Hydraulic conductivity of a wheat crop with a complete cover

J.M. DE JAGER, K.L. BRISTOW* AND W.H. VAN ZYL
Department of Agrometeorology, University of the Orange Free State, P.O. Box 338, Bloemfontein 9300, South Africa

Abstract

The concept of whole crop hydraulic conductivity (ϕ) for the wheat crop was defined and evaluated. Measurements of leaf water potential (ψ_ℓ), soil water potential (ψ_s) and crop evaporation (E) were used. Hydraulic conductivity was found to be linearly related to evaporation rate. This implies that some feedback mechanism operates which requires the maintenance of a constant vertical potential gradient through the crop for the given growth stage.

Introduction

Movement of water from the roots to the leaves of a plant is essential for its survival. In order to maintain a balance between transpiration and absorption, the water column in the conduction system must be continuous. As atmospheric demand increases, transpiration will increase in response to the decrease in water potential which takes place in the xylem sap of the leaves. Water now flows from the high potential areas of the soil and roots to the leaves which are at low potential. Under excessive transpiration, water becomes limiting and the supply may not be able to meet the evaporative demand.

An Ohm's law analogy between the flow of electricity through a conductor and the flow of water through the soil-plant-atmosphere continuum has been used to explain the water transfer process (De Jager and Kaiser, 1977; Hansen, 1974a; Hansen, 1974b; and Lawlor and Lake, 1976). This analogy requires water to move along gradients of decreasing water potential. One complicating factor in the biological system is the change in state of water from liquid to vapour which occurs at evaporating surfaces such as the leaf and soil surface. For this reason water movement through the soil-plant-atmosphere continuum is treated in two stages. In soils and plants the movement of water is by the flow of liquid, while from evaporating surfaces to the air, water transfer is in the form of vapour diffusion. The driving forces and resistances to flow in the liquid and vapour differ entirely and should not be confused.

One dimensional movement of liquid phase water can be expressed according to Campbell (1977) as

$$E = -\phi\frac{\delta\psi}{\delta z} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where

E = the water flux density,
ϕ = the hydraulic conductivity,
$\frac{\delta\psi}{\delta z}$ = the water potential gradient,
ψ = the water potential, and
z = the height.

A practical application of the concept results from the solution of Eqn. 1, but requires pre-knowledge of the value of the hydraulic conductivity, ϕ. If ϕ is known, Eqn. 1 may be used to calculate leaf water potential given transpiration rate and soil water potential. This calculated leaf water potential may then be used to indicate whether the existing atmospheric and soil water conditions are inducing plant water stress and are adversely affecting growth rate. This type of information is essential for the mathematical simulation of crop growth, final yield prediction and irrigation scheduling.

The objective of the work here reported has been to:

- investigate the behaviour of crop hydraulic conductivity (ϕ) of a wheat crop with a complete cover under various soil and weather conditions, and
- establish the relationship of ϕ to atmospheric evaporative demand and soil water condition.

Theory

In order to carry out the investigation the following assumptions were made:

- The whole wheat crop hypothetically approximates a conduit with water flowing into a bottom horizontal plane surface (roots) and evaporating from a top horizontal plane surface (leaves). The momentum exchange surface, computed as 0,77 x crop height (Monteith, 1973), is deemed to be the top effective horizontal plane.
- The bottom surface of concern is situated 0,2 m below the soil surface. This is the level at which the roots were predominantly concentrated during the measurement period. It shall henceforward be referred to as the effective rooting depth.
- The length of the conduit is taken to be equal to the distance between the momentum exchange surface and the effective rooting depth.
- There is no lateral exchange of water vapour above the top effective crop surface.
- A continuous mass flow of water exists from the soil through the conduit (the roots, stems and leaves) and out into the atmosphere, i.e. the liquid flow rate through the plant equals the rate of evaporation at any given time.
- The crop is considered to be an inert conduit. The various interfaces between soil and root and leaf and air are not treated separately and all leaves effectively operate at the momentum exchange surface.

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*Present address: Division of Biological Resources, CSIRO, P/Bag P.O. Aitkenvale, QLD 4814, Australia

- *Soil evaporation is considered* negligible for a crop with full canopy cover.

