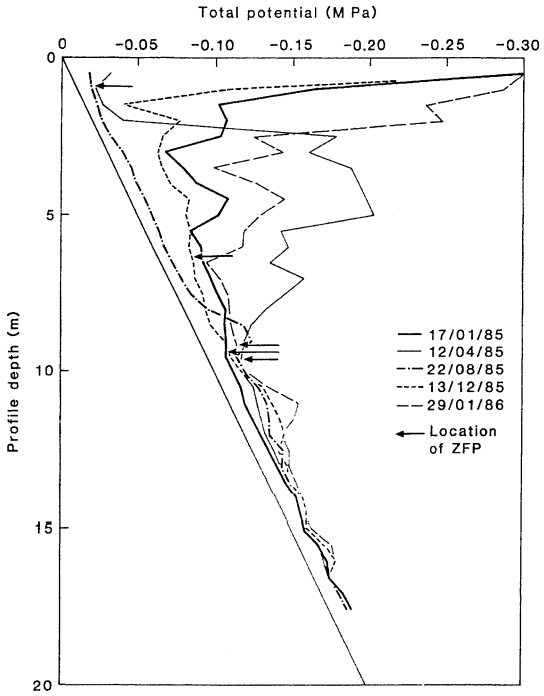


Fig. 8 Soil water profile for hole 6 at various time during an annual cycle. (Sharma *et al.*, 1991)

both neutron probes and tensiometers to measure the moisture content and hydraulic potential respectively. Total potential of pore water pressure over the May to September period of 1992 have been shown in Fig. 9, and Fig. 10.

The field result showed that a ZFP developed in early May as shown in Fig. 9 and moved intermittently downwards to a maximum of 1.5 m as the summer progressed. On 20 August, the ZFP was 1.5 m below ground surface. Because of 36 mm rainfall between 20 and 27 August, hydraulic potentials increased. As heavy rainfall continued (89.1 mm between 27 August to 17 September), the hydraulic potential profile moved toward the gravitational potential line and there was evidence of temporary saturation at the 1 m depth (Fig. 10).

Pumping of the aquifer took place from 25 August to 15 September at an average discharge of 155 $m^3 h^{-1}$. This had the effect of lowering the water table at the measurement site from 4 m to 7.5 m below ground surface. It is important to mention that, lowering the water table had no effect on the soil moisture in this study, where it (the water table) was initially deep and well below the root zone. Although pumping of the aquifer was on going during this period, it is significant that the soil moisture profile above the water table was determined by the balance between rainfall and evaporation.

5. Application difficulties of ZFP method

5. 1 ZFP depth

It is well known that the depth of ZFP is not stationary or fixed, it moves up and down during the year and sometime, it does not exist at all. ZFP depth ranges from few centimeters to few meters below the soil surface. The accurate determination of ZFP in the soil is not easy and need special care and sensitive instruments. The misestimating of the location of

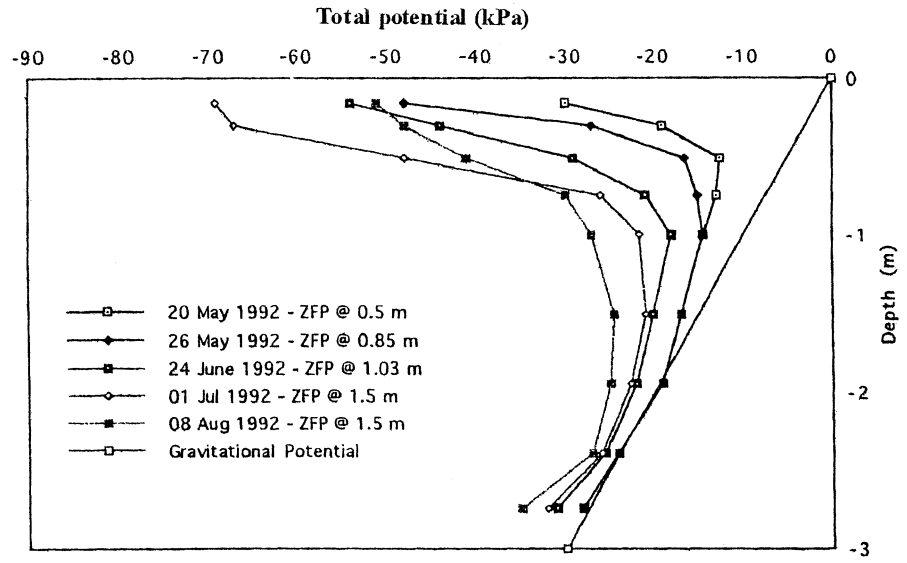


Fig. 9 Downward progression of the ZFP. (from Hosty *et al.*, 1996)

