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Soil Moisture and Groundwater Drawdown in a Dry Grassland Soil

M. Hosty[1] and J. Mulqueen[2]
[1]*Department of Civil Engineering, Regional Technical College, Galway*
[2]*Teagasc, c/o Department of Civil Engineering, University College, Galway*

A study of soil moisture is reported for a free-draining podzolic soil with a watertable at 4 m below ground level. This soil type, derived from limestone glacial deposits, is common in Ireland. Pore-water content and negative pore-water pressure were measured throughout the summer of 1992. Evapotranspiration and drainage to the groundwater were computed using both the zero flux plane and the water balance methods. Examples of soil hydraulic potential and soil moisture content profiles are presented. A mathematical model was used to model the soil moisture profile for a dry summer. Field results showed that a zero flux plane developed in early May and moved intermittently downwards to a maximum depth of 1.5 m as the summer progressed. The hydraulic potential and pore-water-content profiles responded to the continuously changing balance between evapotranspiration and rainfall. Pumping of the aquifer to lower the watertable by 3.5 m had no effect on the soil moisture above the watertable. There was reasonable agreement between measured evapotranspiration and the predicted values derived by Penman's equation (MAFF, 1967). The model study indicated that the zero flux plane reached a maximum depth of 1.75 m in a dry summer.

Keywords: Evapotranspiration; groundwater recharge; soil moisture

Introduction

About 67% of the landmass of Ireland consists of rolling and gently undulating lowlands (Gardiner and Radford, 1980). Most of these lowlands comprise dry free-draining soils overlying moderate to deep watertables, depending on their physiographic location. The soils are mainly under grassland. There is little or no information on their moisture status and dynamics. This paper describes the results of a study of the soil moisture of these dry grasslands and the effects of groundwater drawdown and includes a model study on the effects of a dry summer.

The objectives of the study were (i) to measure soil moisture flux and soil moisture content during the course of a growing season; (ii) to measure the effects of lowering the ground watertable on soil moisture status and content; (iii) to model the results and use the model to predict the soil moisture status of dry grasslands in a year with low rainfall and high evapotranspiration.

Prior to the recent application of soil physical techniques in water balance studies, the difference between rainfall and evapotranspiration was often used to determine moisture balances and deficits, e.g. Gardiner (1986). Rainfall is estimated from rainfall gauges mounted at a point and evapotranspiration by calculation. Errors arise in both measurements and estimates, and give rise to considerable uncertainty (Cooper, Gardner and MacKenzie, 1990). Measurement or estimation of water flux in unsaturated soils is difficult. To use Darcy's equation to estimate flux requires accurate values for hydraulic conductivity over the range of soil moisture contents found in field soils (Hanks and Ashcroft, 1980). This approach is impractical because of the wide range of hydraulic conductivity values found in soils, their spatial variation and hysteresis (Cooper *et al.*, 1990). To overcome these difficulties the zero flux plane (ZFP) and water balance methods may be employed. The ZFP method is used in the summer season in times of low soil moisture and the water balance method in other periods when there is no ZFP.

Methods

Estimation of evapotranspiration and drainage

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 depths soil water moves downwards towards the watertable due to gravity. Dividing the upward from the downward moving soil moisture is a plane where there is zero flux, called the zero flux plane (Cooper *et al.*, 1990). Above this plane, any reduction in the soil moisture content must be due to moisture loss caused by an excess of evapotranspiration over infiltration. Below the ZFP, and assuming no uptake of moisture by roots at these depths, reductions in moisture content must be due to drainage out of the soil, i.e. recharge to the ground watertable.

The ZFP moves downwards as loss to evapotranspiration increases over the growing season. Equations have been developed by Stammers, Igwe and Whiteley (1973) to estimate evapotranspiration and drainage using the ZFP method.

In using the ZFP method it is assumed (Cooper *et al.*, 1990) that:

(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 underestimated.

(3) There is no surface run-off or, if there is, it is accounted for.

Where no ZFP exists, the water balance method must be used. This, typically, occurs from late Autumn to mid-Spring. During this period evapotranspiration may be calculated from Penman's equation (MAFF, 1967) and the drainage is then estimated as the difference between rainfall and evapotranspiration.