- *Storage of water in the* wheat plants is negligible.

Hence, for a complete vegetative surface, the mass flow equation (Eqn. 1) *can* be *transformed* to the integrated form

$$E = -\phi\frac{(\psi_\ell - \psi_s)}{(z_\ell - z_s)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where, for the units used in this study,

E = the crop evaporation rate (mm h^{-1}),
ϕ = the hydraulic conductivity (mm h^{-1}.$mbar^{-1}$),
ψ_ℓ = *the leaf water potential* (bar: 1 bar = 100 kPa)
ψ_s = the soil water potential (bar),
z_ℓ = the height of the momentum exchange surface (m), and
z_s = the depth at which ψ_s is measured (m).

Method

An area of 1 ha of wheat was established at the Agrometeorology Observatory of the University of the Orange Free State. The crop was planted on 14 May, 1979 at a *seeding rate of 100 kg* ha^{-1}. Hydraulic conductivity (ϕ) was evaluated from Eqn. 2 under numerous sets of soil and atmospheric demand conditions which occurred around anthesis when crop height *varied from 0,54 m to* 0,63 m. Water flux density measurements were obtained from a micrometeorological reiterative estimate of crop evaporation (Bristow and De Jager, 1981). *Water flux density was set equal to* evaporation rate. Hourly mean leaf water potential was determined from eight measurements per hour obtained by means of the Scholander pressure chamber (Scholander, *Hammel, Bradstreet* and Hemmingsen, 1965). Soil water potential was determined daily at a depth of 0,2 m using the gravimetric technique of soil water measurement and soil *water characteristic curves* established for the experimental site. From these measurements ϕ was calculated for 40 sets (hourly) of different conditions within the soil-plant-atmosphere *continuum. All measurements* were made between 09h00 and 16h00.

Results and discussion

Daily data and experimental dates are given in Table 1. The observations covered a full range of atmospheric and soil water conditions. The latter varied between field capacity and *wilting* point.

TABLE 1
THE CROP HEIGHT (h), SOIL WATER POTENTIAL (ψ_s), OPEN PAN EVAPORATION (E_o) AND DAILY EVAPORATION (E) DETERMINED BY THE ITERATIVE METHOD PREVAILING ON THE EXPERIMENTAL DAYS UPON WHICH ϕ WAS DETERMINED

Date	Crop height	ψ_s	E_o	E
	(cm)	(bar)	(mm)	(mm)
11/10/79	54	− 7,4	9,6	7,1
15/10/79	55	− 16,4	7,1	6,5
22/10/79	60	− 0,3	7,0	8,6
29/10/79	61	− 2,8	12,4	6,5
01/11/79	62	− 2,2	10,5	7,8
05/11/79	63	− 2,1	13,1	7,8

Fig. 1 illustrates the typical daily scenario of hydraulic conductivity, vertical water potential gradient and *water* flow through the crop. Note the apparent flattening in the water potential gradient curve. This type of curve was noticeable on all the experimental days.

In Fig. 2 the relationship between water potential gradient, $\frac{\delta\psi}{\delta z}$, and water flux density is shown. In the electrical case the relation between potential gradient and current is linear, the slope of the curve being equal to resistance. This is not the case in Fig. 2 where *the water potential gradient appears* to be independent of evaporation rate. The mean $\frac{\delta\psi}{\delta z}$ value for Fig. 2 is 33 bar m^{-1} which is indicated by the solid line. The standard deviation is 3 bar m^{-1}. The existence of a constant vertical water potential gradient implies that hydraulic *conductivity must* be linearly related to crop evaporation rate, at least during the growth stage during which these measurements were made. Deviation of $\frac{\delta\psi}{\delta z}$ from this constant value occurred during the early morning or late afternoon when evaporative demand changed rapidly. Water loss during *these time periods is*, however, low (E < 0,2 mm h^{-1}). Inaccuracies introduced by adopting the constant gradient theory, or even neglecting these periods, would have little impact when, for example, *simulating daytime* leaf water potentials.

