

## References on time of concentration with respect to sheet flow

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### Introduction

Certain references found in the technical literature were reviewed with their statements concerning sheet flow characteristics. Concern was expressed that the maximum sheet flow length in TR-55 was reduced from 300 feet to 100 feet in the recently developed Windows TR-55 software system. Technical information to justify the revision was requested. Though only one of the studies focused on the length of sheet flow (McCuen and Spiess), several give useful insights on the appropriate length, roughness, and depth related to sheet flow. For the following references, some direct quotes from the papers are included along with narrative comments. After a review of the papers, a brief summary of this investigation and some general conclusions are offered for consideration.

### Woodward and Welle, NRCS, Northeast NTC, Hydrology Technical Note N4, 1986.

Quote:

The Manning-kinematic solution is sound, defensible, and easy to use. Therefore, it is recommended that this equation be used to compute  $T_t$  for the overland flow segment. The maximum flow length of 300' with a most likely length of 100' should be used in overland flow computations for unpaved areas. Paved areas may have longer lengths of sheet flow until flow becomes channelized in gutters or low areas of parking lots. The range of mean depth is 0.002' for paved areas to 0.02' for vegetated areas.

Narrative:

One approach to estimating the length of sheet flow may be to define a maximum depth for which sheet flow applies. With respect to depth, the Manning equation may be used to estimate depth based on discharge, Manning  $n$  and slope (assuming a one foot width). There are several ways to estimate the discharge at the end of a selected length of sheet flow. A set of 12 references is included with this paper, which presumes that the statement was based on those references (though the authors did not state which specific reference).

### W. O. Ree, A Progress Report on Overland Flow Studies, USDA, Agricultural Research Service, Southern Plains Branch, 1963.

Quote:

Overland flow occurs in every watershed to some degree. Whether it is extensive enough or the flow length great enough to influence the hydrograph needs to be determined. One method for estimating the average length of overland flow was developed by Robert E. Horton. In his classic work on geomorphology, he shows that the average length of overland flow,  $l_o$ , can be estimated by the relation:

$$l_o = 1 / ( 2 Dd ) \quad (1)$$

Where  $Dd$  is the drainage density defined as:

$$Dd = \text{sum of stream lengths for the watershed} / \text{area of the watershed} \quad (2)$$

Thus, if the length of all channels that are fed directly by overland flow can be measured, it is possible to estimate the average overland flow length. An attempt was made to do this for the 206-acre grassed watershed operated by the Stillwater Hydraulic Laboratory. Every waterway visible on an aerial photograph of the watershed was carefully measured. It was found that the sum of the lengths of all drainageways was about 48,900 feet. This value and the value for the area were substituted into equations 1 and 2 and the average length of overland flow was calculated to be 92 feet.

The determination of what constituted a drainageway was quite a subjective one. By searching for still smaller channels it would be possible to produce a different estimate of  $l_o$ . Nevertheless, it is thought that the estimate made does indicate the order of magnitude of overland flow and that it is large enough to have an important role in the determination of the hydrograph of outflow.

Narrative:

The calculation of overland flow (sheet flow) length by equation 1 requires the sum of stream lengths and area of the watershed to be in consistent units. For example, if  $D_d$  is 48,900 feet, the area of the watershed also should be in square feet or 206 acres times 43,560 square feet per acre. These values result in the average overland (sheet) flow length of 92 feet.

Even though this relationship was developed using geomorphic data, it also has a physical interpretation. If all flow concentrations are identified on a map of the watershed,  $l_o$  represents the average maximum distance from locations in the watershed to the nearest flow concentration. This applies to distances from points along the watershed boundary to the nearest flow concentration as well as points within the watershed which are between flow concentrations. This average value of sheet flow length may vary according to the definition of flow concentration and how it is measured. It also represents a watershed average value and not the sheet flow length which falls on the path used to calculate time of concentration. This procedure is most applicable in small undeveloped watersheds with a relatively homogeneous drainage network. Using this procedure in developed or partially developed areas has limitations in that the density of identified flow concentrations may vary significantly within the watershed (for example, dense in developed and wide-spread in undeveloped areas). The "average" value may not have practical meaning because of this variability. Dividing the watershed into subwatersheds could be considered in such cases. The practical use of this procedure is related to getting a general estimate of sheet flow length in a watershed. As an alternative, after the flow concentrations are identified, sheet flow distances may be measured at several locations in a watershed to get a similar general idea or estimate. Another use of the procedure would be to develop estimates of average sheet flow length for various geomorphic regions or urban development characteristics.

