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.

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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)

Country	Site	Order	Bulk Density (Mg/m^3)	pH	Organic Matter (%)	Percentages in Four Particle Size Ranges (mm) > 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

value of the infiltration capacity would do as long as it is greater than the observed rainfall intensity. Once the infiltration capacity is reduced to the extent that runoff begins to occur, the spatially averaged infiltration capacity, i.e., I_m, is assumed to be constant over time. An initial infiltration amount followed by a constant infiltration capacity is commonly used in engineering practices, especially in situations where the Hortonian process is likely to be dominant (Pilgrim, 1987; Pilgrim and Cordery, 1993). In Yu et al. (1997a), this constant infiltration capacity was allowed to vary spatially so that the actual infiltration rate would vary positively with rainfall intensity. As rainfall intensity increases, the surface area for which infiltration capacity is exceeded would increase, resulting in an increased actual rate of infiltration averaged over the whole area. equation 4 for the actual infiltration rate follows from an exponential distribution of the infiltration capacity which varies in space (Yu et al., 1997a). In this article, the infiltration model that is based on an initial infiltration amount followed by a spatially variable infiltration capacity is called a spatially variable infiltration model, or SVIM for short.

Runoff Routing and Model Evaluation

Once the actual infiltration rate is determined, the rainfall excess for each time interval, R_i, which is the difference between rainfall intensity and actual infiltration rate for the time interval, is routed to the plot exit to produce the modeled hydrograph:

$$\hat{Q}_i = \alpha \hat{Q}_{i-1} + (1-\alpha) R_i \qquad (5)$$

for time interval i, where $\hat{Q}_i$ is the modeled runoff rate at the plot exit. The parameter α is related to the lag and the time interval used in rainfall and runoff measurements. equation 5 is an approximate solution of the kinematic wave equation assuming a constant lag (Yu et al., 1997a). This routing scheme will be used in conjunction with both the Green-Ampt and the SVIM equations to produce hydrographs for individual storm events. Common use of equation 5 does not discriminate between the two infiltration models being compared.

The two parameters, namely K_e and B for the Green-Ampt model or F_o and I_m in the case of SVIM along with the routing parameter α were estimated for each event by minimizing the sum of squared errors, SSE, between the observed (Q_i) and modeled ($\hat{Q}_i$) runoff rates:

$$SSE = \sum_{i=1}^{N} \left(Q_i - \hat{Q}_i\right)^2 \qquad (6)$$

where N is the number of data points for each measured storm hydrograph. The Levenberg-Marquardt method (Press et al., 1992) was used for optimization purposes.

Model performance is measured by the coefficient of efficiency, E (Nash and Sutcliffe, 1970), defined as:

$$E = 1 - \frac{\sum_{i=1}^{N} \left(Q_i - \hat{Q}_i\right)^2}{\sum_{i=1}^{N} \left(Q_i - \overline{Q}\right)^2} = 1 - \frac{SSE}{\sum_{i=1}^{N} \left(Q_i - \overline{Q}\right)^2} \qquad (7)$$

The coefficient of efficiency is commonly used as a measure of model performance in hydrology (e.g., Loague and Freeze, 1985) and for evaluating various methods to estimate the Green-Ampt parameters (e.g., Risse et al., 1995a,b). In addition, the standard error of estimates expressed as:

$$se = \sqrt{\frac{SSE}{N-M}} \qquad (8)$$

where M is the number of parameters, is calculated to compare with the sampling error due to the discrete representation of the runoff rate at small time intervals.

