Comparison of Lumped and Quasi-Distributed Clark Runoff Models Using the SCS Curve Number Equation

Murari Paudel[1]; E. James Nelson[2]; and William Scharffenberg[3]

Abstract: The Clark synthetic unit hydrograph and the Soil Conservation Service (SCS) curve number method has been used to simulate the rainfall and runoff behavior of a watershed for many years. Methodologies like Clark generally rely on the use of lumped or average rainfall and runoff parameters defined for the watershed, even though such parameters are spatially variable. In an attempt to leverage spatial parameters derived from geographic information, a modified Clark (ModClark) method or quasi-distributed model was developed for HEC-HMS. The ModClark method was initially developed to use the national network of WSR-88D radar (NEXRAD) rainfall data but few has been published on its application which is likely because of the difficulties in obtaining usable and reliable radar rainfall data and because of a lack of despisal preprocessing tools required to parameterize a ModClark simulation. While the original implementation and testing of the ModClark method required the use of NEXRAD data in specific formats, this study shows that it is possible to use any real or synthetic rainfall data whether it is spatially distributed or not. By not restricting the use of the distributed ModClark method to the use of spatially varying rainfall, distributed loss methods such as the commonly used SCS curve number can vary spatially over a grid and the effects of distributed watershed loss parameters can be analyzed with or without distributed rainfall. The implementation of the ModClark method in HEC-HMS is validated by comparing results to the Clark method using identical CN values. Further tests and examination of the SCS equation demonstrate that the runoff computed from distributed CN is always greater than the runoff computed from the traditional composite or area-averaged CN for ordinary ranges of rainfall depths. Moreover, by allowing a relatively fine grid resolution, the ModClark method determines the overall runoff from the watershed using a discharge weighted approach as opposed to weighted CN, which as reported in the National Engineering Handbook Part 630 is more accurate.

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Introduction

Hydrologic processes such as rainfall, infiltration, and runoff are by their very nature variable across both space and time. Traditional hydrologic simulation models used by engineers for evaluation and design have limitations in accounting for these variations. Temporal variations in hydrologic models are primarily derived from rainfall, which is the driving function of a runoff event. As long as the temporal variations in rainfall are understood, they can be accounted for in a simulation model. However, spatial variations in watershed properties affecting infiltration and surface runoff can be much more difficult to incorporate.

Early simulation models, adopted now as standard practice, did not have the ability to account for spatial variations because of both computational and data limitations. While many of these limitations have been overcome through the increased computational power of standard desktop computers and the widespread availability of geographic data easily downloaded from the internet, the ability to adopt geographic information system (GIS) tools to standard hydrologic modeling paradigms has lagged. This limitation has inhibited more widespread acceptance of simulation models that account for spatial variations (Sui and Maggio 1999).

This study focuses on the performance comparison of the Clark unit hydrograph runoff transformation method based on traditional lumped hydrologic modeling processes and the more recent ModClark method based on a quasi-distributed hydrologic model, in computing the hydrologic response from a watershed. In both simulations, the SCS curve number (CN) equation is used to determine the direct runoff from the rainfall input. The SCS method is chosen because it is commonly used and understood and because of its common implementation for both Clark and ModClark models. The Clark method was first implemented in the HEC-1 (U.S. Army Corps of Engineers Hydrologic Engineering Center 1998) computer program, which became a standard for performing routine hydrologic studies. Later HEC-1 evolved into the HEC-HMS (U.S. Army Corps of Engineers Hydrologic Engineering Center 2001) computer program which was part of a next generation of computer programs developed by the U.S. Army Corps of Engineers (Davis 1993). As part of the update from HEC-1 to HEC-HMS, new technologies and methods, including the ModClark method which accounts for spatial variations in rainfall and runoff on the watershed, were implanted (Charley

[1]Graduate Research Assistant, Brigham Young Univ., 300 CB, Provo, UT 84602. E-mail: mpaudel@et.byu.edu

[2]Professor, Civil and Environmental Engineering, Brigham Young Univ., 242 K CB, Provo, UT 84602 (corresponding author). E-mail: jimn@byu.edu

[3]HEC-HMS Lead Developer, U.S. Army Corps of Engineers Institute for Water Resources, Hydrologic Engineering Center CEIWR-HEC-HH, 609 Second St., Davis, CA 95616. E-mail: william.scharffenberg@usace.army.mil

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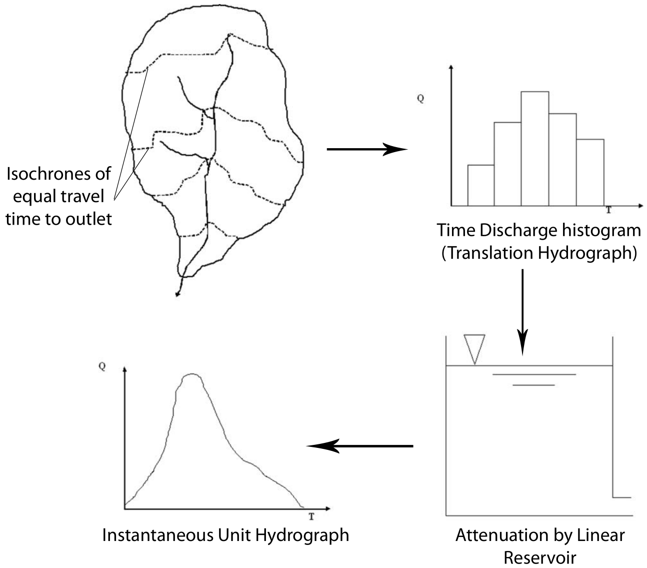

Fig. 1. Clark conceptual model (Kull and Feldman 1998, ASCE)

