A COMPARISON OF THE GREEN-AMPT AND A SPATIALLY VARIABLE INFILTRATION MODEL FOR NATURAL STORM EVENTS

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ABSTRACT. *Rainfall-runoff data collected from bare plots (20-216 m^2) at 1-min intervals were used to compare the performance of the Green-Ampt infiltration model and a spatially variable infiltration model (SVIM). The two models have the same number of parameters. For 60 natural storm events from six sites in Australia and South-East Asian countries, the average Nash-Sutcliffe model efficiency was 0.77 for the Green-Ampt model and 0.83 for the SVIM. At all sites, the SVIM consistently outperformed the Green-Ampt model when compared to runoff data at a range of time intervals and storm events, including events of very long duration. A larger hydrologic lag is needed for the Green-Ampt model to fit the measured hydrographs in comparison to the SVIM, suggesting that the Green-Ampt model tends to underestimate the infiltration rate when rainfall intensity is high. Measured rainfall and runoff rates show a positive relationship between rainfall intensity and infiltration rate. Considerable spatial variability in the infiltration capacity at the plot scale is implied by this positive relationship. This spatial variability clearly needs to be accommodated in infiltration models, and the SVIM represents a simple formulation of the infiltration rate as a function of rainfall intensity to address this spatial variability. SVIM parameters can be related to the Green-Ampt parameters, and they could therefore be estimated directly using soil properties.*

Keywords. *Green-Ampt, Infiltration model, Spatial variability.*

Accurate estimation of infiltration is critical to determining surface runoff. Infiltration modeling is particularly important for predicting surface runoff and soil loss during individual storm events. In the context of runoff prediction to drive physically based soil erosion models, Yu et al. (1997a) used an infiltration model that takes into account the spatial variability of the infiltration characteristics at the plot scale, while the temporal decrease of the infiltration rate was assumed negligible once runoff commences. They used measured 1-min rainfall and runoff data from six sites in Australia and Southeast Asian countries to estimate model parameters and to evaluate the model performance. It has been suggested that the infiltration model be compared with other infiltration models with a similar degree of complexity which have been widely used in the context of runoff and soil loss predictions.

In the mid 1980s, the USDA initiated the Water Erosion Prediction Project (WEPP) to "develop a new generation of water erosion prediction technology . . ." (Nearing et al., 1989; Laflen et al., 1997). In WEPP, the Green-Ampt infiltration model (Green and Ampt, 1911) as formulated by Mein and Larson (1973) was used to determine surface runoff for both the hillslope and watershed models (Flanagan et al., 1995; Ascough et al., 1997). The Green-Ampt infiltration model was used probably because of a clear physical basis of the model and of the existence of Green-Ampt parameter values for a wide range of soils (Rawls and Brakensiek, 1983), although van der Zweep and Stone (1991), Risse et al. (1992, 1994) all showed that estimated Green-Ampt parameters using soil properties are usually inadequate and parameter values are better calibrated from measured runoff data.

Considerable efforts have been made to determine the Green-Ampt parameters and their temporal variation for continuous simulation using the WEPP erosion model (Risse et al., 1994, 1995a,b; Zhang et al., 1995a,b). In these studies, only measured runoff amounts for individual events were used for calibration purposes. As described by Risse et al. (1995b), for example, "hydraulic conductivity was manipulated until predicted runoff was equal to measured runoff". Although total runoff amount is important, it is just as important to model the infiltration and runoff rates as they vary within a storm event, since the Green-Ampt model was meant to describe how infiltration rate varies in time. Infiltration models are therefore best calibrated and evaluated using data on runoff rates as distinct from runoff total for natural storm events.

The Green-Ampt model has also been applied to small rangeland and agricultural watersheds (typically 10^{-1} to 10^2 km^2) (e.g., Aston and Dunin, 1979; Van Mullem, 1991; James et al., 1992). Since the major attraction of the Green-Ampt model is the involvement of physically meaningful parameters and the potential of using data on soil properties collected during standard soil surveys to estimate these infiltration parameters, the Green-Ampt model is commonly evaluated and compared with the runoff curve number method (USDA SCS, 1985). The latter is a simple and widely used empirical model primarily to predict runoff amount. Thus when the Green-Ampt model is applied to small watersheds, the emphasis has been mostly on runoff amount, and to a lesser extent on peak runoff rate.

Article was submitted for publication in March 1998; reviewed and approved for publication by the Soil & Water Division of ASAE in November 1998.

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In this article, model performance of the Green-Ampt infiltration model and that considered by Yu et al. (1997a) are compared using rainfall-runoff data recorded at 1-min intervals. Since the emphasis of this article is on the infiltration component of the runoff model, identical flow-routing and parameter estimation techniques are applied to the same data set.