Results

For the same 60 site-events considered by Yu et al. (1997a), the estimated parameters for the Green-Ampt and SVIM models and model efficiency are summarized in table 2. It can be seen that the coefficient of efficiency is consistently higher for each site using the SVIM equation compared to the Green-Ampt equation. The average E for all site-events is 0.77 using the Green-Ampt equation and 0.83 using the SVIM equation (table 2). Figure 1 shows a comparison of the model efficiency for individual storm

Table 2. A summary of the average estimated Green-Ampt parameter values and a comparison of the model efficiency (E) and the standard error of estimates (se)

				α		Green-Ampt		SVIM	
Sites	No. of Events	K_e (mm/h)	B (mm^2/h)	Green-Ampt	SVIM	E	se (mm/h)	E	se (mm/h)
Goomboorian, Australia	10	7.31	38.8	0.555	0.476	0.91	4.0	0.94	3.1
Imbil, Australia	10	16.3	75.7	0.886	0.857	0.79	4.3	0.80	3.8
Kemaman, Malaysia	10	3.18	9.61	0.583	0.557	0.91	5.2	0.92	4.8
Los Baños, the Philippines	10	25.8	25.3	0.830	0.776	0.79	4.4	0.83	4.0
VISCA, the Philippines	10	76.8	157	0.900	0.673	0.55	1.1	0.72	0.9
Nan, Thailand	10	28.1	72.2	0.789	0.688	0.69	2.6	0.79	2.0
Combined	60	26.2	66.6	0.758	0.671	0.77	3.6	0.83	3.1
Largest events (Δt = 1 min)	6	21.1	54.6	0.807	0.749	0.74	2.3	0.83	2.2
Largest events (Δt = 6 min)	6	18.3	60.3	0.513	0.372	0.80	1.7	0.90	1.6
Largest events (Δt = 15 min)	6	18.4	63.6	0.363	0.224	0.86	1.4	0.93	1.3
Largest events (Δt = 15 min, α = 0)	6	20.6	67.2	0.0	0.0	0.63	2.1	0.86	1.8

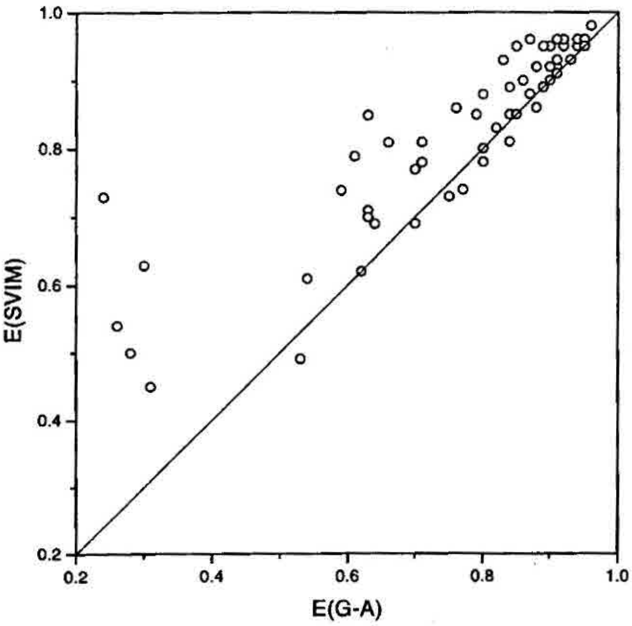

Figure 1–Coefficient of efficiency (E) of the Green-Ampt model (G-A) in comparison with that of the SVIM for 60 storm events from six sites in Australia and Southeast Asia.