Site Description and Instrumentation

The study site is located in the townland of Lisheen, near Thurles, Co. Tipperary, on a dry morainic hillock at an elevation of 129 m OD. It is in dry grassland and is typical of the gently rolling grassland landscape of the general region. Two test pits were excavated: test pit 1 on the higher portion of the hill and test pit 2 on slightly lower ground. Test pit 1 was on the dominant land form on which the instrumented site was located. The soil overburden was 4 m thick, overlying jointed and permeable Waulsortian limestone (Hitzman, 1992). The soil was derived from glacial drift of predominantly limestone origin and consisted of a 0.27 m thick topsoil overlying a sandy loam which became progressively more stony with depth. The rooting depth was about 0.5 m. Below 1 m, large limestone boulders (> 1 m in cross section) became more plentiful with depth. The soil may be classed as a grey brown podzolic. At test pit 2 the soil overburden was 0.9 m thick and was also a grey brown podzolic soil. The watertable in both test pits was about 4 m below ground level. Rainfall for the area averages 875 mm per annum.

The following instruments were located at the experimental site: one automatic soil moisture tensiometric monitoring station, four neutron probe access tubes to a maximum depth of 3 m, eight soil-moisture gypsum blocks in the top 0.25 m soil layer for soil moisture tensions above 80 kPa and one tipping-bucket rain recorder.

The soil moisture monitoring station consisted of a battery of nine tensiometers inserted at increasing depths in the soil up to a maximum depth of 2.7 m and connected to a manifold of latching valves. Each tensiometer was scanned sequentially through its valve using a negative pressure transducer and the data were stored in a data logger and downloaded weekly onto a computer. Instruments at depth were installed in bore holes, made with an 85 mm drill because of the stones and boulders. The annulus between the instrument and the borehole wall was filled with slurried soil from the subsoil and topsoil, as appropriate, to maintain the soil layering.

Results

The zero flux plane

The ZFP first became established between 13 and 20 May as evapotranspiration exceeded rainfall (Figure 1). As the summer

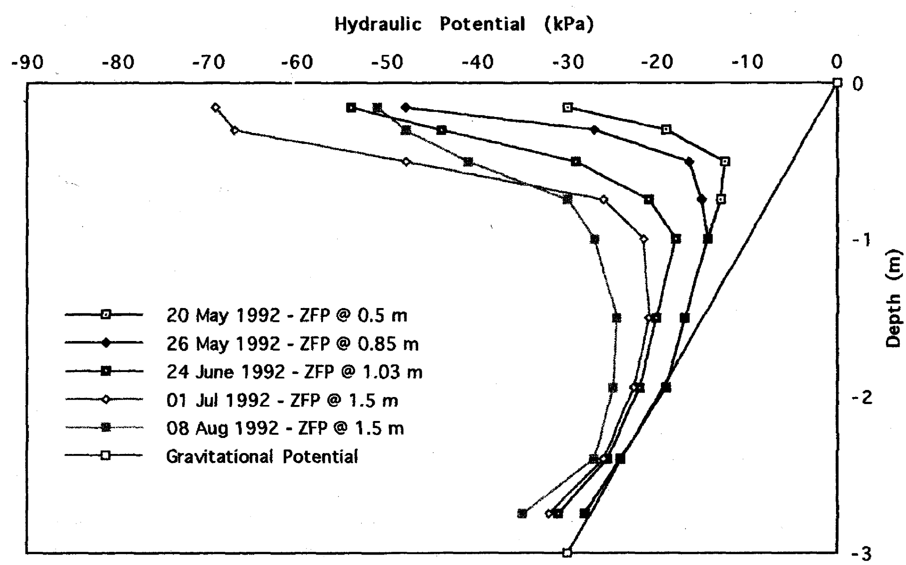

Figure 1: Downward progression of the zero flux plane (ZFP).

progressed it gradually moved down the soil profile to reach a maximum depth of 1.5 m during July and August.

Soil moisture response to rainfall

Figure 2 shows profiles of hydraulic potential for 6 and 14 July, a period when 25 mm of rain fell. This rainfall was sufficient to increase the hydraulic potentials down to 0.5 m. Strong positive hydraulic gradients became established between the soil surface and the 0.5 m depth plane on 14 July, indicating drainage downwards. At the same time, there were still strong negative gradients between the 0.5 m and 1.5 m depth planes, indicating upward flows in this soil layer. Thus, the water distribution in the soil profile represents a continuously changing balance between rainfall and evapotranspiration.

Soil moisture response to drawdown of the watertable by pumping

Pumping of the aquifer took place from 25 August to 15 September at an average discharge of 155 m^3/h. This had the effect of lowering the watertable at the measurement site from 4 m to 7.5 m below ground surface. On 20 August the ZFP was 1.5 m below ground surface. As a result 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 (Figure 3). Although pumping of the aquifer was on-going during this period, it is significant that the soil moisture profile above the watertable was determined by the balance between rainfall and evapotranspiration.