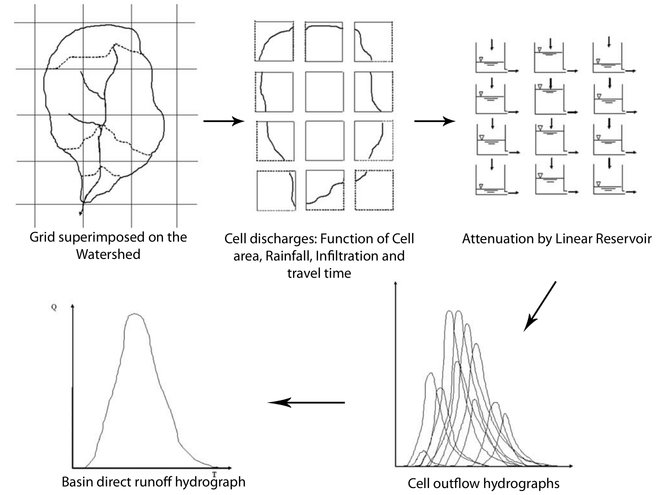

Fig. 2. ModClark conceptual model (Kull and Feldman 1998, ASCE)

et al. 1995). The watershed modeling system (WMS), capable of processing digital spatial data sets for watershed analysis, is used in this study to process geospatial data and generate input files for the two models (Nelson 2006).

The study consists of two parts. First, results from the watershed runoff using the Clark and ModClark methods were compared using identical CN values to demonstrate the performance and accuracy of using the HEC-HMS ModClark model and the WMS preprocessing of the required spatial input parameters. After verifying that the ModClark method produces identical results to Clark for nonspatially varying CN, the CN values were allowed to vary over the ModClark grid in order to demonstrate the importance of analyzing watershed runoff using distributed rather than lumped watershed loss parameter values. Sensitivity studies of the precipitation depth and various CN and area combinations on basin runoff were also carried out to further examine the differences in runoff depth calculations between lumped and distributed CN.

Clark Unit Hydrograph Method

The Clark method is a well established unit hydrograph approach to rainfall runoff simulation in which the basin shape, watershed storage, and timing can be accounted for. However, rainfall and loss parameters are lumped by determining average values over the domain. The Clark model is one of a handful of unit hydrograph methods that is widely accepted and has been applied in established models like HEC-1 and HEC-HMS.

The Clark method uses a time-area curve, a watershed storage coefficient (R), and the time of concentration to develop a translation hydrograph. The model is illustrated conceptually in Fig. 1. The watershed is divided into several areas of equal travel time to the outlet. From these areas, a mass curve (time-area curve) is developed and used to determine a time discharge histogram. The time discharge histogram is then routed through a linear reservoir to account for watershed storage (Clark 1945) using the following equation:

$$O(t) = C_a I = C_b O(t-1) \tag{1}$$

where $C_a = \Delta t / R + 0.5\Delta t$; $C_b = 1 - C_a$; $O(t)$ = ordinate of an instantaneous unit hydrograph (IUH) at time t; I = ordinate of translation hydrograph for interval $t-1$ to t; R = storage coefficient for linear reservoir; and Δt = time interval for which the IUH is defined.

Besides the time interval and storage coefficient (R), the overall time of concentration or length of time for water to travel from the hydraulically most remote point in the watershed to the outlet is required to compute runoff with the Clark method. Time of concentration can generally be estimated knowing the length, slope, and surface properties of the longest flow path, whereas the storage coefficient R can be estimated with empirical equations as some multiple of the time of concentration and then adjusted through calibration (Dodson & Associates 1992). The time interval is user defined and short enough to capture temporal variations in the storm being modeled.

Modified Clark Method

The ModClark method in HEC-HMS discretizes the watershed domain into a uniform grid. It is a linear quasi-distributed transformation method that is based on the Clark conceptual unit hydrograph. This method is different than the Clark model because spatial differences in rainfall and losses can be accounted for using the grid. Rainfall excess determined for each grid cell is then lagged based on the travel time to the outlet for that grid cell and then routed through a linear reservoir using Eq. (1) to account for the effects of watershed storage. Instead of a single time of concentration and a generalized time-area curve that is used to develop the Clark IUH (see Fig. 1), the travel time for each cell is based on the travel time to the watershed outlet (Peters and Easton 1996).

The results from each cell are combined to produce the final hydrograph, as shown conceptually in Fig. 2. If the same CN value was used for each grid cell then ModClark theoretically should produce the same result as Clark where the time-area curve is essentially derived from the times of travel and areas of the individual grid cells.

Implementation and Use of ModClark

ModClark was implemented in HEC-HMS for hydrologic analysis to facilitate using spatially varying rainfall and watershed properties (Charley et al. 1995). Since the ModClark method divides the watershed into relatively small grid areas, each of which can be thought of as a quasi-subwatershed, there is a possibility of capturing the variability introduced by distributed rainfall and watershed loss parameters. The method was originally developed with a primary motivation of incorporating the NEXRAD radar rainfall data (Davis 1993) and the ModClark preprocessing utilities were constrained to developing meteorological models based on the Hydrologic Rainfall Analysis Project (HRAP) grid of radars that are provided at a resolution of approximately 4 km. This limitation restricted the applications to relatively large watersheds and from which the NEXRAD radar data could be obtained.

However, the evolution of radar rainfall data that can be applied to hydrologic modeling applications with quantifiable uncertainty (Ajami et al. 2004) has been slow. For this reason and because the GIS preprocessing tools to support ModClark have not been widely available, very few applications involving ModClark have been developed or published. However, in addition to accounting for spatial variations in rainfall, the method can be used to account for variations in soil and land use used to derive CN and other watershed loss methods. By implementing a set of GIS preprocessing for the ModClark model that allows a meteorological model to be defined from gauge or standard synthetic design storms the effect of calculating distributed runoff can be performed without the constraint to use radar data. Such tools are available in WMS and were used as the basis of deriving the test watersheds of this study.