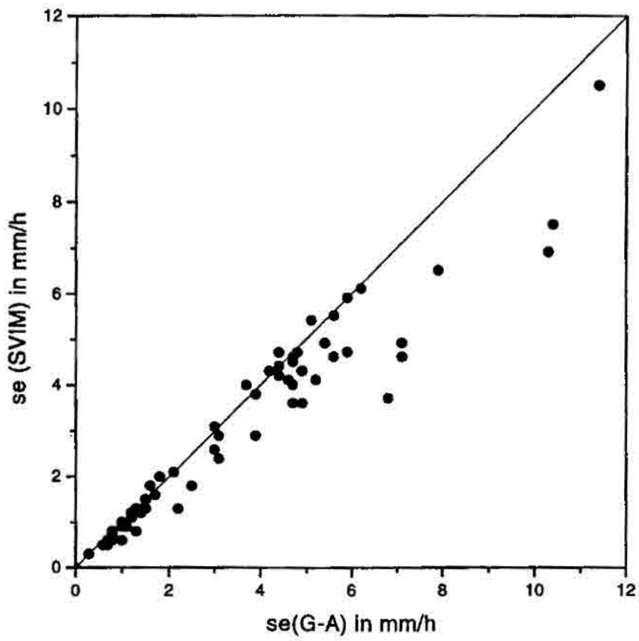

Figure 2–A comparison of the standard error of estimates (se) between the Green-Ampt (G-A) and the SVIM for 60 storm events from six sites in Australia and Southeast Asia.

events using the two infiltration models. For events with a high coefficient of efficiency, although the SVIM equation fitted the observed hydrograph better, the difference between the two models is not great. For events with a low coefficient of efficiency, the SVIM equation performed much better in comparison with the Green-Ampt equation in fitting the observed hydrographs. Using the SVIM, 20 storm events from the six sites have an E value less than or equal to 0.8, and the average value of E for these 20 site-events is 0.67. The average E value using the Green-Ampt equation for the same 20 site-events is only 0.57. A plot of the standard error using the two infiltration equations also shows that the standard error is consistently less using the SVIM equation than using the Green-Ampt equation (fig. 2). The average standard error for all 60 site-events is 3.1 mm/h using the SVIM in comparison with 3.6 mm/h using the Green-Ampt model (table 2). The ratio of the standard error to the sampling error varies between 0.5 and 3.3 using the SVIM as compared to 0.6 and 4.3 using the Green-Ampt model. On average, this error ratio is 2.1 for the SVIM and 2.5 for the Green-Ampt model.

Comparing the estimated value of using the two infiltration equations shows that the estimated α for the Green-Ampt model is consistently larger than that for the SVIM for all sites (table 2). From the parameter α, an estimate of the average hydrologic lag time, K, can be made for each site (Yu et al.,1997a):

$$K = \frac{\alpha}{1-\alpha}\Delta t \qquad (9)$$

where Δt is the sampling interval. The lag time using the estimated α and SVIM varies from 0.9 min at Goomboorian to 6.1 min at Imbil. Using the Green-Ampt model, the estimated lag time based on the optimized routing parameter α is increased for all sites from 1.2 min at Goomboorian to 9.0 min at VISCA. The increase in the estimated lag varies from 0.1 min at Kemaman to 7.0 min at VISCA. In general, the lower the model efficiency, the higher the increase in the estimated lag. As the hydrologic lag increases, the peak runoff rate decreases. Thus larger lag times obtained in order to fit the measured hydrograph using the Green-Ampt infiltration equation suggest that at high rainfall intensity, the rate of infiltration is underestimated by the Green-Ampt equation. Large lag was required to provide the necessary attenuation effect on the overestimated rate of rainfall excess. The observation that the Green-Ampt equation tends to underestimate the infiltration rate at high rainfall intensity is further supported by the observed relationship between rainfall intensity and infiltration rate, as will be shown later.

Since the Green-Ampt equation describes a decrease in the infiltration capacity over time, one would think that the Green-Ampt equation might be most appropriate for storm events of particularly long duration. Such a decrease might be better established using a long time series for which the trend would tend to overwhelm the noise. Thus, to further compare the two infiltration models, the largest event in terms of storm duration for each of the six sites was grouped together. The average duration of these events is 21.7 h. These events are also the largest in terms of storm depth except for Los Baños and VISCA in the Philippines, where they are the second largest. For this subset of 6 largest storm events, table 2 shows that the SVIM equation still outperforms the Green-Ampt equation in terms of the model efficiency and standard error of estimates, regardless of the measurement intervals, Δt, or whether a common zero value of α is adopted.

