The Spatial Computation of Sub-basin Green and Ampt Parameters

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1999 AWRA Student Paper Competition

Abstract: HEC-1, developed by the Hydrologic Engineering Center, has been used for many years by hydrologists and engineers to estimate surface water runoff caused by rainfall events. Besides the rainfall data itself, the most sensitive set of input parameters for HEC-1 are the soil loss parameters. Most commonly, the SCS (NRCS) Curve Number approach is used to compute soil losses. Another method available for computing soil losses in HEC-1 is the Green and Ampt method. But this method is used infrequently due to the difficulty in obtaining the required Green and Ampt data. The purpose of this study is to present a new, automatic, method of computing Green and Ampt parameters from commonly available Geographic Information System (GIS) data. Studies were performed with data from Maricopa County, Arizona that compare the new method with a previous method of computing Green and Ampt parameters. Excellent correlation was found between the computed parameters in the new method and the computed parameters in the old method.

Introduction

When creating a watershed model, there are three basic parameters that determine the volume of flow from each of the watershed's sub-basins. These three parameters are the sub-basin area, the amount of precipitation in the sub-basin, and the percentage of water infiltrated into the sub-basin's soil, often called the *Runoff Coefficient*.

The area, precipitation, and the runoff coefficient are all important sub-basin parameters. But the runoff coefficient is, by far, the most difficult parameter to determine. It is also an extremely sensitive parameter—a low runoff coefficient will underestimate the amount of sub-basin runoff while a high runoff coefficient will overestimate the amount of sub-basin runoff. Therefore, it is extremely important to accurately estimate sub-basin runoff coefficients using the best data and most advanced computation methods available. During a precipitation event, the percentage of water infiltrated into an area of ground changes with time. This means that the runoff coefficient changes during that precipitation event. One method of taking this change in runoff coefficient into account is the Green and Ampt method (Green and Ampt, 1911). HEC-1, developed by the Hydrologic Engineering Center, and other popular hydrologic modeling software (Savabi, 1993) have the option of using the Green and Ampt method for determining soil losses. But because of difficulty in obtaining input data for the Green and Ampt method (Lakhtakia et al., 1998), it is infrequently used.

Some researchers, such as Nearing et al. (1996), have provided algorithms to compute some parameters required for input into the Green and Ampt method with success. In their methods, curve numbers and/or soil data were converted to Green and Ampt input parameters.

The purpose of this study is to describe, implement, and test an accurate method for computing sub-basin Green and Ampt parameters from readily available soil and land use data. This procedure for computing the Green and Ampt parameters from soil and land use data was implemented in the Watershed Modeling System (WMS). The algorithm is based on methods used in Maricopa County, Arizona and presented in Sabol et al. (1995). Using the algorithm presented in this study, soil and land use data available from local, state, and national Geographic Information System (GIS) databases can be used to compute Green and Ampt parameters for input into HEC-1 and other hydrologic modeling software.

The Green and Ampt Method of Determining Soil Infiltration

W.H. Green and G.A. Ampt (1911) developed the Green and Ampt method of determining the amount of precipitation that infiltrates into the soil during a precipitation event. The basic equation used in the Green and Ampt model is given by Equation 1:

$$f < i,\ f = K_s\left(1 + \frac{\psi\,\theta}{F}\right)$$
$$f \geq i,\ f = i$$

Equation 1: The Green and Ampt infiltration model (Sabol et al., 1995)

Where:

f = infiltration rate (L/T),

i = rainfall intensity (L/T),

K_s = hydraulic conductivity, wetted zone, steady-state rate (L/T),

ψ = average capillary suction in the wetted zone (L),

θ = soil moisture deficit (dimensionless), equal to the effective soil porosity times the difference in final and initial volumetric soil saturations, and

F = depth of rainfall that has infiltrated into the soil since the beginning of rainfall (L).

The Green and Ampt method has been incorporated into HEC-1, a widely used watershed simulation program developed by the Hydrologic Engineering Center.