Rearrangement of Eqn. 1 and substitution of 33 bar m^{-1} for the water potential *gradient gives*

$$\phi = 0{,}03\,E \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

if the same units are used as in Eqn. 2. This predicts that the ease with which water flows through the crop improves as the actual water flux *increases. Results obtained* by other authors (Stoker and Weatherley, 1971; Hansen, 1974a; Hansen, 1974b, and Lawlor *et al.*, 1976) on plant resistances confirm this result. These *authors found that plant resistance* diminished as the flux increases.

De Jager and Kaiser (1977) stated that hydraulic conductivity *is analogous* to electrical conductivity and that it determines the rapidity with which stressed conditions are induced. A value of 0,2 mm h^{-1}.$mbar^{-1}$ was suggested as being appropriate for *the maize crop* just prior to the induction of stress. First approximations thus suggest that the hydraulic conductivity of a whole maize crop could be as much as six times that of a whole wheat *crop*.

Evidently some feedback mechanism operates tending to improve conductivity as evaporative demand and rate of water *movement increases.* As evaporative demand increases in the *early morning,* $\frac{\delta\psi}{\delta z}$ will increase to a value which it will hold for the rest of the day until evaporative demand abates. The daily course of the vertical water potential gradient (Fig. 1) together with data observed by Bristow *et al.* (1981), support this conclusion.

The scatter in the plotted points describing the control of water potential gradient by crop *evaporation rate (Fig. 2) could* result from soil water potential, ψ_s, being measured at only one