Although the same routing technique was used in connection with both the Green-Ampt and SVIM equations to model hydrographs at the plot exit, the storage effect which is important at small time scales (Skaggs et al., 1969; Yu et al., 1997a), may mask the true differences between the Green-Ampt and SVIM equations. As the time interval increases, the storage effect would decrease, other factors being equal. In other words, the difference between rainfall and runoff, known as the apparent rate of infiltration becomes essentially the actual rate of infiltration at large time intervals. The original 1-min data for these longest storms were accumulated at 6-min and 15-min intervals so that the storage effect on outflow hydrographs can be gradually reduced. As the time interval increases, which routing technique is used to calculate runoff hydrographs would become less and less relevant, and model efficiency at the same time becomes a fairer indicator of the difference between the Green-Ampt and the SVIM alone. Through data accumulation, the infiltration component of the runoff models, hence the difference between the Green-Ampt and SVIM equations, can be accentuated. However, for all three time intervals considered, SVIM once again consistently outperforms the Green-Ampt model (table 2). As the time interval increases and the data are smoothed through accumulation, the coefficient of efficiency improves for both models. As noted previously in relation to individual storm events, the difference between the two infiltration models is reduced when the model performance is improved.

The 15-min data accumulation interval is larger than the estimated average hydrologic lag for these sites. If we assume that the storage effect is negligible at 15-min intervals, the routing parameter α can be set to zero, thus the runoff rate becomes the rate of rainfall excess (see eq. 5). Using the 15-min rainfall and runoff data for the six largest storm events, the infiltration parameters were estimated once again with $\alpha = 0$ to eliminate the routing component of the runoff model, thus giving a completely unbiased comparison of the two models. Table 2 shows that the model efficiency is reduced for both the Green-Ampt infiltration model and the SVIM when the storage effect is neglected. The decrease of E, however, is much greater for the Green-Ampt model than for the SVIM. For the Green-Ampt model, the average E value is 0.63 which is less than the average E value using the original 1-min data. For the SVIM, on the other hand, the average E value of 0.86 is greater than the average E values using the 1-min data. Greater reliance of the Green-Ampt model on the routing component to fit the observed hydrographs again shows that the infiltration rate may have been underestimated and hydrologic routing is needed to attenuate the overestimated rate of rainfall excess.

It is relevant at this stage to point out some of the crucial differences between the two infiltration models. In the commonly used form of the Green-Ampt model, the spatial variation in the infiltration characteristics is not taken into account. The Green-Ampt equation only describes a decrease of infiltration capacity with infiltration amount at a point in the landscape, and once rainfall intensity exceeds the infiltration capacity, the actual infiltration rate is no longer dependent on the rainfall intensity. A spatially uniform effective hydraulic conductivity is assumed when the Green-Ampt equation is applied to field situations. In the SVIM, on the other hand, a high but unknown infiltration capacity was assumed prior to the commencement of runoff. Once the runoff occurs, the actual infiltration is allowed to increase up to a maximum value of I_m. An examination of whether the actual infiltration rate is more a function of time or more a function of rainfall intensity would shed further light on the difference between the two infiltration models.

For a runoff event, the apparent infiltration rate (the difference between rainfall intensity and runoff rate) can be plotted against either time or rainfall intensity for a range of time intervals. As mentioned previously, as the time interval increases, the difference between rainfall and runoff increasingly becomes a better measure of the actual rate of infiltration. According to the Green-Ampt model, a graph of the apparent infiltration would show a decrease over time, while the SVIM suggests a positive relationship between the apparent infiltration rate and rainfall intensity. We have examined many storm events graphically, and they all show that the actual infiltration rate is well related to the rainfall intensity. The expected decrease of the actual infiltration rate over time is much less evident. The apparent rate of infiltration for most storm events, and for most parts of these events, shows considerable high-frequency fluctuations. The apparent rate of infiltration varies considerably from one time interval to another even if runoff occurs for both intervals. To illustrate some of the features that have been commonly noted, results for a typical event will be presented.