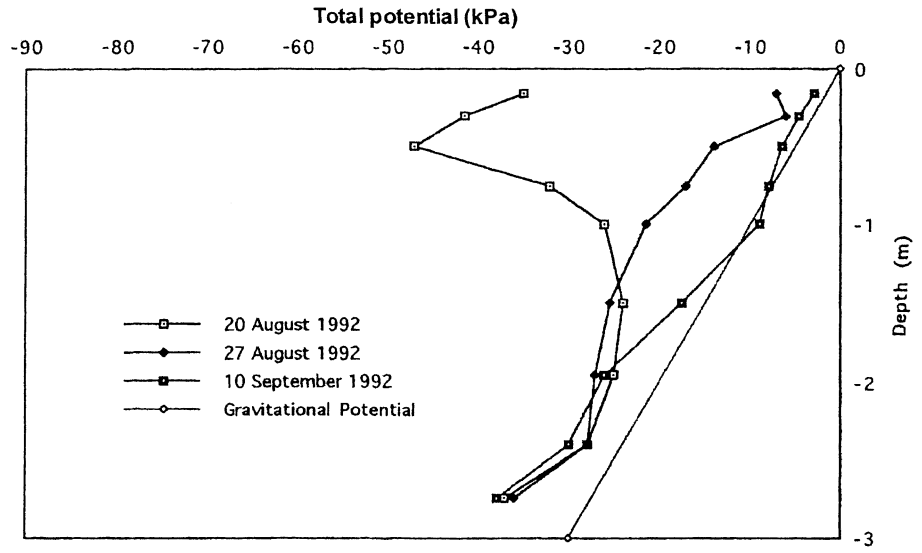


Fig. 10 Hydraulic potential profiles before and during pumping tests. (from Hosty *et al.*, 1996)

ZFP leads to misestimating of soil water storage. This in turn, causes a considerable error in calculating both recharge ground water and evaporation rate.

5. 2 Root zone

For its success, the ZFP method requires that there be no extraction of water by roots beneath the ZFP since all losses of water in this region are assumed to be due to drainage and all losses of water above ZFP assumed to be due to evaporation as well. Given that some roots are known to penetrate to at least 6 m, this is unlikely to be strictly fulfilled.

However, and for drainage estimation, the following points make it probable that extraction from below the ZFP is at most relatively

small (Cooper, 1979). :

(a) Although no quantitative information is available on the distribution of roots, within the profile, the overwhelming majority has been observed within the upper meter of soil. Provided that water is fairly readily available, it is expected that these roots will extract most of the water with only a tiny proportion coming from lower in the profile.

(b) As the ZFP gets deeper, the fraction of roots below it becomes steadily less.

(c) There is, at all times, at least one meter of soil above the ZFP at a tension of less than one bar (100 kPa). Drying within the upper 2 m, where potentials reach several bars, proceeds quite steadily to the end of the experiment, so that water must be available even at these tensions.

Moreover, and related to evaporation estimation, ZFP method gives a good agreement with transpiration calculations based on meteorological data, when it was known that roots penetrated below the ZFP, supporting the view that the root extraction from below the ZFP does not introduce a major error in using the method (Dolman *et al.* 1988).

5. 3 Non-existence of ZFP

ZFP method is useful when accurate measurements at short time scales are required, and when frequent measurements can be made. However, the method failed to estimate the soil water during periods when rainfall exceeds saturated hydraulic conductivity Ksat. In other word, if ZFP is at land surface (no ZFP existed), the method cannot be used, as only downward movement throughout unsaturated zone occurred.

The biggest limitation of the ZFP method is that it can be only used under conditions where a ZFP exists specially in dry season. In wet areas, this may be infrequently. However, in many drier areas, ZFP may be observed for well over half of the year. When ZFP cannot be observed, the meteorological estimates of evaporation, although not totally satisfactory, is reasonable and drainage estimated during these periods, for any depth below the ground surface, may then be calculated from a simple water balance of the soil profile (Stammer *et al.,* 1973 ; Arya *et al.,* 1975 ; Cooper, 1979, 1980 ; Cooper *et al.,* 1990 ; Kirsch, 1993) by using the equation.

$$D=R-E-\int_0^z \{\theta(t_1)-\theta(t_2)\}dz$$

5. 4 Preciseness of measurements

Although, ZFP method is based on measurements made directly in the controlling medium, the soil, special care should be given to the instruments in the field. Therefore, high density of instruments and high frequency of measurements needed to get relatively accurate results.