For the comparison studies developed hereafter, the Clark model represents a hydrologic model in which the CN values are lumped or spatially averaged and the rainfall response is determined using the Clark transformation method. Similarly, the ModClark model represents a quasi-distributed grid-based model in which the CN values can be varied over each grid cell and the rainfall response of the watershed is determined using the ModClark method of runoff transformation.

Comparisons are made between these two model formulations for the following purposes:

1. The HEC-HMS ModClark model behaves similarly to the Clark model as it should. This comparison will serve to verify that the concept of ModClark as programed in HEC-HMS is functioning as expected and WMS or a similar GIS interface can be used to properly parameterize a ModClark simulation without the requirement of using spatially varying NEXRAD rainfall data (though it could be used where available).
2. There is a distinct and predictable response in the watershed when the CN is allowed to vary spatially as it is with the ModClark model as opposed to when it is lumped or averaged as it must be with the Clark model.
3. The ModClark method, when implemented with a relatively high grid resolution, computes runoff from the SCS equation using the more accurate weighted discharge rather than the weighted CN approach (USDA-NRCS 2004).

Methodology

Geospatial watershed information is valuable for developing parameters for any hydrologic response model, including both the Clark and ModClark models. These data, including digital elevation models (DEMs), land use, and soils are readily available in common GIS data formats (Hartman and Nelson 2001). The DEMs are used to delineate the watershed area as well as to calculate slope, flow path distances, aspect, and other related hydrologic modeling parameters.

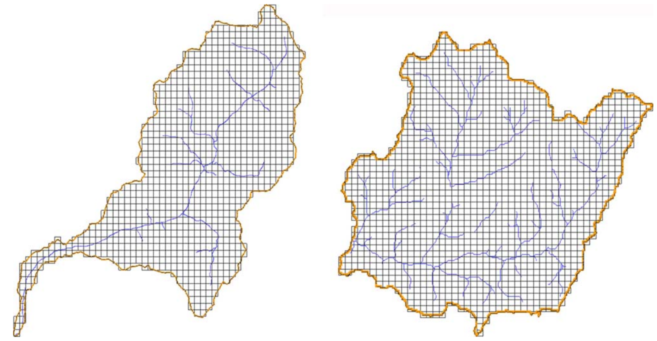

Fig. 3. American Fork and Virgin River Watershed defined using a 50×50 grid for the ModClark model

To identify the variation in infiltration, storage, and runoff behavior, which in this case is simulated using CN, land use and soil information of the watershed are required. Rainfall depth and duration are the driving inputs and essential for any surface runoff model. For lumped models that use the Clark unit hydrograph, an averaged value of all such parameters is used. However, for the quasi-distributed ModClark model, the variation in these parameters over the grid cells within the watershed can be evaluated.

Different GIS software programs are available, which can be used to process the digital spatial files and create the necessary input for either the Clark or ModClark models. To date, the primary tool used to create the quasi-distributed ModClark parameters is HEC Geo-HMS, which required the model to be defined using the 4-km^2-gridded radar rainfall data. While the use of spatially varying rainfall data such as the NEXRAD product is ideal for rainfall runoff simulations, technical problems associated with developing accurate ground estimates continue and therefore the availability of such data remains limited and its application underdeveloped.

In this study, the preprocessing tools have been designed to separate the overlying watershed grid from the rainfall data so that grids of any resolution can be used together with any of the possible HEC-HMS rainfall (meteorological) models. Making the computational grid independent of the rainfall model thus increases the potential uses of the ModClark method and its ability to better capture spatial variations associated with hydrologic calculations. The WMS has been used in this research because it has an interface for the necessary GIS-based processing of the digital watershed data, the Clark simulation in HEC-1, and the ModClark simulation in HEC-HMS. Fig. 3 shows the ModClark grids from a delineated watershed for the American Fork and Virgin River case studies.

Two different watersheds of varying sizes, shapes, and land uses are studied to make a comparison between the runoff responses from the HEC-1 Clark and the HEC-HMS ModClark models. In this study, HEC-1 was used for the Clark simulations rather than HEC-HMS because of the ability to define a time-area curve from the actual watershed DEM data, which is something that was not carried over to HEC-HMS. The HEC-HMS always uses a synthetic time-area curve based on "typical" geometry, whereas in HEC-1, a basin specific time-area curve of actual run-

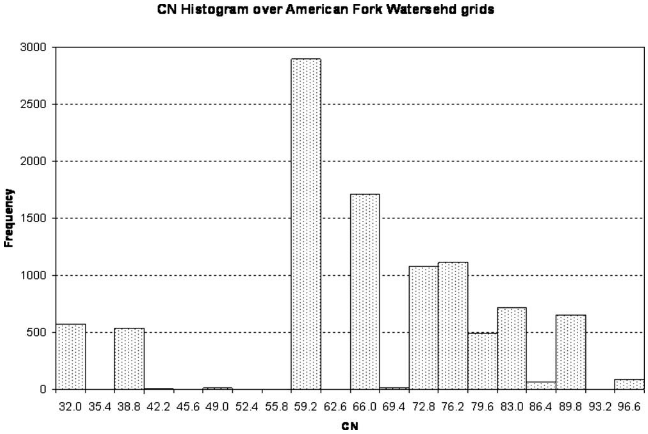

Fig. 4. CN histogram for American Fork Watershed using ModClark grid

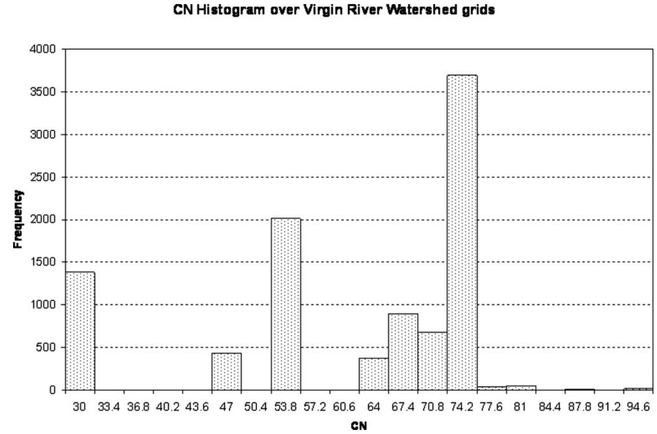

Fig. 5. CN histogram for Virgin River Watershed using ModClark grid

off patterns derived from a DEM can be used. Both models use the SCS CN method to calculate losses from identical storms, with the only difference in the two models being the way rainfall excesses are transformed to a runoff hydrograph. If the implementation of ModClark is correct, it should produce nearly identical results to the Clark model.