The sub-basin Green and Ampt parameters required by HEC-1 include:

1. The hydraulic conductivity, XKSAT (K_s in Equation 1),
2. The wetting front capillary suction, PSIF (ψ in Equation 1),
3. The volumetric soil moisture deficit at the start of rainfall, DTHETA (θ in Equation 1),

4. The percent of impervious area in the sub-basin, RTIMP, and
5. The initial loss, IA.

HEC-1 uses a two-step process to compute losses using the Green and Ampt method (Sabol et al., 1995). In the first phase, all rainfall is lost into the soil until the lost rainfall totals the initial loss, IA. In the second phase, the XKSAT, PSIF, and DTHETA values entered into the HEC-1 Green and Ampt model are used to compute the infiltration at each time step in the HEC-1 model using a modified form of Equation 1. This infiltration is subtracted from the total rainfall during each time step to determine the rainfall excess. The Green and Ampt model is a highly accurate, physics-based model for determining infiltration. But the input data for the Green and Ampt model is hard to determine. Sabol et al. (1995) described a method of computing the input data for the Green and Ampt model using readily available geographic land use and soil type data as an overlay to a watershed model. Though this method produces very accurate results, it is time consuming and is not automated. This study presents a new, accurate method for automatically determining the Green and Ampt parameters required for each sub-basin in an HEC-1 watershed model.

Description of the Interface

Given a digital, geographically based watershed model, geographic land use data, geographic soil type data, and a set of tables, this algorithm automatically computes the Green and Ampt parameters for each sub-basin in a digital watershed model.

Input Requirements

The following input parameters are required to compute Green and Ampt parameters in WMS:

1. A digital, geographically based watershed model (Figure 1).

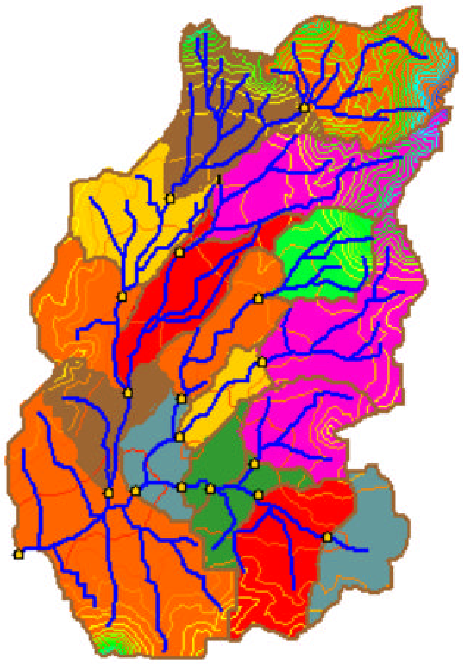

Figure 1: The Gavilan Peak Watershed model (Courtesy of Bing Zhao, Flood Control District of Maricopa County)

2. A digital, geographically based soil type coverage (Figure 2).

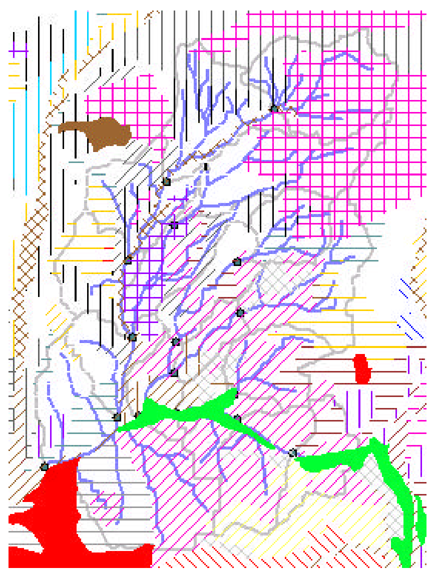

Figure 2: Soil types overlaying the Gavilan Peak Watershed (Courtesy of Bing Zhao, Flood Control District of Maricopa County)

3. A digital, geographically based land use coverage (Figure 3).

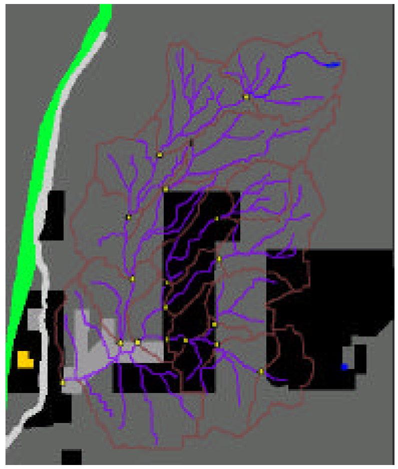

Figure 3: Land uses overlaying the Gavilan Peak Watershed (Courtesy of Bing Zhao, Flood Control District of Maricopa County)

4. A table relating each soil type ID to hydraulic conductivity (XKSAT), soil percent impervious (RTIMPs), and percent effective (Pct. Effective) (Figure 4).