Sometimes errors are associated with moisture content measurements (Van Hylckama, 1980). This could be large relative to the change of moisture content between successive measurements ; therefore, this method is usually applied over a period of at least 1 week.

Using neutron probes near the soil surface may lead to incorrect measurements, therefore, accurate, sensitive tools should be used. As shown in table 2, most of authors used neutron probes to measure the moisture content. The sources of error in soil water measurements with a neutron probe can be summarized as follow (McGowan *et al.,* 1980) :

a) Systematic errors that occurred as a result of calibration, soil damage from access tube installation and damage to surface soil and vegetation.

b) Random errors which, happened because of random count error, relocation error and inherent soil variability errors as well.

Time Domain Reflectometry, TDR, may be used more widely hitherto, because its preciseness and convenience to monitor both moisture content distribution and unsaturated soil water movements.

Careful measurements of matric potential and proper installation of tensiometers are crucial and important to detect ZFP in precise way.

5. 5 Hysteresis

Almost all the soil moisture characteristic curves show hysteresis due to the ink bottle effect. Since the sizes of soil pores change successively, the existing of the ink bottle effect is generally recognized (Miyazaki, 1993). Care must be exercised in incorporating the effect of hysteresis, by using the appropriate part of sorption or desorption relationship. In most cases where the effective rainy seasons is distinct (Wellings and Bell 1980) the desorption curve could be used without introducing much error (Sharma *et al.,* 1991).

6. Potentialities of ZFP method

Although many researchers used ZFP to estimate the water flux in soil to measure recharge to ground water, to compute drainage or evapotranspiration, and to calculate unsaturated hydraulic properties, but there was no study that focused on the ZFP phenomena itself. Since ZFP is governed with many parameters, the studying and analyzing these factors could contribute much to implement several new aspects of applications. The developing of ZFP could be achieved by improving measurements tools and technique, implementing new experiments in laboratory to monitor and study ZFP and using numerical model and simulation for analysis as well.

Measurement

Although it could be concluded that ZFP is uncertain for some field uses, the errors associated with estimation of soil moisture content may be minimized through use of more accurate methods for measuring water content or increasing the number of neutron probe access tubes sampled at the field both action would likely make estimation of ET more reliable.

More accurate methods of quantifying soil water content may include, for example, time-domain reflectometry. Errors associated improperly location of ZFP may be minimized by using time-domain reflectometry method. There is no doubt the fact that accurate definition of the total hydraulic head distribution with the depth, making identification of the ZFP more precise.

Laboratory Experiments

Careful experiments should be carried out in the laboratory to monitor and observe the ZFP in soil column. The factors affecting the ZFP movement will be tested and analyzed. Salt movement and accumulation in soil should be deeply investigated using different types of soils.

Numerical model

One of the powerful tools, which may help much in dealing with ZFP phenomenon, is numerical model. HYDRUS-2D model is used for simulation of water flow and solute transport in two-dimensional variably saturated media. The program numerically solves the Richards' equation for saturated-unsaturated water flow and the Fickian-based advection-dispersion equation for solute transport. Using HYDRUS-2D model could give good assistance to analyze the experimental results and to simulate the complex problems. For example, Hydrus-2D could simulate different topographical problems, such as sloped soil, which are difficult to be simulated at the laboratory.

Salt transportation and accumulation

In fact, the maintaining of ZFP higher than the salt accumulated subsoil, nuclear disposals, contaminated layers.... etc., is practically very important. Therefore the control of ZFP in unsaturated soil is of a great interest where there are many applications especially related to the environmental, agricultural and civil engineering. In addition to hydrological fields. Such knowledge allows us to select the suitable depths in the soil to bury the contaminated disposals in safe way. This knowledge is also important to determine when to irrigate, to calculate the amount of water to apply, and to estimate drainage below the root zone. Furthermore, preserving ZFP above the salt accumulated subsoil is very important to agricultural field. Selecting the convenient depths into the soil to establish an oil pipes network is

affected as well by the ZFP. Protecting the ground water from contamination will be achieved partially by ZFP control.

References

Abdallah, M.A. and Werner, E. (2001) : Field determination of the water balance of the Areuse River delta, Switzerland. Hydrological Sciences-Journal-des Sciences Hydrologiques, **46** (5) 747–760.