The two watersheds are (1) the American Fork Watershed with an area of 167.05 km^2 (64.5 sq mi) and (2) the Virgin River Watershed with an area of 2,474.47 km^2 (955.4 sq mi.). In either case it would not be a good practice to compute runoff excess from a single averaged CN over the basins, particularly the larger Virgin River Watershed, but for the purposes of illustrating the effects of lumped CN, they are computed that way in this study.

Rainfall for the study was obtained from the NOAA Atlas for the 100-year 24-h events for each of the watersheds, though for the purpose of this study any rainfall depth significant enough to generate runoff could be used. The basin average rainfall depth meteorological model is used with a standard SCS Type II 24-h temporal distribution (Wanielista 1997) of the storm for both the Clark and ModClark models so that the rainfall input is identical for both methods.

Watersheds were delineated using 30-m resolution seamless DEM data obtained from the USGS NED web server (USGS 2008a,b). The CN values were derived from spatial land use and soil data downloaded from the EPA web server (EPA 2008). These data can be used to classify a separate CN for each grid cell in the ModClark model as well as a composite value for the Clark model using standard SCS tables relating hydrologic soil classification and land use.

In order to validate the implementation of the ModClark model, a lumped CN simulation is performed for both watersheds using the composite CN for the Clark model and the identical CN for all grid cells in the ModClark model. The average composite CN of 59.3 was used for the American Fork Watershed and 64.9 for the Virgin River Watershed. A second ModClark simulation is then run using the unique CN values derived at each grid cell. A histogram of CN for the American Fork and Virgin River watershed grids is shown in Figs. 4 and 5, respectively.

Results

Comparison between Clark and ModClark Methods with the Same CN

As a basis for validating the implementation of the ModClark model in HEC-HMS, a comparison is done with the Clark model.

Fig. 6 illustrates the results for the American Fork Watershed. Here, the resulting hydrographs obtained from simulating the runoff from the 100-year 24-h storm with the Clark and ModClark models using the same CN as well as distributed CN with the ModClark model are shown. It can be seen clearly that the two smaller hydrographs are nearly identical as they completely overlap throughout. These hydrographs are the result of the Clark model and ModClark model with lumped CN. Any discrepancy between them could be attributed to numerical round off associated with the ModClark discretization of the watershed into smaller grid cells and resulting numerical differences in algorithm implementation. The hydrograph in Fig. 6 with increased volume and higher peak represents the runoff that results from using spatially varying CN values in the ModClark grid. The peak flow and runoff volumes are considerably higher using the ModClark

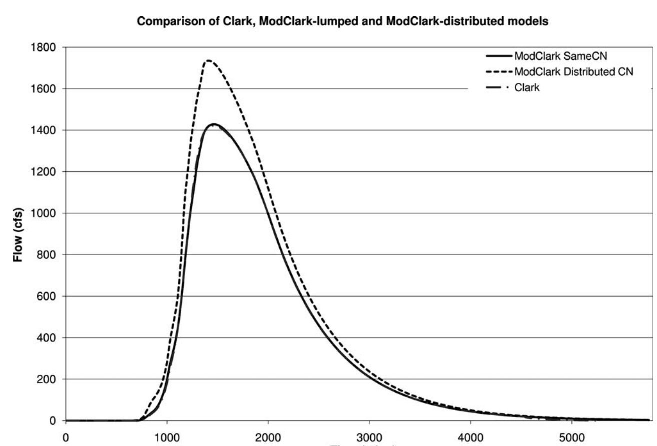

Fig. 6. Comparison between Clark and ModClark hydrographs for American Fork River Watershed with both averaged and distributed CN used for all grid cells

Table 1. Comparison of Computed Flow Data between Lumped (Clark) and Quasi-Distributed (ModClark) Methods in the American Fork River Watershed for Both Same and Variable CN

Flow statistics	Lumped CN (59.3) ModClark	Lumped CN (59.3) Clark	Distributed CN ModClark	Variation (lumped and distributed CN in ModClark) (%)
Peak discharge (cfs)	1,429	1,425	1,735	21.41
Total rainfall (in.)	4.0	4.0	4	0
Total loss (in.)	3.27	3.27	3.14	3.98
Total excess (in.)	0.73	0.73	0.86	17.81
Time to peak (h)	24 h 24 min	24 h 15 min	23 h 30 min	3.69

Note: Unit: 1 in.=2.54 mm.

model with variable CN rather than the lumped Clark model. This case study demonstrates the importance of considering the spatial variability of rainfall loss parameters.

From the summary table in the HEC-HMS simulation and output files in the HEC-1 simulation, the rainfall, loss, and runoff volumes can be extracted. Table 1 summarizes the results from the Clark and both ModClark simulations.

The tabular results further corroborate the hydrograph analysis, showing the comparison of the computed flow data from the Clark and ModClark simulations with constant CN values to be virtually the same. The 101.6 mm (4.0 in.) of total rainfall over the watershed resulted in 83.06 mm (3.27 in.) of loss and 18.54 mm (0.73 in.) of runoff. The peak flows and time to peak are slightly different but within variations that might be expected from the separate algorithm implementations.