Soil moisture content in the root layer (0 to 0.25 m depth)

During the test period, the lowest soil moisture suction recorded was −1200 kPa at a depth of 0.05 m (26 June). Throughout the test period there was no evidence of wilting, although the grass may have suffered some moisture stress for short periods.

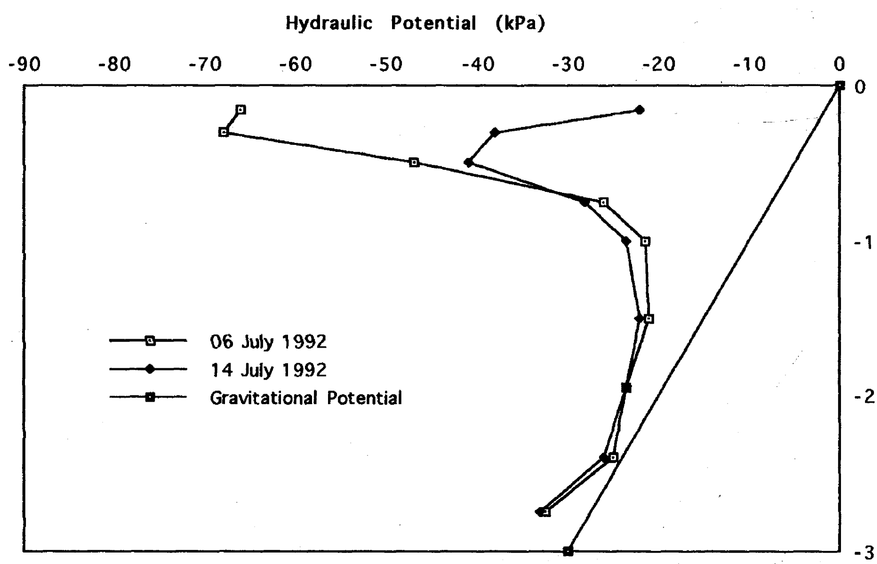

Figure 2: Hydraulic potential profiles in response to rainfall.

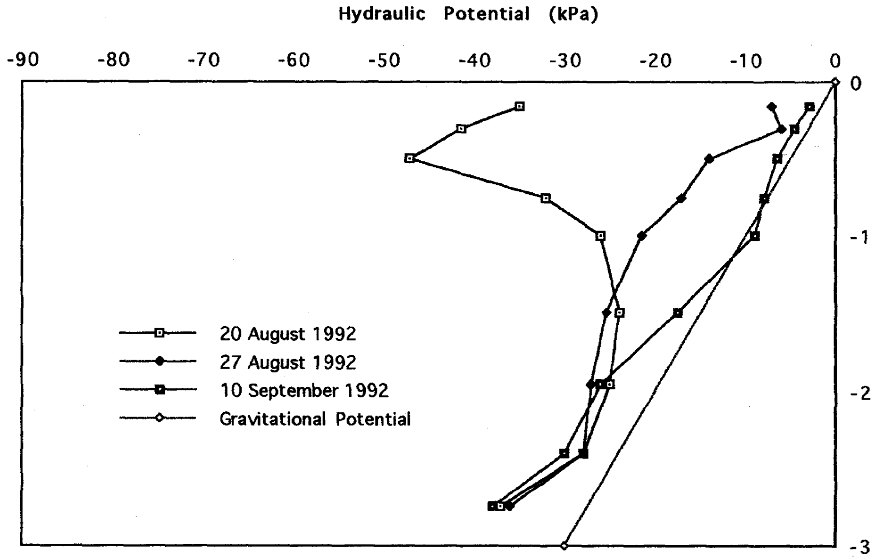

Figure 3: Hydraulic potential profiles before and during pumping tests.

Calculation of evapotranspiration and drainage

After the appearance of the ZFP, evapotranspiration and drainage were calculated on a weekly basis. There was a large variation in profile moisture content (Figure 4) due to variation in the stone content. For this reason, the area between profiles was calculated by sub-dividing the total area into horizontal sub-areas and summing. Table 1 shows the calculated evapotranspiration and drainage to the groundwater for a few periods. Taking into account that there may have been significant differences between average weather conditions and those in 1992, there is reasonable agreement between the two estimates of evapotranspiration. It is evident from Table 1 that there was a steady decline in drainage until the end of August when heavy rainfall again restored significant drainage fluxes.