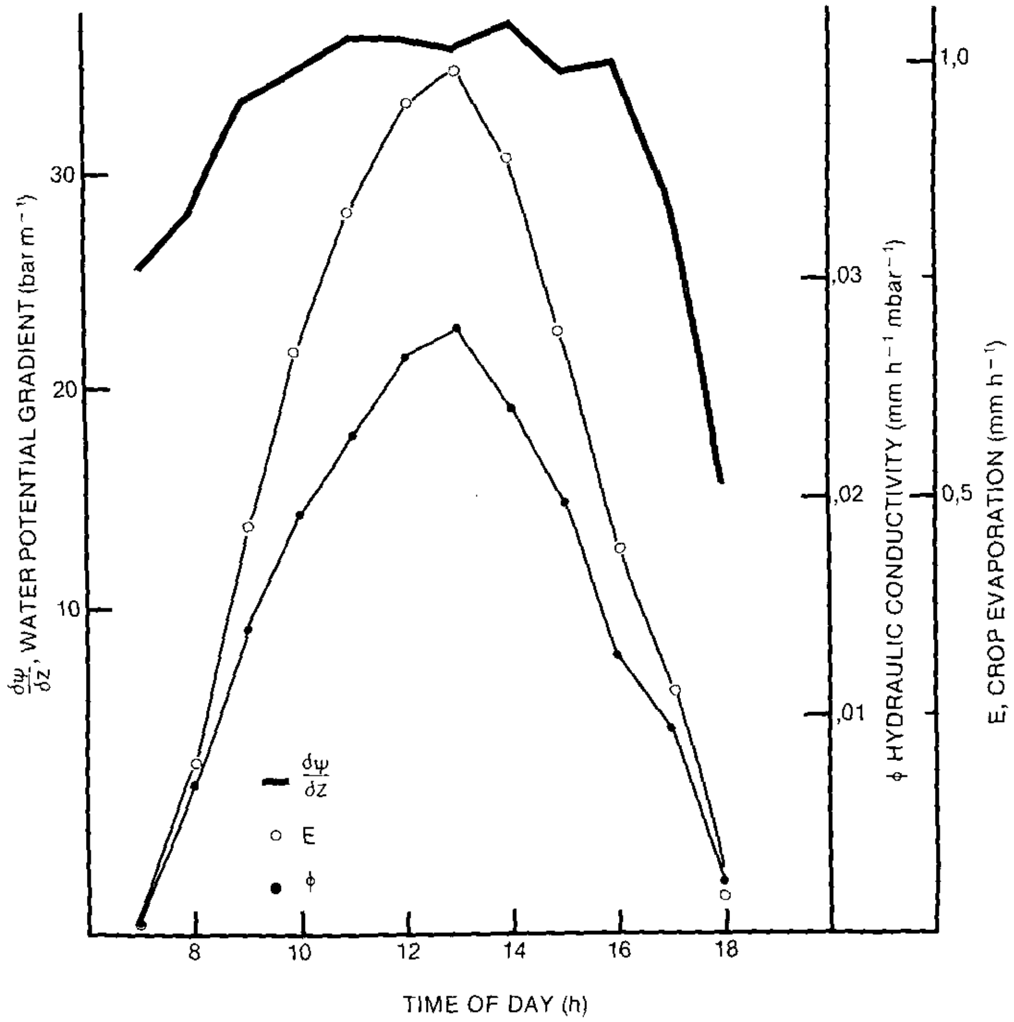

Figure 1

Diurnal variation in hydraulic conductivity, ϕ, crop evaporation rate, E, and water potential gradient through the whole wheat crop system, $\frac{\partial\psi}{\partial z}$*, on 1979/10/29.*

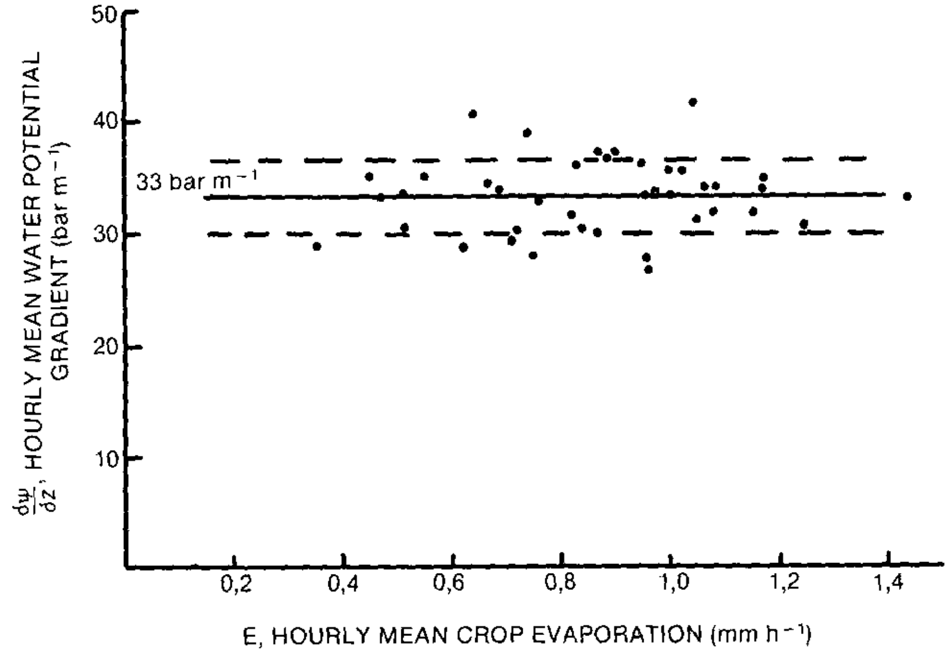

Figure 2

The relationship between the vertical water potential gradient, $\frac{\partial\psi}{\partial z}$*, and crop evaporation rate, E.*

depth (0,2 m). The consequence of soil water potential gradients upon the determination of ϕ deserves to be investigated.

Conclusion

The first approximation function determined in this work suggests that ϕ depends to a large extent upon E. During anthesis ϕ was found to be a predictable function of E, *viz.* $\phi = 0{,}03$ E. Variable ϕ implies that some feedback mechanism operated within the wheat crop which regulated the potential gradient $(\frac{\delta\psi}{\delta z})$ in accordance with E so that it remained constant. As a result, ψ_ℓ (measured − ve) decreased in the early morning to a certain value which was maintained constant for the major part of the day. In the late afternoon ψ_ℓ again increased tending towards the value of ψ_s as the soil plant system reached a state of water status equilibrium under night conditions.

Acknowledgements

The authors wish to acknowledge the assistance of Mr A. van Rooyen in the cultivation of the wheat crop and the collection of field data. The financial support of the Water Research Commission is gratefully acknowledged.

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