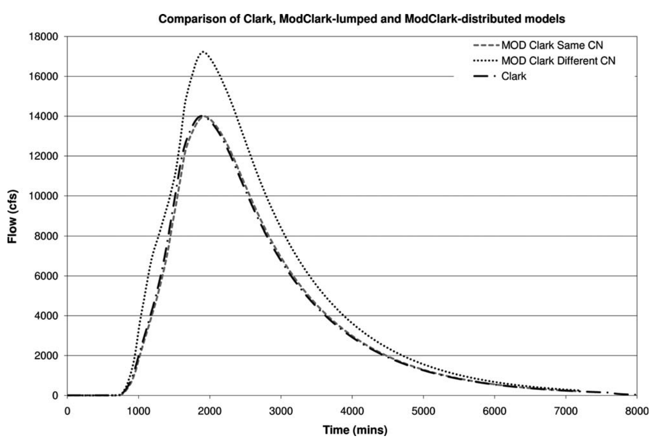

Fig. 7. Comparison between Clark and ModClark hydrographs for Virgin River Watershed with both averaged and distributed CN used for all grid cells

In the ModClark model with spatially distributed CN, the amount of loss is lesser and runoff/peak flow is higher than for the single-valued CN used with Clark model. The peak flow increased from 1,429 to 1,735 cfs, a 22.41% increase, for the same rainfall depth. The change in infiltration loss volume is also significant with a variation of 3.98% in the loss volume between lumped and distributed models.

Similarly, for the Virgin River Watershed, the hydrographs are as shown in Fig. 7. As with the American Fork model, when the lumped CN (64.9) is used for each ModClark grid cell, the hydrographs of the Clark and ModClark models are nearly identical.

The higher peak and increased volume of runoff resulting from spatially varying CN are consistent for the Virgin River Watershed.

Examination of the summary data for the Virgin River Watershed indicates that a total of 88.9 mm (3.5 in.) of rainfall results in 69.85 mm (2.75 in.) of loss and 19.05 mm (0.75 in.) of runoff. These depths are the same for both the Clark and ModClark (constant CN) methods. The resulting peak flows and time to peak are again, for all intents and purposes, identical. Table 2 shows the comparison of these values as well as the variation in computed flow data between the results obtained from the Clark model with lumped CN and the ModClark model with variable CN.

In the Virgin River Watershed, the peak flow is found to increase from 13,991 to 17,226 cfs, an increase of 23.12%. There is also considerable variation of 6.54% in the loss volume between the lumped and distributed models.

With the results from the above tables and graphs, the validity of the ModClark model implementation has been established. The results further illustrate a significant variation in results using an averaged or lumped CN value in the Clark model and spatially distributed CN values in the ModClark model. For the Clark model, only a single or lumped CN is possible. However, for the ModClark model, a separate CN can be computed for each grid

Table 2. Comparison of Computed Flow Data between Lumped (Clark) and Quasi-Distributed (ModClark) Methods in the Virgin River Watershed for Both Same and Variable CN

Flow statistics	Lumped CN (64.9) ModClark	Lumped CN (64.9) Clark	Distributed CN ModClark	Variation (lumped and distributed CN in ModClark) (%)
Peak discharge (cfs)	13,991	14,005	17,226	23.12
Total rainfall (in.)	3.5	3.5	3.5	0
Total loss (in.)	2.75	2.75	2.57	6.54
Total excess (in.)	0.75	0.75	0.93	24
Time to peak (h)	32 h 6 min	32 h 0 min	31 h 48 min	0.93

Note: Unit: 1 in.=2.54 mm.

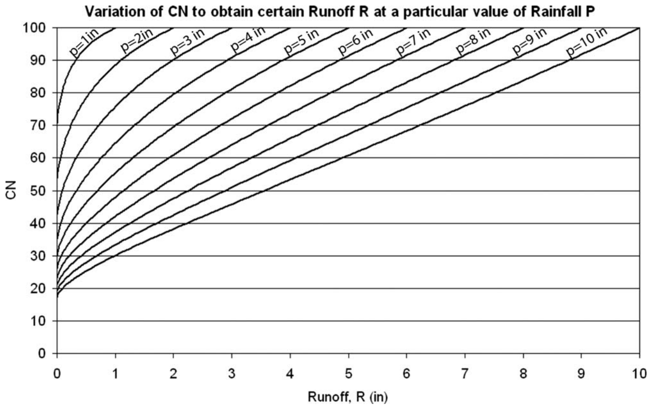

Fig. 8. Variation in CN value to obtain a runoff for different values of rainfall (unit: 1 in. = 2.54 mm)

cell according to the spatial variation in land use and soil, as if they were a thousand different separate subbasins.

With distributed CN models, the time to peak for the American Fork and Virgin River watersheds are found to decrease (i.e., the peak occurs earlier) but the variation between the lumped and quasi-distributed models is not significant. The variation is significantly higher for the peak flow, losses, and runoff values.

Discussion

The case study results show that the runoff response of the watershed is less for the same storm when CN is averaged as with the Clark model, compared to spatially varying CN as with the ModClark model. Qualitatively, a composite CN takes high-runoff areas and blends them into lower-runoff areas, resulting in less total runoff. This variation indicates that the use of ModClark is more conservative over the traditional Clark model when estimating runoff rate and volume.

The SCS equation defines runoff from a watershed as

$$R = \frac{P^2}{P+S} \tag{2}$$

This equation does not consider the initial abstraction (Ia) term, which is generally accepted as $0.2S$. Modifying Eq. (2) to include the Ia term transforms the equation to (U.S. Army Corps of Engineers Hydrologic Engineering Center 1994)

$$R = \frac{(P-\mathrm{Ia})^2}{(P-\mathrm{Ia}+S)} \tag{3}$$

where R=watershed runoff; P=rainfall; Ia=initial abstraction; and

$$S = \text{storage} = \frac{1{,}000}{\mathrm{CN}} - 10 \tag{4}$$

Composite watershed CN values are determined using the area-weighted averaging equation

$$\mathrm{CN}_{\mathrm{comp}} = \frac{\Sigma A_i \mathrm{CN}_i}{\Sigma A_i} \tag{5}$$

Area-weighted averaging of CN is linear. Conversely, the CN equation itself does not vary linearly. As can be seen in Fig. 8, for a range of CN values, the runoff tends to linearity with increasing rainfall but is highly nonlinear for smaller rainfall values.