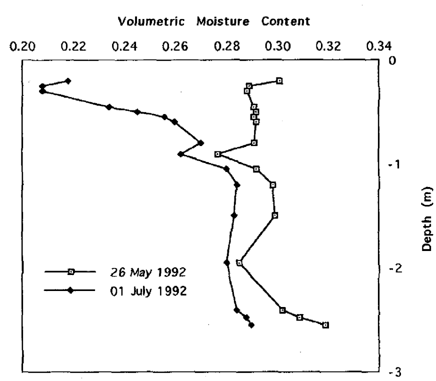

Figure 4: Volumetric moisture content of the soil.

Table 1. Evapotranspiration and drainage at Lisheen, 1992

Period	Evapo-transpiration (mm)	MAFF Ep[1] (mm)	Drainage (mm)
12 May to 3 June	69	55	49
4 June to 1 July	87	75	17
2 July to 2 August	67	82	15
3 August to 20 August	38	38	8

[1] Ep – potential evapotranspiration calculated for average weather conditions using Penman's formula (MAFF, 1967).

Modelling of soil moisture for a dry year

Rainfall data were available for Templetuohy, about 2 km distant from the measurement site, for a 29-year period (1961 to 1989). The rainfall data were plotted on probability paper and return periods derived for annual and seasonal (May to August) low rainfalls. The lowest annual rainfall occurred in 1971 and the lowest seasonal rainfall was in 1984. This latter period was modelled by inputting the daily rainfall data. Potential evapotranspiration data for Carlow, about 50 km to the east, were used for the same period. The model LEACHM developed by Wagenet and Hutson (1989) was used to model the data. This model describes the soil water regime and the flux of chemicals leached in an unsaturated soil. LEACHW, which is a module in LEACHM, describes the soil pore-water regime only.

LEACHW requires the following input data:

(i) meteorological data – dates and amount of rainfall and estimates of evapotranspiration;

(ii) soil profile data – profile depth, particle size analysis, hydraulic conductivity estimates, depth to watertable;

(iii) crop data – time of planting and harvest, wilting point for crop.

The output from LEACHW comprises:

(i) a table of profile pore-water retentivity and hydraulic conductivity data;

(ii) a cumulative mass balance summary for the soil profile;

(iii) soil profile pore-water content, hydraulic potential and hydraulic flux.

Figure 5 shows comparisons of measured and predicted hydraulic potential profiles for 1992 and Table 2 shows a comparison of predicted depths of the ZFP with measured depths. Figure 5 and Table 2 indicate moderately close agreement between predicted and measured values. The predicted hydraulic potential profiles in the dry May to August period of 1984 are shown in Figure 6 for three dates to illustrate the results. They indi-

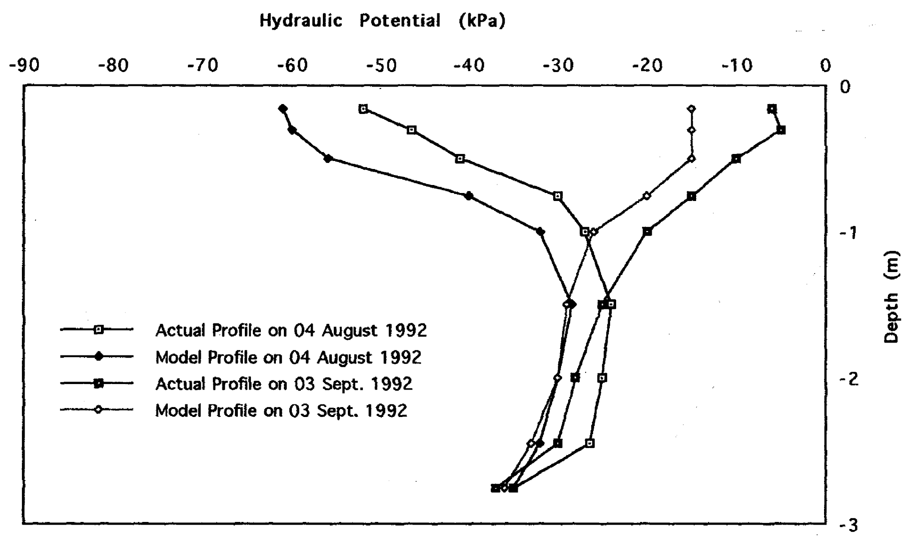

Figure 5: A comparison between predicted and measured hydraulic potential profiles on two dates at Lisheen showing the zero flux plane (ZFP) at the same elevation.