The SVIM model performed very well for Goomboorian, Australia, and Kemaman, Malaysia (table 2). The model performance is least satisfactory for VISCA in the Philippines. Los Baños shows an about average model performance in terms of the coefficient of efficiency (table 2). An event from this average site was selected for further illustration. It was the largest event for the site with a total rainfall depth of 83.7 mm. The storm occurred on 9 August 1993 and lasted for 1379 min. Thus this event was selected with a bias towards larger storm duration in order to favor the Green-Ampt equation. Figure 3 shows the observed rainfall intensity and runoff rate at 15-min intervals. In the same graph, the infiltration capacity described by the Green-Ampt equation is also shown. The estimated effective hydraulic conductivity is 2.75 mm/h and the parameter B in equation 2 is

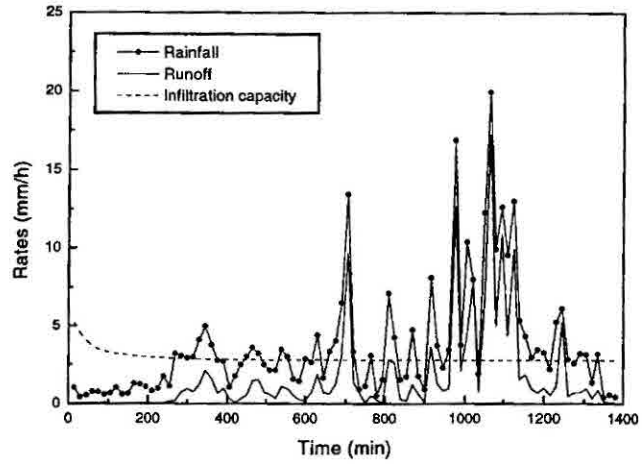

Figure 3–Rainfall intensity, runoff rate, and infiltration capacity calculated using the Green-Ampt equation at 15-min intervals, for the 9 August 1993 storm event at Los Baños, the Philippines. The Green-Ampt parameters for the event are K_e = 2.75 mm/h and B = 0.616 mm²/h.

0.616 mm²/h. At 15-min intervals, the variation in runoff rate follows closely that in rainfall, and as expected there is no apparent lag between rainfall and runoff (fig. 3). The estimated α using the SVIM is only 0.045, and the lag time K equals 0.71 min from equation 9. All these observations suggest that the storage effect on runoff hydrograph is weak at this time interval, although the effect cannot be completely eliminated. Thus, the difference between rainfall and runoff can be regarded as a reasonably good measure of the actual infiltration rate. This difference between rainfall and runoff, called simply as infiltration rate, is plotted first against time (fig. 4) then against rainfall intensity (fig. 5). The Green-Ampt equation is also plotted in figure 4 using the estimated parameter values for the event. Similarly, in figure 5, the SVIM equation is shown using the estimated parameter value for I_m. Note that the curve in figure 5 does not represent the best fit of the scatter plot for equation 4, because the effects of dynamic storage and routing

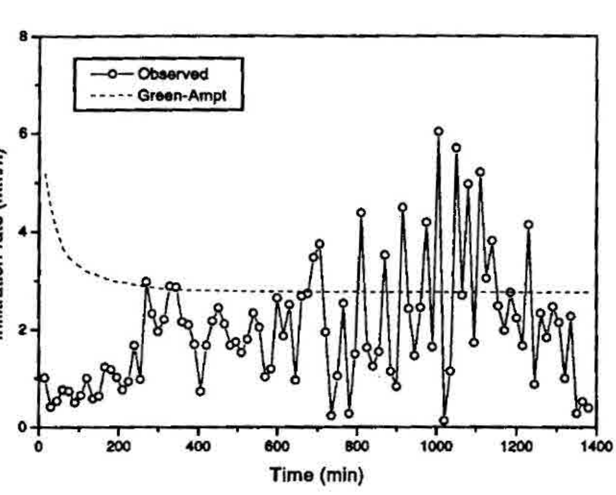

Figure 4–The time series of the apparent infiltration rate (the difference between rainfall intensity and runoff rate) at 15-min intervals for the 9 August 1993 storm event at Los Baños, the Philippines. The dashed line represents the Green-Ampt equation with the same parameter values as in figure 3.