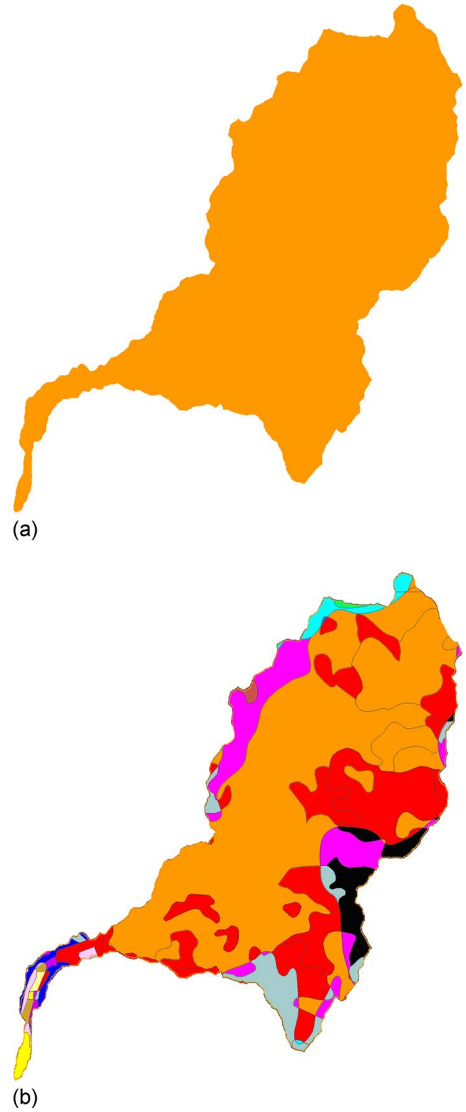

Fig. 9. (a) Lumped watershed CN; (b) variable CN according to soils and land use

This implies that for cases when a composite CN value is used to determine watershed runoff, the result will be lesser if runoff is determined for the watershed by summing the runoff computed using unique CN values for individual areas. In the development of the CN equations as discussed in the National Engineering Handbook (NEH), Part 630 Hydrology, a weighted CN as well as a weighted-discharge method are discussed (USDA-NRCS 2004). The weighted CN method computes an area-weighted average CN and then uses that CN to compute the runoff from the SCS equation, as illustrated in Fig. 9(a). On the other hand, as illustrated in Fig. 9(b), the weighted-discharge method computes the runoff depth from the SCS equation for each unique land use and soil combination and then area-weights these individual runoff depths to get the total runoff. Since watershed and subbasins are not naturally divided along boundaries of similar CN, the weighted CN method has been used almost exclusively in the implementation of the SCS loss method. However, the NEH manual establishes that the method of weighted discharge is more accurate than the method of weighted CN (USDA-NRCS 2004).

The original implementation of ModClark grid cells were de-

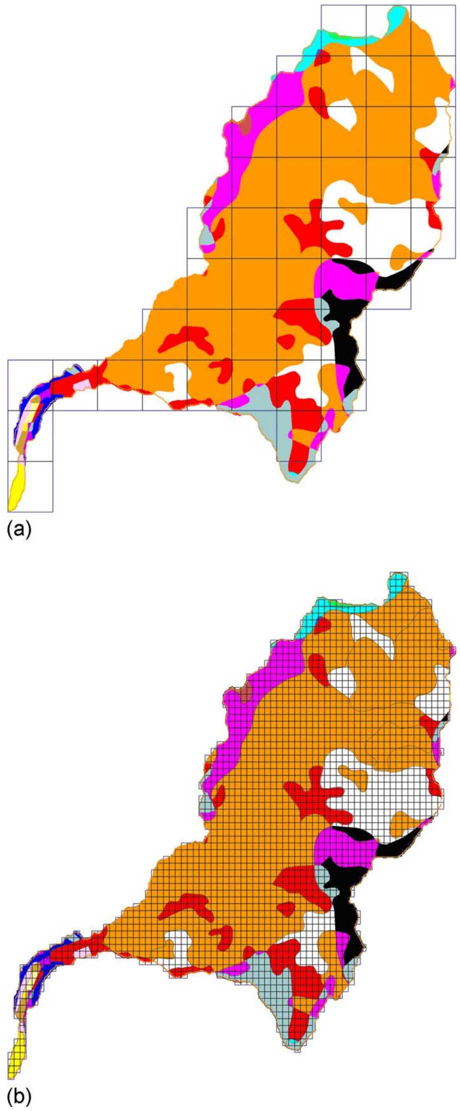

Fig. 10. (a) Conventional HRAP grid used in ModClark; (b) new fine resolution grid implemented in WMS

rived from the 4-km NEXRAD grid cells. At this resolution, CN computed for each grid cell will be averaged, as shown in Fig. 10(a). However, as shown in Fig. 10(b), if the grid cells become small enough by using a higher resolution, the individual cells are no longer averaged in most cases but instead are defined by the single land use and soil combination they contain.

Therefore, as finer and finer grid resolutions are used, the computation of runoff using CN and the ModClark method approaches the more accurate weighted-discharge method. Furthermore, the case studies indicate that the weighted-discharge method always produces more runoff for normal ranges of precipitation depths.

A series of experiments and an analysis of the SCS runoff equation [Eqs. (2) and (3)] were performed to verify that the runoff is always greater for distributed or weighted-discharge CN values than it is for a lumped or weighted CN values, as was apparent from the previously discussed case studies.