MATERIALS AND METHODS

RAINFALL AND RUNOFF DATA

Rainfall and runoff data were collected at 1-min intervals using tipping bucket devices (Ciesiolka et al., 1995) from six experimental sites in tropical and subtropical regions of Australia and Southeast Asia. Apart from plots with various treatments, one bare plot was established at each site to determine the soil erodibility parameters. Data for this article were from bare plots. These bare plots were kept virtually free from vegetation through weed control, either chemically or using hand hoes. No further disturbance of these bare plots occurred after the commencement of these experiments. The plot size varies from 20 to 216 m^2 and plot length from 5 to 36 m (table 1). The slope at most sites is quite steep, up to 50% at VISCA (Visayas State College of Agriculture, Baybay, Leyte, the Philippines). Soil properties at the six experimental sites are summarized in table 1. Mean annual rainfall and exact locations of these sites are given in Yu et al. (1997a).

Discrete representation of the continuous rainfall and runoff processes using tipping bucket technology results in a sampling error associated with the 1-min rainfall and runoff data. This sampling error quantifies the magnitude of the noise in the rainfall and runoff data at 1-min intervals. The standard deviation of the sampling error at the 1-min interval is 2.4 mm/h for rainfall at all sites, while it varies from 0.6 to 3.8 mm/h for runoff depending on the plot and tipping bucket sizes (Yu et al., 1997b). The standard deviation of the sampling error in the runoff data can be compared with the standard error of the estimated hydrographs to indicate the model's goodness-of-fit.

GREEN-AMPT INFILTRATION MODEL

In WEPP hillslope and watershed erosion models, the infiltration rate is calculated using the Green-Ampt equation:

$$f = K_e\left(1 + \frac{N_s}{F}\right) \tag{1}$$

where K_e is the effective hydraulic conductivity in mm/h, N_s the effective matric potential in mm, and F the cumulative infiltration in mm (Stone et al., 1995). When rainfall intensity is less than the infiltration rate determined by equation 1, no surface runoff occurs. Thus equation 1 defines an infiltration capacity, the maximum rate of infiltration that could possibly occur for a given set of parameters and the cumulative infiltration amount. As the amount of water infiltrated accumulates, the infiltration capacity decreases. To estimate the two parameters for individual storm events, it is easier to rewrite equation 1 in the form:

$$f = K_e + \frac{B}{F} \tag{2}$$

See, for example, Skaggs et al. (1969). The new parameter B in mm^2/h is the product of the effective hydraulic conductivity and the effective matric potential. K_e and B are the two parameters to be estimated using measured rainfall and runoff rates. The effective matric potential, if needed, can be determined by:

$$N_s = \frac{B}{K_e} \tag{3}$$

To apply the infiltration equation to storm events with variable rainfall intensity, it is necessary to determine whether surface ponding occurs for each and every time interval. Chu (1978) developed a method to calculate the infiltration rate during an unsteady rain, and this method was implemented in WEPP (Stone et al., 1995). Chow et al. (1988) provided a flow chart for the method and numerical examples which are particularly useful for testing and verifying the program codes.

A SPATIALLY VARIABLE INFILTRATION MODEL (SVIM)

In Yu et al. (1997a), an initial infiltration amount, F_o in mm, is followed by a variable infiltration rate, f_a, expressed as a function of the rainfall intensity, P, in the form:

$$f_a = I_m(1 - e^{-P/I_m}) \tag{4}$$

where I_m, along with F_o, are model parameters. The parameter I_m is interpreted as a spatially averaged infiltration capacity in mm/h. f_a, as distinct from f in equation 1, is the actual rate of infiltration, and f_a varies dynamically as a function of rainfall intensity within a storm event. In this model, an initial infiltration amount was used because the infiltration capacity would be so much higher than the rainfall intensity at the early stage of a storm event that any quantification of this infiltration capacity would be fraught with uncertainty. In fact, any

Table 1. Soil properties at the six sites in Australia and Southeast Asia (after Coughlan, 1997)

						Percentages in Four Particle Size Ranges (mm)			
Country	Site	Order	Bulk Density (Mg/m^3)	pH	Organic Matter (%)	> 0.2	0.2-0.02	0.02-0.002	< 0.002
Australia	Goomboorian	Inceptisols	1.45	6.0	1.3	40	53	5	2
Australia	Imbil	Inceptisols	1.60	5.5	1.7	72	7	13	8
Malaysia	Kemaman	Ultisols	1.55	4.9	1.7	22	43	16	19
Philippines	Los Baños	Alfisols	1.06	6.2	5.1	< — 9 — >		35	56
Philippines	VISCA	Inceptisols	0.88 - 1.17	5.6	4.7	< — 9 — >		65	26
Thailand	Nan	Ultisols	-	5.7	3.7	5	14	38	43