Coupled soil–atmosphere modelling for soil evaporation

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Received August 11, 1992

Accepted September 9, 1993

Traditional methods of evaluating evaporation provide an estimate of the maximum or potential rate of evaporation determined on the basis of climatic conditions. Methods such as these are appropriate for open water or fully saturated soil surfaces. Actual rates of evaporation from unsaturated soil surfaces are generally greatly reduced relative to the potential rate of evaporation. A theoretical model for predicting the rate of evaporation from soil surfaces is presented in this paper. The model is based on a system of equations for coupled heat and mass transfer in soil. Darcy's Law and Fick's Law are used to describe the flow of liquid water and water vapour, respectively. Heat flow is evaluated on the basis of conductive and latent heat fluxes. Dalton's Law is used to calculate the rate of soil evaporation to the atmosphere based on the suction at the soil surface. The soil–atmosphere model was used to predict soil evaporation rates, water-content profiles, and temperature profiles for a controlled column evaporation test over a 42 day period. The values computed by the soil–atmosphere model agreed well with the values measured for two columns of Beaver Creek sand in the evaporation test.

Key words: modelling, evaporation, unsaturated, soil surfaces.

Les méthodes traditionnelles pour évaluer l'évaporation fournit une évaluation du taux d'évaporation potentiel ou maximum déterminé sur la base des conditions climatiques. De telles méthodes appropriées pour les surfaces d'eau libres ou de sol complètement saturé. Les taux réels d'évaporation à la surface des sols partiellement saturés sont en général grandement réduites par rapport au taux potentiel d'évaporation. Un modèle théorique pour prédire le taux d'évaporation à la surface des sols saturés est présenté dans cet article. Le modèle est basé sur un système d'équations pour le transfert couplé de chaleur et de masse dans le sol. Les lois de Darcy et de Fick sont utilisées pour décrire respectivement l'écoulement du liquide et de la vapeur d'eau. L'écoulement de chaleur est évalué sur la base des flux de chaleur latente et conductrice. La loi de Dalton est utilisée pour calculer le taux d'évaporation du sol vers l'atmosphère sur la base de la succion à la surface du sol. Le modèle sol-atmosphère a été utilisé pour prédire les taux d'évaporation, les profils de teneur en eau, et les profils de température pour un essai contrôlé d'évaporation dans une colonne durant une période de 42 jours. Les valeurs calculées par le modèle sol-atmosphère concordaient bien avec les valeurs mesurées pour deux colonnes de sable de Beaver Creek dans l'essai d'évaporation.

Mots clés : modélisation, évaporation, non saturé, surfaces de sol.

[Traduit par la rédaction]

Can. Geotech. J. **31**, 151–161 (1994)

Introduction

Prediction of the flux boundary condition with respect to water flow across the soil–atmosphere boundary is essential for many problems in geotechnical engineering. Examples include the design of soil cover systems for the long-term closure of hazardous-waste sites, saturated–unsaturated groundwater-flow modelling, and the prediction of heave for shallow foundations on expansive soils.

Two principal processes govern the exchange of water between the soil surface and the atmosphere. Water enters the soil surface as liquid through the process of infiltration. Alternately, water exfiltrates from the soil surface as vapour through the process of evaporation. The process of infiltration depends primarily on soil properties such as hydraulic conductivity and is reasonably well understood. The evaluation of the evaporative fluxes from a soil surface is more difficult, since the rate of evaporation depends on both soil properties and climatic conditions. Accurate prediction of evaporative fluxes is critical, for example, in the design of soil cover systems which are to function as oxygen barriers for mine tailings that produce acid drainage.

This paper presents a theoretical approach for the evaluation of evaporative fluxes based on measured soil properties and climatic conditions. The theoretical model is used to simulate evaporative fluxes for comparison with the measured results from a sand column evaporation test conducted under controlled climatic conditions. The theoretical approach presented considers nonvegetated or bare soil surfaces. This work forms the basis of a more general formulation which could incorporate the effects of a vegetative cover on evaporation rates from soil surfaces.

Background

Engineers have traditionally used a term defined as potential evaporation (PE) to estimate evaporation or evapotranspiration rates. The term, which has been in use for at least 40 years, was first introduced by Thornthwaite (1948). Potential evaporation may be defined as the upper limit or maximum rate of evaporation from a pure water surface under given climatic conditions. The potential rate of evaporation may be computed using the Dalton-type equation (Gray 1970):

[1] $E = f(u)\ (e_s - e_a)$

where E is rate of evaporation (mm/day), e_s is the saturation vapour pressure of water at the temperature of the surface (mm Hg or kPa), e_a is vapour pressure of the air in the atmosphere above the water surface (mm Hg or kPa), and $f(u)$ is a turbulent exchange function which depends on the mixing characteristics of the air above the evaporating surface.

The use of the apparently simple expression given in [1] is considered a direct approach (van Bavel 1967; Granger 1989). However, the application of [1] to field problems can be difficult. Accurate evaluation of the turbulent exchange

Printed in Canada / Imprimé au Canada