While computing a complete runoff hydrograph using weighted discharge is not available in HEC-1 or HEC-HMS, the runoff excess, as given by the SCS equation, was computed using the distributed CNs for both watersheds [see Fig. 9(b) for an illustration of this using the American Fork Watershed]. With this method, runoff (R) is determined for each individual area with a separate CN and the same average precipitation as the case study using Eq. (3). The weighted runoff R is calculated using the following equation:

$$R = \frac{\Sigma A_i R_i}{\Sigma A_i} \tag{6}$$

where R=total runoff depth from the watershed; and R_i=runoff from each individual area A_i with different CN.

The runoff excess for the American Fork Watershed, using the same rainfall depth, was 21.84 mm (0.86 in.) or identical to the excess computed using the ModClark method and variable CN (see Table 1). Similarly, the rainfall excess for the Virgin River Watershed was identical to the ModClark simulation with a variable CN at 23.62 mm (0.93 in.). This indicates that the ModClark implementation can be used to compute the weighted-discharge method of runoff excess. This result was further tested by varying the grid resolution in the ModClark model and comparing the results with the values from the weighted-discharge method. The runoff depths in ModClark became identical as the grid size became smaller.

In order to determine the effects of using distributed versus composite CN over a range of precipitation values, the percent difference in runoff between the two, as defined by Eq. (7), was repeatedly solved for values of rainfall (P) beginning at 2.54 mm (0.1 in.) and incremented by 2.54 mm (0.1 in.) up to 508 mm (20.0 in.) using the American Fork model.

$$\%\text{difference} = \frac{R_{\text{Dist}} R_{\text{comp}}}{R_{\text{Dist}}} \tag{7}$$

where R_{Dist}=runoff from the model shown in Fig. 9(b) using the distributed CN (discharge weighted method) and R_{comp} is the runoff from the model shown in Fig. 9(a) using the composite CN (CN weighted method). These values are derived from the SCS Eq. (2) as follows:

$$R_{\text{Dist}} = \frac{P^2}{P + \left(\frac{1{,}000}{\text{CN}_1} - 10\right)} * A_1 + \frac{P^2}{P + \left(\frac{1{,}000}{\text{CN}_2} - 10\right)} * A_2 + \ldots \ldots ... + \frac{P^2}{P + \left(\frac{1{,}000}{\text{CN}_n} - 10\right)} * A_n \tag{8}$$

$$R_{\text{comp}} = \frac{P^2}{\left[\frac{1{,}000}{\left(\frac{A_1 * \text{CN}_1 + A_2 * \text{CN}_2 + \ldots \ldots \ldots + A_n * \text{CN}_n}{A_1 + A_2 + \ldots \ldots \ldots + A_n}\right)} - 10\right]} * (A_1 + A_2 + \ldots \ldots \ldots + A_n) \tag{9}$$

If the terms R_{Distr} and R_{comp} in Eqs. (8) and (9) are equated and a value of 254 mm (10.0 in.) is substituted for P then

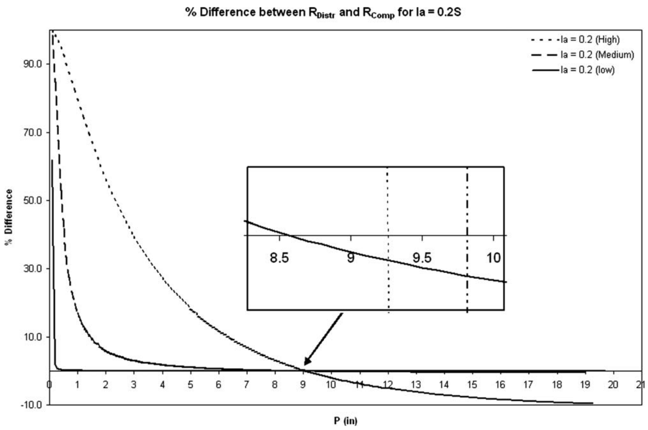

Fig. 11. Percent difference between R_{Distr} and R_{comp} with high variation in CN over the watershed (unit: 1 in. = 2.54 mm)

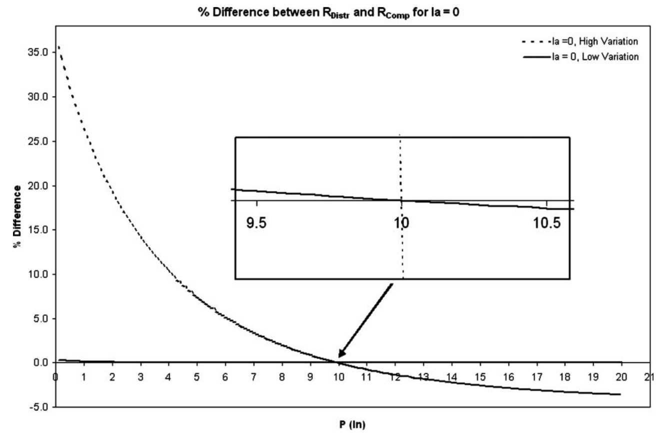

Fig. 12. Percent difference between R_{Distr} and R_{comp} with low variation in CN over the watershed (unit: 1 in. = 2.54 mm)

$$\frac{1{,}000 * A_1}{\frac{1{,}000}{\mathrm{CN}_1}} + \frac{1{,}000 * A_2}{\frac{1{,}000}{\mathrm{CN}_2}} + \ldots \ldots + \frac{1{,}000 * A_n}{\frac{1{,}000}{\mathrm{CN}_n}} = \frac{1{,}000 * A}{\frac{1{,}000 * A}{A_1\mathrm{CN}_1 + A_2\mathrm{CN}_2 + \ldots \ldots A_n\mathrm{CN}_n}}$$

or

$$A_1\mathrm{CN}_1 + A_2\mathrm{CN}_2 + \ldots\ldots + A_n\mathrm{CN}_n = (A_1\mathrm{CN}_1 + A_2\mathrm{CN}_2 + \ldots . + A_n\mathrm{CN}_n)$$

or

$$R_{\mathrm{Distr}} = R_{\mathrm{comp}}$$

This shows that at $P = 254$ mm (10.0 in.), the values of R_{Distr} and R_{comp} become equal. It can also be shown that for values of $P < 254$ mm (10.0 in.), $R_{\mathrm{Distr}} > R_{\mathrm{comp}}$, and for $P > 254$ mm (10.0 in.) $R_{\mathrm{comp}} > R_{\mathrm{Distr}}$.