Arya, L.M., Farrell, D.A. and Blake, G.R. (1975) : A Field Study of Soil Water Depletion Patterns in Presence of Growing Soybean Roots, I. Determination of Hydraulic Properties of the Soil. Soil Science Society of America Proceeding, **39** : 424–430.

Bouwer, H. (1989) : Estimation and enhancing ground water recharge' in Sharma, M.L., (Ed.). Ground water Recharge, pp. 1–10, A.A. Balkema Publish Co., Rotterdam/ Boston.

Cooper, J.D. (1979) : Water use of a tea estate from soil moisture measurements. East Africans Agricultural and forestry Journal, **43** : 102–121.

Cooper, J.D. (1980) : Measurements of Water Fluxes in Unsaturated Soil in Thetford Forest. Report 66. Institute of Hydrology, Wallingford.

Cooper, J.D., Gardner, C.M.K. and Mackenzie, N. (1990) : Soil control on recharge to aquifers. Journal of Soil Science, **41** : 613–630.

Diez J.A., Caballero R., Roman R., *et al.* (2000) : Integrated fertilizer and irrigation management to reduce nitrate leaching in Central Spain. J ENVIRON QUAL, **29** : 1539–1547.

Dolman, A.J., Stewart, J.B. and Cooper, J.D. (1988) : Predicting forest transpiration from climatological data. Agricultural and Forest Metrology, **42** : 339–353.

Dreiss, S.J. and Anderson, L.D. (1985) : Estimating vertical soil moisture flux at a land treatment site. Ground Water Publishing Co., Westerville, **23** : 503–511.

Gardner, M.K., Cooper, J.D., Wellings, S.R., Bell, J.P., Hodnett, M.G., Boyle, S.A. and Howard, M.J. (1990) : Hydrology of the unsaturated zone of the chalk of south-east England, In Chalk. pp. 611–618, Thomas Telford, London.

Healy, R.W., (1989) : Seepage through a hazardous-waste trench cover. Journal of Hydrology, **108** : 213–241.

Hillel, D. (1971) : Soil and Water. Academic Press, New York and London.

Hillel, D. (1998) : Environmental Soil Physics. Academic Press, New York and London.

Hosty, M. and Mulqueen, J. (1996) : Soil moisture and ground water drawdown in a dry grassland soil. Irish J. Agr. Food Res., **35** : 17–24.

Inoue, M. Tomohisa, Y. and Yasuji, N. (1985) : Application of neutron moisture meter for estimation of evaporation in a sand dune field. J. Fac. Agric., Tottori Univ., **21** : 27–35.

Kalms, J.M., Vauclin, M. and Vachaud, G. (1979) : Modalites d'alimentation hydrique de deux varietes de riz pluvial en Cote d'Ivoire (Centre)" in : Isotopes and Radiation in Research on Soil-Plant Relationships, by IAEA-SM-235, Vienna, p. 271–287.

Kanamori, H. (1995) : Influence of Plow Sole on Moisture Movement in Growing Non-rice Crops on Paddy Based Land, Study on diversified crop water requirements in Philippines. Trans. of JSIDRE, **175** : 95–108.

Kirsch, S.W. (1993) : A field Test of a soil-based measure of evaporatranspiration. Soil Science, **156** : 396–404.

Kutilek, M. and Nielsen, D.R. (1994) : Soil Hydrology. pp. 191–193, CATENA VERLAG, 38162 CREMLINGEN-Destedt, GERMANY.

McGowan, M. and Williams, J.B. (1980) : The water balance of an agricultural catchment, I. Estimation of evaporation from soil water records. Journal of soil Science, **31** : 217–230.

Miyazaki, T., Hasegawa, S. and Kasubuchi, T. (1993) : Water flow in soils. pp. 6–11, Marcel Dekker, INC., New York.

Payne, W.A., Wendt, C.W. and Lascano, R.J. (1990) : Bare fallowing on sandy fields of Niger, West Africa. Soil Sci. Soc. Am. J., 54 : p. 1079–1084.

Ragab, R., Finch, J. and Harding, R. (1997) : Estimation of Ground water recharge to Chalk and Sandstone aquifers using Simple soil models. Journal of Hydrology, **190** : 19–41.

Richards, L.A. (1954) : Multiple tensiometer for determining vertical component of the hydraulic gradient in soil. Soil Science Society of America Proceeding, **18** : 7–10.