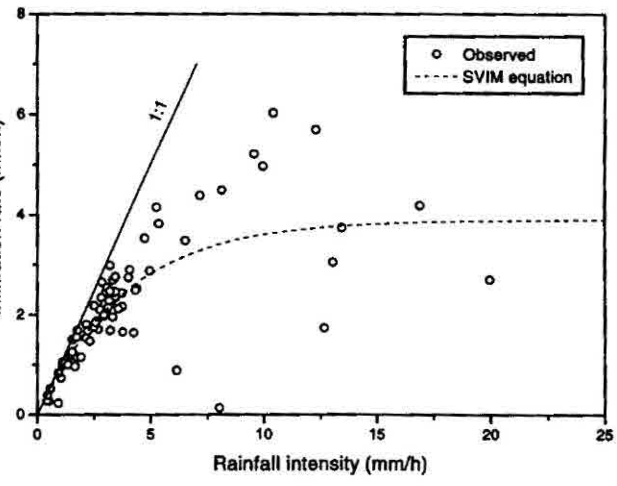

Figure 5–The relationship between 15-min rainfall intensity and the apparent infiltration rate (the difference between rainfall intensity and runoff rate) for the 9 August 1993 storm event at Los Baños, the Philippines. The dashed line represents equation 4 with I_m = 3.90 mm/h.

technique are not represented in these graphs. Figure 4 shows that the actual infiltration rate varies widely with time. There is no apparent decrease in the actual rate of infiltration over time. The Green-Ampt theory implies that once runoff occurs, the actual infiltration rate defines an infiltration capacity which should never be exceeded henceforth during the storm event. A comparison of figure 3 and figure 4 clearly shows that this is hardly the case. Figure 5 shows that the actual infiltration increases with rainfall intensity and the rate of the increase tends to slow down at high rainfall intensity. The SVIM approach attempts to capture the essential features of the relationship between rainfall and infiltration, and equation 4 is the most parameter-efficient way of doing this.

It is important to be able to select parameter values for SVIM, as for any other models. Ideally, the parameter values for infiltration models should be determined using easily measurable soil properties. For the 60 site-events considered in this article, it is found that the parameters for SVIM, i.e., F_o and I_m, can be related to the Green-Ampt parameters. Both the Green-Ampt and the SVIM parameters were estimated using the measured rainfall and runoff data at the original 1-min intervals. Since both I_m and K_e conceptually characterize the infiltration capacity of the plot, and both are related to the average rate of infiltration, a relationship between the two parameters is expected. In figure 6, the estimated I_m is plotted against K_e for the 60 site-events. I_m is mostly greater than K_e as expected, because I_m represents the average infiltration capacity when the entire plot generates surface runoff. I_m is thus a measure of the maximum plot-averaged rate of infiltration. Furthermore, K_e increases with I_m. A second-order polynomial was used to fit the estimated parameter values, resulting in an empirical relation between I_m and K_e:

$$\log I_m = 0.534 + 0.316 \log K_e + 0.402(\log K_e)^2$$

$$r^2 = 0.80 \qquad (10)$$

To develop an empirical relation between the initial infiltration amount, F_o, and the Green-Ampt parameters, it