Similarly, if the Ia term is considered nonzero as in Eq. (3), then it can be shown that $R_{\mathrm{Distr}} > R_{\mathrm{comp}}$ for all $P < 203.2$ mm (8.0 in.) and $R_{\mathrm{comp}} > R_{\mathrm{Distr}}$ for all $P > 254$ mm (10 in.). Using the American Fork Watershed as an example, several experimental calculations using high, medium, and low variations in CN were performed and the percent difference using Eq. (7) was determined. Fig. 11 shows that with the higher variation in CN, R_{Distr} becomes equal to R_{comp} when P approaches 254 mm (10.0 in.). With lower variation in CN, the theoretical value of P approaches 203.2 mm (8.0 in.) [it can only reach 203.2 mm (8.0 in.) as the variation approaches 0 or, in other words, all CN values are the same]. Fig. 12 shows that, for Ia = 0, the transition point at which $R_{\mathrm{Distr}} = R_{\mathrm{comp}}$ always occurs for a precipitation depth of 10.0 and is independent of the variation in CN.

Both cases show that the percentage difference is comparatively high at small precipitation depths and when the variation in CN is low, the percentage variation between R_{Distr} and R_{comp} becomes small because for small variations in CN, distributed CN essentially becomes composite or the average CN.

Further experiments using different percentages of S for Ia ($0.2S$, $0.1S$, $0.05S$, etc.) showed that the lower limit of the transition (when there are relatively small differences in CN) occurred at $(1 - M_{\mathrm{Ia}}) * 10$, where M_{Ia} is the multiplier of S used in determining Ia. The upper limit for the transition remained at 10.0 for all cases stemming from the constant 10 used in the CN equation [Eq. (4)].

These results further validated what was initially observed from the comparison of the Clark and ModClark modeling case studies. Specifically, because of the nonlinearity of the CN equation for low values of rainfall, computing the runoff with a composite or average CN value will be less than the runoff computed with distributed or weighted-discharge CN. As the rainfall approaches 254 mm (10.0 in.) and the SCS equation approaches linearity, the magnitude of the difference decreases but is still lesser.

It should be noted that all models are subject to uncertainty and therefore it is a good practice to use measured rainfall and streamflow data when available to calibrate a runoff simulation. Using calibrated CN values, composite or distributed, would accurately reflect anticipated runoff for the particular watershed and storm conditions. However, in practice, many hydrologic models are applied to regions where observed data are not available or feasible to collect. In such cases, the ModClark quasi-distributed model would be a more conservative choice for values of rainfall $< \sim 203.2$ mm (8.0 in.) when the standard assumption of Ia $= 0.2S$ is made.

Conclusions

The ModClark method of transforming rainfall excess to a hydrograph was implemented in HEC-HMS as a means of accounting for spatial variability in watershed parameters. While specifically developed as a means of using NEXRAD radar rainfall data, it also allows loss calculations such as the SCS CN to be determined spatially. The WMS interface allows for the definition of an HEC-HMS ModClark model with nonspatial rainfall data such as can be defined from the design storms where a basin average or rainfall gauge data are used.

Two case studies were examined to test the definition of ModClark models that allowed for runoff volume to be computed spatially without the requirement of spatially varying rainfall data. When compared to the Clark model, the ModClark simulations produced identical results when the similar average CN value determined for the watershed was used for the single Clark basin and all ModClark grid cells.

Having validated the implementation of ModClark with the

Clark model from which it was derived, the CN values were allowed to vary spatially for the grid cells according to available land use and soil definitions derived from spatial data sets of the USGS and NRCS. In both case studies, the volume and peak of the resulting hydrographs were greater when CN varied spatially. Further analysis of the SCS CN equation reveals that the runoff volumes will be higher for rainfall less than 203.2 to 254 mm (8.0 to 10.0 in.) (when assuming Ia is equal to 0.2*S*) when distributed CN values are used in a model such as ModClark versus the more traditional lumped approach as required for a Clark simulation.

This analysis leads to the following specific conclusions:

1. The ModClark method, as implemented in HEC-HMS, functions well and provides an important capability for defining spatially different loss parameters, even in the absence of radar rainfall data.
2. The Clark and the ModClark models give the same results if the grid-based CN values in ModClark method are replaced by the same CN for each grid cell in the entire basin. This result shows that the ModClark model as used in HEC-HMS is equally reliable as the well-established Clark model.
3. The lumped CN, as used by unit hydrograph transformation methods such as the Clark model, underestimates the runoff volume and peak flow as compared to the results from the spatially varying ModClark method. This result led to a further examination of the SCS equation for which the following conclusions were made:
   - When the traditional value of Ia is defined by 20% of the potential storage ($Ia=0.2S$), the runoff from a distributed modeling method is greater for all values of rainfall less than 203.2 mm (8.0 in.) with some variations in this value depending on the relative differences in CN. It was found that the value of precipitation at which the runoff from the lumped model will be higher varies between 203.2 to 254 mm (8.0 to 10 in.) depending upon the relative differences in CN.
   - When the Ia is neglected, the runoff from a distributed modeling method is greater for all values of rainfall less than 254 mm (10.0 in.) It was found that the value of precipitation at which the runoff from the lumped model will be higher is 254 mm (10.0 in.) irrespective of the relative differences in CN.
4. The ModClark model was found to use the weighted-discharge method as discussed in NEH Part 630, which is more accurate than the CN-weighted method of runoff computation. By using the ModClark model with proper grid resolution, the practice of dividing the watershed into subbasins that are hydrologically similar is not necessary.

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