Richards, L.A., Gardner, W.R. and Ogata, G. (1956) : Physical Processes Determining Water Loss from Soil. Soil Science Society of America Proceeding, **20** : 310–314.

Roman, R., Cabllero, R., Bustos, A., Diez, J.A., Cartageno, M.C., Ballejo, A. and Caballero, A. (1996) : Water and solute movement under conventional corn in Central Spain, I Water balance. Soil Sci. Soc. Am. J., **60** : 1530–1536.

Roman, R., Caballero, R. and Bustos, A. (1999) : Field water drainage under traditional and improved irrigation schedules for corn in central

Spain. Soil Sci. Soc. Am. J. **63** : 1811–1817.

Royer, J.M. and Vachaud, G. (1974) : Determination direct de l'evapotranspiration et de l' Infiltration par measures des teneurs en eau et des succions. Hydrological Sciences bulletin, **19** : 319–336.

Sharma, M.L. (1985) : Estimating Evapotranspiration. IN advances in Irrigation, vol. 3. D. Hillel (ed.). Academic Press, New York.

Sharma, M.L., Bari, M. and Byrne, J. (1991) : Dynamics of seasonal recharge beneath a semiarid vegetation on the Gnangara mound, western-Australia. Hydrol process, **5** : 383–398.

Simmers, I. (1987) (Ed.) : Estimation of natural ground water Recharge. P. 510, D. Reidel Publish. Co., Dordrecht.

Stammers, W.N., Igwe, O.C. and Whiteley, H.R. (1973) : Calculation of evaporation from measurements of soil water and the soil water characteristics. Canadian Agricultural Engineering, **15** : 2–5.

Stone, L.M., Horton, M.L. and Olsen, T.C. (1973) : Water loss from an irrigated sorghum field, I. Water flux within and below the root zone. Agronomy Journal, **65** : 492–495.

Tang, C.Y. (1996) : Interception and recharge processes beneath a Pinus elliotii forest Hydrol process, **10** : 1427–1434.

Thony, J.L., Hamburger, J., Vauclin, M. and Vachaud, G. (1979) : Etude detaillee de I evaporation sur sol nu. in : Isotopes and Radiation in Research on Soil-Plant Relationships, p. 247–258, IAEA-SM-235,Vienna.

Tsujimura, M., Numaguti, A., Tian, L. *et al.* (2001) : Behavior of subsurface water revealed by stable isotope and tensiometric observation in the Tibetan Plateau, J. Meteorol Soc. Jpn., **79** : 599–605.

Van Bavel, C.H.M., Burst, K.J. and Strik, G.B. (1968) : Hydraulic properties of a clay loam soil and the field measurements of water uptake by roots, II, The water balance of the root zone. Soil Science Society of America Proceeding, **32** : 317–321.

Van Hylckama, T.E.A. (1980) : Weather and evapotranspiration studies in a salt cedar thicket, Arizona, U.S. Geol. Surv. Prof. Pap., 491-F : 78 pp.

Villegas and Morris. (1990) : ZFP recession under monocropped and intercropped cowpea and sorghum. Agron j, **82** : 845–851.

Wellings, S.R. (1984). : Recharge of the upper chalk aquifer at a site in Hampshire, England, Water Balance and Unsaturated Flow. Journal of Hydrology, **69** : 259–273.

Wellings, S.R. and Bell, J.P. (1980) : Movement of water and nitrate in the unsaturated zone of upper chalk near Winchester, Hants, England. Journal of Hydrology, **68**, 119–136.

Yamamura, Y., Cho, T. and Kuroda, M. (1988) : Evaluation on Consumptive Use of Water in Actual Fields affected by Soil Moisture Movement —In case of the Kuroboku soil in the Southern Kyusyu—. Trans. JSIDRE, **134** : 35–44.

Appendix

Water balance equation above ZFP can be written as :

$$R=E+\Delta\theta \tag{1}$$

where :

R is the rainfall over the period t_1 to t_2,

E is the evaporation over the period t_1 to t_2,

$\Delta\theta$ is the volumetric water content change above ZFP.