ID	XKSAT	RTIMP	Pct. Effective	Soil Description
3	0.58	0.00	100.00	Antho-Carrizo-Maripo c
6	0.62	0.00	100.00	Anthony-Arizo complex
8	0.96	0.00	100.00	Arizo cobbly sandy loa
10	0.94	0.00	100.00	Brios-Carrizo complex,

Figure 4: A table relating soil ID's to XKSAT, RTIMPs, and Pct. Effective (Courtesy of Bing Zhao, Flood Control District of Maricopa County)

5. A table relating each land use ID to initial abstraction (IA), land percent impervious (RTIMPl), percent vegetation (Percent Veg.), and a saturation value (Figure 5).

ID	IA	RTIMP	Percent Veg.	Saturation	Land Use Descr
1	0.300	5.00	0.00	normal	Rural
2	0.300	15.00	50.00	normal	LLotRes
3	0.250	30.00	50.00	normal	SLotRes
6	0.100	80.00	75.00	normal	N.Retail

Figure 5: A table relating land use ID's to IA, RTIMPl, Percent vegetation, and a saturation value (Courtesy of Bing Zhao, Flood Control District of Maricopa County)

Computing the Green and Ampt Parameters

To compute Green and Ampt parameters in the Watershed Modeling System (WMS), the required data (land use, soil type, watershed data, etc.) must either be read into the WMS from a Geographic Information System (GIS) or generated in the WMS. Green and Ampt soil type and land use look-up table values (XKSAT, RTIMPs, Percent Effective, IA, RTIPMl, Percent Vegetation, Saturation, and descriptions) must also be read into the WMS or be assigned for each soil or land use ID.

After land use and soil type ID's are assigned to each land use and soil polygon and Green and Ampt input parameters are assigned to each land use and soil type ID, the Green and Ampt parameters for each sub-basin can be computed. Figure 6 shows how the land use and soil type data is used to compute Green and Ampt parameters.

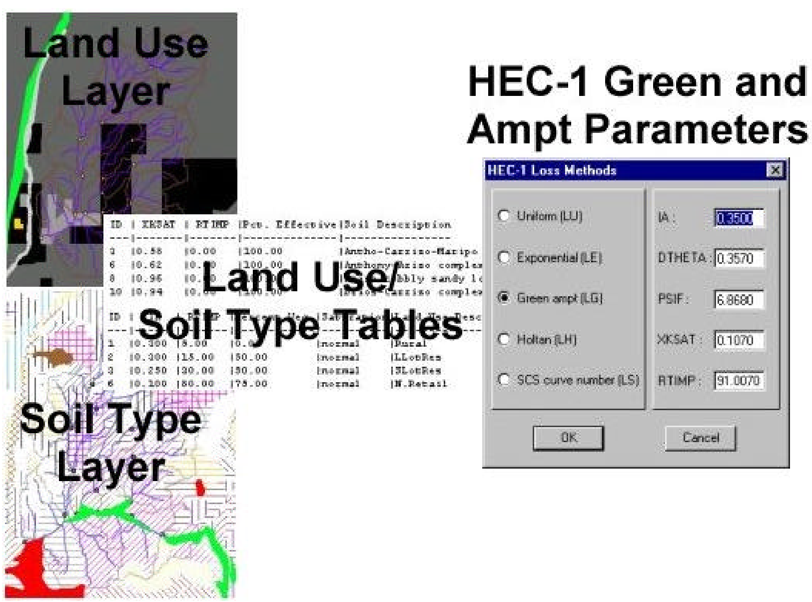

Figure 6: Computing Green and Ampt input parameters

Two types of watershed models can be created in the WMS. One type, described by Nelson and Smemoe (1999), uses vector-based data called a *drainage coverage* to define the boundaries and streams of each sub-basin in the watershed. In a drainage coverage, sub-basin boundaries are defined by closed sets of polylines, or polygons. Polylines, or arcs, define streams and other linear attributes in a watershed. The other type of watershed model, described by Jones, Wright, and Maidment (1990) uses a set of triangles, called a *triangulated irregular network* (TIN), to define the watershed and to compute watershed geometric parameters. In a TIN, sub-basin boundaries and streams are defined along the edges of triangles. The Green and Ampt parameters for each sub-basin in a watershed model are computed using the following method:

- When using a drainage coverage-based watershed model, each sub-basin is divided up into square grid cells of a specified size. When using a TIN-based watershed model, the computation size is based on the size of the triangles in the TIN.
- For each grid cell or triangle, the area (A_i), soil type ID, and land use ID are determined.
- The soil hydraulic conductivity (K_s), soil percent impervious (R_s), and percent effective soil area (Eff) are obtained from the soil type ID and a look-up table.
- The initial abstraction (I_a), land percent impervious (R_l), percent vegetation (Veg), and the degree of saturation (dry, normal, or saturated) are obtained from the land use ID and a look-up table.
- For each grid cell or triangle, i, the following parameters are calculated:
    - First, the logarithm of the soil hydraulic conductivity is calculated and multiplied by the area of the computation step—

      $$K_{s_i} = \left(\ln K_s\right) \times A_i$$

      Equation 2: Computing $(K_s)_i$, the hydraulic conductivity component, for a soil element.

    - Second, the percent impervious for the computation cell is calculated from both the land use and soil type percent impervious and multiplied by the area of the computation step—

If $\left(\left(R_s \times \frac{Eff}{100}\right) + R_l\right)$ is less than 100, $R_i = \left(\left(R_s \times \frac{Eff}{100}\right) + R_l\right) \times A_i$.

Otherwise, $R_i = 100.0 \times A_i$.

Equation 3: Computing R_i, the percent impervious area component, for a soil-land use element.

- Third, the initial abstraction is determined from the land use value for initial abstraction and multiplied by the area of the computation step— $I_{a_i} = I_a \times A_i$

  Equation 4: Computing $(I_a)_i$, the initial abstraction component, for a land use element.

- Fourth, the ratio of the hydraulic conductivity, K_s, to the bare ground hydraulic conductivity is computed from the percentage vegetation covering the area and multiplied by the area of the computation step— If *Veg* is greater than 10, $C_{k_i} = \left(\frac{Veg - 10}{90} + 1.0\right) \times A_i$. Otherwise, $C_{k_i} = 1.0 \times A_i$

  Equation 5: Computing $(C_k)_i$, the ratio of the hydraulic conductivity to the bare ground hydraulic conductivity component, for a land use element.

- If the grid cell or triangle's saturation value is dry or normal, the area of the cell is added onto the total dry area (A_d) or normal area (A_n) for the sub-basin.
- If the soil data and land use data exists for the cell or triangle, the cell (triangle) area is added onto the area of soil data (A_s) and the area of land use data (A_l) for the sub-basin.

- After the above values are determined for each grid cell or triangle in the watershed, K_s, R, I_a, and C_k are computed for each sub-basin in the watershed according to the equations below:

$$K_s = e^{\left(\frac{\sum_{i=1}^{n} K_{s_i}}{A_s}\right)},\ R = \frac{\sum_{i=1}^{n} R_i}{A_l},\ I_a = \frac{\sum_{i=1}^{n} I_{a_i}}{A_l},\ C_k = \frac{\sum_{i=1}^{n} C_{k_i}}{A_l},\ K_s = K_s \times C_k$$

Equations 6: Equations for computing Ks, R, Ia, Ck, and the adjusted Ks for each sub-basin.

- Based on the chart on page 4-11 of Sabol et al. (1995), an array is maintained internally in WMS that relates values of hydraulic conductivity (K_s) for a basin to the basin's wetting front suction (ψ) and volumetric moisture deficit (θ) values. This array is specific to Maricopa County, Arizona. Other counties might have similar arrays that relate values of K_s to ψ and θ.
- Based on the sub-basin K_s (unadjusted by C_k) determined above, ψ and θ are calculated by linear interpolation from the internal WMS array values. θ for the basin is computed based on dry and normal θ-values and area weighted based on the total dry area (A_d) or normal area (A_n) for the sub-basin. The saturated θ-value is 0.0. The total θ-value for each sub-basin is computed according to Equation 7.

$$q = \frac{A_d}{A_l} q_d + \frac{A_n}{A_l} q_n$$

Equation 7: Computing the total volumetric moisture deficit (q-value) for each sub-basin.