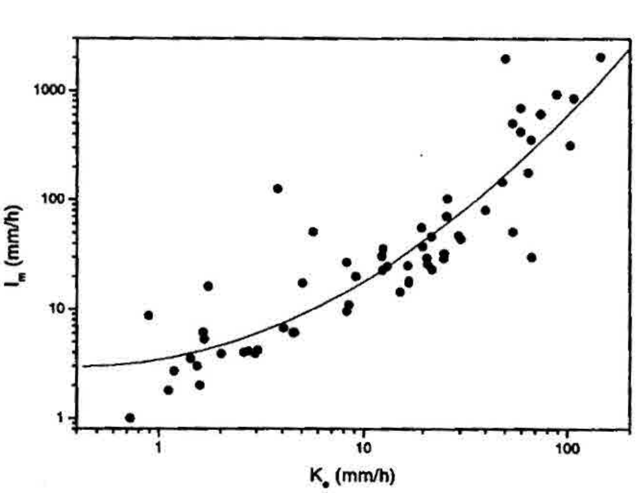

Figure 6–The relationship between the SVIM parameter I_m and the Green-Ampt parameter K_e estimated using 1-min rainfall and runoff data for 60 site-events. The fitted curve represents equation 10.

is hypothesized that the infiltration rate at the time when runoff first occurs must be intrinsically related to the effective hydraulic conductivity. Thus:

$$K_e\left(1 + \frac{N_s}{F_o}\right) = f(K_e) \qquad (11)$$

where $f(K_e)$ represents a function of the effective hydraulic conductivity. Rearranging the equation above, we find that a one-parameter empirical equation relating F_0 to K_e and N_s works reasonably well:

$$\ln\left(\frac{N_s}{N_s + F_o}\right) = -0.0385K_e, \qquad r^2 = 0.50 \qquad (12)$$

A scatter plot of the transformed F_0 against K_e and the equation above is shown in figure 7. Thus for a given set of K_e and N_s, the parameters F_0 and I_m for the SVIM can be estimated using equation 12 and equation 10, respectively, and vice versa. The strong correlation between the Green-Ampt and SVIM parameters suggests that since Green-Ampt parameters can be predicted using soil properties (Rawls and Brakensiek, 1983), it is possible therefore to relate the SVIM parameters to soil properties directly.

Discussion

At the plot scale, validation of the Green-Ampt infiltration model and estimation of its parameters, especially the effective hydraulic conductivity, have been carried out mostly using event runoff totals (e.g., Risse et al., 1995a,b; Zhang et al., 1995a,b). The problem with using runoff total is that there is no independent test of the appropriateness of the model structure because a unique value of the effective hydraulic conductive can always be obtained for a given runoff amount. This is tantamount to a situation where the timing and the magnitude of the estimated hydrograph can be quite wrong while the total area under the curve is conserved to produce the correct amount of runoff. Measurement of runoff rates at small time intervals (Ciesiolka et al., 1995) at the plot scale allows the assumptions of the Green-Ampt infiltration theory to be tested in a rigorous way because the theory describes how the infiltration capacity changes over time during a storm event. This comparison of two different infiltration models shows that it is vital to use measured runoff rates as distinct from runoff total to validate infiltration models and to estimate model parameters.

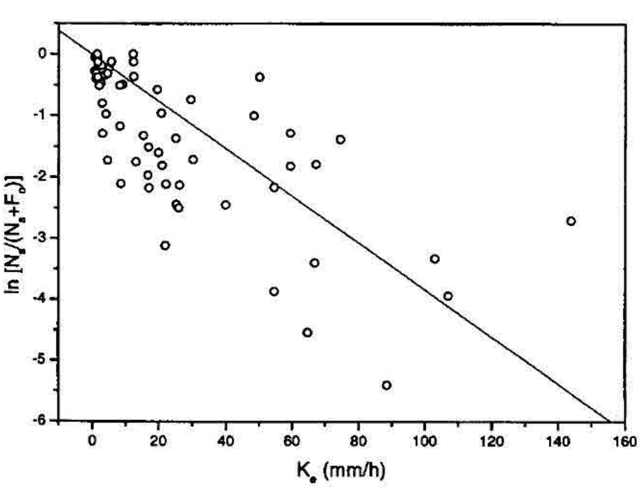

Figure 7–The relationship between a transformation of the SVIM parameter F_o involving the effective matric potential N_s and the Green-Ampt parameter K_e estimated using the 1-min rainfall and runoff data for 60 site-events. The straight line represents equation 12.