Since the decrease of water content (θ) between z_0 (t_1) and z_0 (t_2) due to evaporation is approximated by $\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_2)-\theta(t_1)\Big]dz$

Volumetric water content change $\Delta\theta$ above ZFP is given by

$$\begin{aligned}\Delta\theta&=\int_0^{z_0(t_1)}\theta(t_2)dz-\int_0^{z_0(t_1)}\theta(t_1)dz\\&\quad+\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_2)-\theta(t_1)\Big]dz\\&=\Big[\int_0^{z_0(t_2)}\theta(t_2)dz-\int_{z_0(t_1)}^{z_0(t_2)}\theta(t_2)dz\Big]\\&\quad-\int_0^{z_0(t_1)}\theta(t_1)dz+\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_2)-\theta(t_1)\Big]dz\\&=-\int_0^{z_0(t_1)}\theta(t_1)dz+\int_0^{z_0(t_2)}\theta(t_2)dz\\&\quad\Big[-\int_{z_0(t_1)}^{z_0(t_2)}\theta(t_2)dz\frac{1}{2}\Big[\int_{z_0(t_1)}^{z_0(t_2)}\theta(t_2)-\theta(t_1)\Big]dz\Big]\\&=-\int_0^{z_0(t_1)}\theta(t_1)dz+\int_0^{z_0(t_2)}\theta(t_2)dz\\&\quad-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz.\end{aligned}\tag{2}$$

Substitution of (2) into (1) gives

$$\begin{aligned}R=E&-\int_0^{z_0(t_1)}\theta(t_1)dz+\int_0^{z_0(t_2)}\theta(t_2)dz\\&-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz\end{aligned}$$

or ;

$$\begin{aligned}E=R&+\int_0^{z_0(t_1)}\theta(t_1)dz-\int_0^{z_0(t_2)}\theta(t_2)dz\\&+\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz\end{aligned}$$

Since water balance equation for whole soil profile is

$$R=E+D+\Delta\theta \tag{3}$$

where :

R is the rainfall over the period t_1 to t_2,

E is the evaporation over the period t_1 to t_2,

D is the drainage over the period t_1 to t_2,

$\Delta\theta$ is the volumetric water content change from zero to arbitral depth Z.

$$\begin{aligned}R&=E+D+\int_0^{Z}\Big(\theta(t_2)-\theta(t_1)\Big)dz\\D&=R-E-\int_0^{Z}\Big(\theta(t_2)dz+\int_0^{Z}(\theta(t_1)\Big)dz\\D&=R-R-\int_0^{z_0(t_1)}\theta(t_1)dz+\int_0^{z_0(t_2)}\theta(t_2)dz\\&\quad-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz\\&\quad-\int_0^{Z}\Big(\theta(T_2))dz+\int_0^{Z}(\theta(t_1)\Big)dz\\D&=R-R-\int_0^{z_0(t_1)}\theta(t_1)dz+\int_0^{z_0(t_2)}\theta(t_2)dz\\&\quad-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz\\&\quad-\Big(\int_0^{z_0(t_2)}\theta(t_2)dz+\int_{z_0(t_2)}^{Z}(\theta(t_2))dz\Big)\\&\quad+\Big(\int_0^{z_0(t_1)}\theta(t_1)dz+\int_{z_0(t_1)}^{Z}(\theta(t_1))dz\Big)\\D&=\int_{z_0(t_1)}^{Z}\Big(\theta(t_1))dz)-\int_{z_0(t_2)}^{Z}(\theta(t_2))dz\Big)\\&\quad-\frac{1}{2}\int_{z_0(t_1)}^{z_0(t_2)}\Big[\theta(t_1)+\theta(t_2)\Big]dz.\end{aligned}\tag{4}$$

ゼロフラックス面（ZFP）法の適用性に関する現状と展望

マグディ・カリル*・坂井　勝*・溝口　勝*・宮﨑　毅*
* 東京大学大学院農学生命科学研究科生物・環境工学専攻　〒113-8657 東京都文京区弥生 1-1-1

要　　旨

ゼロフラックス面（Zero Flux Plane : ZFP）法は，土壌中の ZFP を利用して蒸発，蒸発散および地下水涵養などの水循環過程を予測する手法である。しかし，ZFP 法そのものに関する体系的な議論は成されていない。本総説では，ZFP の物理的定義とそれを使った蒸発量と排水量の数学的導出法について述べ，次に ZFP 法についての既存のデータを包括的に分析し，各水循環過程の予測に対する適性，また ZFP 法を使用する上での問題点を挙げた。さらに，ZFP を制御することは土壌中の塩類集積防止や汚染物質の拡散防止に多大な役割を果たすと考えられるので，ZFP 挙動の実験手法と予測手法について，今後の研究展望を論じた。

キーワード：ゼロフラックス面，不飽和土壌，ハイドラス 2D，塩類集積，土壌汚染

受稿年月日：2003 年 5 月 16 日
受理年月日：2003 年 10 月 8 日