Table 2. Actual depths of zero flux plane (ZFP) compared with depths predicted from LEACHW for Lisheen, 1992

Date	Depth (m) of ZFP	
	Actual	Model
3 June	0.85	0.85
9 June	0.85	1.03
17 June	1.03	1.03
24 June	1.03	1.03
1 July	1.03	1.25
6 July	1.25	1.50
14 July	1.50	1.50
22 July	1.50	1.50
26 July	1.50	1.50
2 August	1.50	1.50
13 August	1.50	1.50
20 August	1.50	1.50
27 August	1.30	1.20

cate that the maximum depth of the ZFP was likely to have been at 1.75 m below ground level and that below this depth hydraulic gradients were always positive, indicating recharge to the groundwater. Strongly negative hydraulic gradients towards the soil surface above the ZFP indicate upwards flow to evapotranspiration. Hydraulic potentials less than –1500 kPa (wilting point) were predicted on only one day, at a depth of 0.05 m.

Discussion

The measurements of soil moisture content and pore-water pressure over the May to September period of 1992 on a free-draining grey brown podzolic soil showed that the soil moisture content and flux are determined by the balance between rainfall and evapotranspiration. In dry weather, negative hydraulic gradients become established in the upper soil layers in response to excess evapotranspiration and positive hydraulic gradients persist in the deeper soil layers indicating continued drainage to the watertable. The zone of negative gradients is separated from the zone of positive gradients by a ZFP which moves downwards in the soil as evapotranspiration exceeds rainfall. Soil moisture suction did not reach wilting point in 1992 at any depth in the soil. Lowering the watertable had no effect on the soil

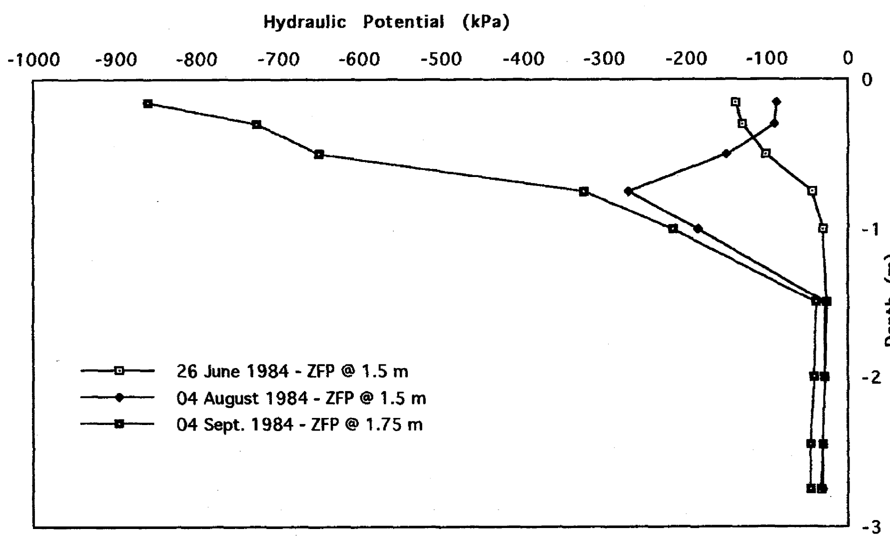

Figure 6: Predicted hydraulic potential profiles at Lisheen for the dry summer of 1984.

moisture in this study, where it (the water-table) was initially deep and well below the root zone. The LEACHW model was calibrated using the field data measured in 1992. It was then applied to predict the hydraulic potential profiles in the soil for the dry summer of 1984. It indicated a maximum depth of the ZFP of 1.75 m below ground level and wilting point was predicted only on one day and this only at a depth of 0.05 m.

The soil moisture measurements from this study confirm the suitability of soils derived predominantly from limestone for cropping. They indicate that shallow-rooted crops such as grass and root crops had good reserves of soil moisture available to them, as matric potentials for much of the year were in the range of –15 kPa to –40 kPa, the optimum for maximum crop growth (Taylor and Ashcroft, 1972). The results of the investigation are similar to those of Cooper *et al.* (1990) for a number of sites and Gardner *et al.* (1989) and Wellings (1984) for chalk aquifers in England.

The procedures employed in this study can be used to compute groundwater recharge and in conjunction with pore-water samples to determine leaching fluxes from soils, sludge disposal grounds and landfills. In addition, modelling of soil moisture can provide valuable predictions in many situations, for example, in relation to crop growth, groundwater recharge and soil conditions for trafficability.

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