Measured rainfall and runoff rates show that the apparent rate of infiltration is primarily a function of rainfall intensity, and to a much lesser extent a function of time. The observation that the apparent rate of infiltration is positively related to rainfall intensity is best explained by assuming that the infiltration capacity varies in space. One of the simplest possible distribution functions available is the one-parameter exponential distribution. This particular distribution function was assumed to characterize the spatial variation in the infiltration capacity at the plot scale (Yu et al., 1997a). It is important to stress that the spatial variation of the infiltration capacity is implied by the data on rainfall intensity and the associated runoff rate. Spatial variability is not based on direct measurement at these six sites, although spatial variability in equilibrium infiltration rate and saturation hydraulic conductivity at the field/catchment scales have been well documented in literature (Nielsen et al., 1973; Sharma et al., 1980; Hawkins, 1982; Hawkins and Cundy, 1987; Loague and Gander, 1990; Govindaraju et al., 1996), and widely accepted in the scientific community.

Bare plots are unnatural, representing relatively homogenous surfaces with essentially constant slopes. The issue of spatial variability would be even more important in other field situations. If spatial variability in infiltration characteristics is important at the plot scale of 10^1 to 10^3 m^2, as seems to be the case, spatial variability must be unavoidable and should be accommodated in all infiltration models when we attempt to predict runoff at hillslope or watershed scales (up to about 10^6 m^2, Foster and Lane, 1987; Baffaut et al., 1997).

Since the complexity of the two infiltration models considered in this article is the same, with two parameters for the infiltration component and one for runoff routing, a legitimate case can be made using the SVIM infiltration equation as a viable alternative to the Green-Ampt infiltration equation in erosion prediction models. Furthermore, since the initial infiltration amount and plot-averaged infiltration capacity can be empirically related to the effective hydraulic conductivity and matric potential, these SVIM parameters could also be estimated directly using soil properties as in the case of Green-Ampt parameters. This is an area for further research.

While it is shown that the parameters for Green-Ampt and SVIM are correlated, the relationships between them may also depend on the scale at which the rainfall and runoff data were collected. The SVIM parameters should be related to the scale of application in addition to soil properties because the spatially variable aspect of the SVIM would be a function of the variability in soil properties over the area of interest in addition to particle size and bulk density which determine the effective hydraulic conductivity. Furthermore, although the SVIM has been tested and found to perform well at selected sites with different crop covers, i.e., pineapples at Goomboorian, and maize and mung bean at Los Baños (Yu et al., 1997c), no systematic comparison and evaluation of the infiltration models and their parameters have yet been made for a range of vegetative cover and use land conditions. This is again another area for further research.

Conclusion

In this article, data on runoff rate, as distinct from storm runoff total, were used to compare two simple infiltration models. Both models have the same number of parameters. In comparison with the Green-Ampt infiltration model, the SVIM consistently fits the observed hydrographs better for the six experiment sites, for a range of time scales, and even for very long storm events, which might be assumed to favor the Green-Ampt model. A larger hydrologic lag time was consistently estimated for the Green-Ampt model to fit the measured hydrographs in comparison to the SVIM, suggesting that at high rainfall intensity the Green-Ampt model underestimates the infiltration rate and overestimates the rainfall excess rate. Measured rainfall and runoff rates show a positive relationship between rainfall intensity and infiltration rate. Spatial variability in the infiltration capacity at the plot scale is implied by this positive relationship. 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.

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