- For each sub-basin, the C_k-adjusted K_s is assigned to the HEC-1 XKSAT, ψ is assigned to PSIF, θ is assigned to DTHETA, I_a is assigned to IA, and R is assigned to RTIMP.

Case Study: The Gavilan Peak Watershed in Maricopa County, Arizona

In order to test the spatial Green and Ampt computations, a watershed model with 17 sub-basins was successfully delineated in the WMS for the Gavilan Peak Watershed in the vicinity of the community of New River in northern Maricopa County, Arizona.

Hydrologic parameters were defined, the HEC-1 model was run, and the resulting hydrographs were compared with hydrographs developed using the county's current practices. The final model is shown in Figure 7.

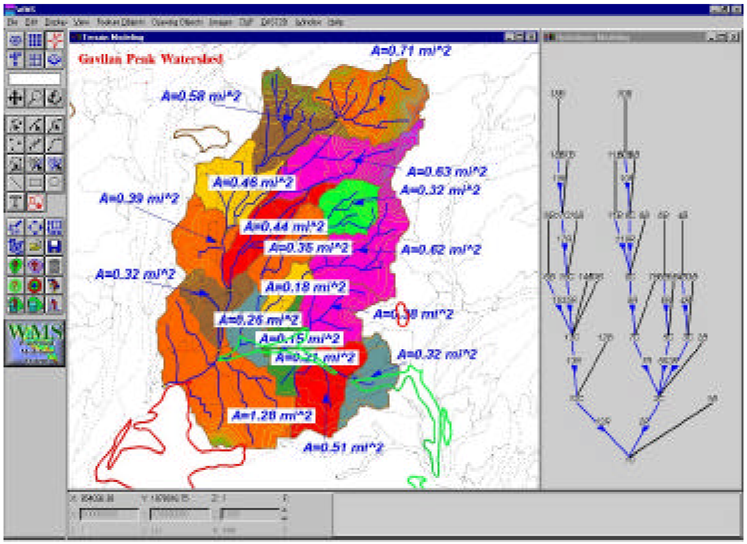

Figure 7: The Gavilan Peak Watershed Model

Using current county practices, basic GIS operations were used to determine the values required for the computation of Green and Ampt parameters described in this study. These values include the percentage of each kind of land use and soil type in each sub-basin. After these parameters were determined, the Green and Ampt parameters were calculated using a calculator.

One of the primary purposes of this study was to compare results of Green and Ampt parameters computed by WMS with the same parameters computed using current practices. Table 1 shows that there is excellent agreement between the Green and Ampt parameters computed in the WMS and Green and Ampt parameters computed using current practices for a single sub-basin:

Table 1: Comparison Between WMS and Hand-Computed Green and Ampt Parameters

HEC-1 Parameter	*WMS Value*	*Hand-Computed Value*
IA	8.18 mm	8.17 mm
DTHETA	0.304	0.303
PSIF	167.13 mm	167.64 mm
XKSAT	3.33 mm/hr	3.42 mm/hr
RTIMP	30.39 %	30.34 %

With a new, accurate algorithm for automatically computing Green and Ampt parameters from spatial land use and soil type data, watershed loss parameters can be computed more efficiently and timely than with traditional methods.

Conclusion

The Green and Ampt method is one of the methods available for computing sub-basin loss rates in HEC-1. Besides the rainfall data itself, the most sensitive set of input parameters for HEC-1 are the soil loss parameters. The SCS (NRCS) Curve Number approach is used most frequently to compute soil losses because it provides the easiest approach for computing losses. The ability to compute losses using the physically-based Green and Ampt method is available in HEC-1, but this method is used infrequently due to the difficulty in obtaining the required Green and Ampt input data. The purpose of this study was to develop and present a new, automatic, method of computing Green and Ampt parameters from commonly available Geographic Information System (GIS) data. Studies were performed with data from Maricopa County, Arizona that compare this new method with a previous, hand-based, method of computing Green and Ampt parameters. Excellent correlation was found between the computed parameters in the new method and the computed parameters in the old method.

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