Quote:

Supply rate Inch/hr	Depth at outflow Inches
1	0.26
2	0.39
3	0.50
4	0.59

Narrative:

The table above was developed using an overland flow equation developed by Horton which estimates the depth of overland flow based on Manning  $n$ , slope, supply rate (rainfall intensity), and overland flow length. This gives an order of magnitude of the depth of overland flow of 0.59 inch (0.05 feet) for a 4 inch per hour rainfall intensity.

Quote:

Channel research at Stillwater, Oklahoma, has included a study of low flows. These were conducted in flat-bottomed channels 3 feet wide and 96 feet long, with a bed slope of 5 percent. The sides of the channels were low concrete curbs about 0.2 foot high. While these tests were made primarily in connection with the studies of the hydraulics of vegetation-lined waterways, the low flow data may be useful in the investigation of overland flow problems.

Narrative:

The report includes results of these tests for different kinds of grass cover and cover density. Results of one test were plotted which show relationship of discharge to depth at the end of the 96 foot slope. A discharge of 0.01 cfs / foot of width had a depth of 0.05 feet.

**Engman, E. T., Roughness Coefficients for Routing Surface Runoff, ASCE Hydraulics Division Conference, Frontiers in Hydraulic Engineering, August, 1983.**

Quotes:

Data used in this study were collected on plots to evaluate erosion rates and volumes for different soils and management practices by the Agricultural Research Service-USDA stations in West Lafayette, Indiana, Oxford, Mississippi, and Tucson, Arizona. The plots were typical of those used in erosion research and varied in length from about 10 to 20 m and in width from about 1.7 to 4 m. Simulated rainfall was applied to the plots at a constant intensity that varied from plot to plot and location but were generally was between 5 to 10 cm / hr. Runoff was measured with a flume and continuous stage recorder that provided accurate timing and the shape of the hydrograph.

In using these roughness values one should be aware of two potential limitations: (1) These values are valid for so-called sheet flow or overland flow before significant channelization occurs. Thus these data will be valid for relatively short slopes. Exactly what length of slope these values will be valid for is unknown at this time. However, as slopes approach 50 to 100 meters in length one would expect channelization to begin or else very large and unreasonable depths of overland flow would be calculated; (2) These values include the effect of rain drop impact which tends to increase the effective roughness.

Narrative:

The author includes a table of Manning n values for sheet flow surfaces. Some values from that table are included in Table 3-1 of TR-55 (1986 printing). The author states these values of Manning n apply to relatively short slopes. They were developed on plots of 10 to 20 meters in length and so have that limited applicability. With respect to depth, high Manning n for dense grass and woods would definitely produce an unreasonable depth if the sheet flow length were extended to 300 feet. This reference reinforces the case for considering both length and depth of sheet flow simultaneously.

**Engman, E. T., Roughness Coefficients for Routing Surface Runoff, ASCE Journal of Irrigation and Drainage, Vol. 112, No. 1, pages 39-49, February 1986.**

Quote:

Information for choosing roughness coefficients is fairly common for streams, channels and canals. Typically, Manning's n values can be estimated with guidance from descriptive information and photographs. However, very little information is available for shallow depth of overland flow over natural surfaces.

Narrative:

This paper is related to the reference by Engman above. It contains a summary of a literature review concerning overland flow and additional analyses of plot data. The published table of Manning n values is somewhat different from the 1983 paper. It contains some different cover, tillage practices, and surface residue categories as well as some changes in recommended Manning n for some surfaces.

The author reports the mean, standard deviation, and range of Manning n determined for each cover type and the number of experiments with each cover type. The range of values indicate Manning n can vary by a factor of about 1.5 to 3 or greater for most surface types. The sheet flow travel time will thus have a possible wide range based on the estimate of Manning n for the surface. The estimated depth of flow could also have a wide range of values based on the Manning n selected. TR-55 uses a single value of Manning n for each cover type. It masks the variability of the underlying data. Using the mean of the various cover and tillage conditions, the travel time value which is calculated could have an error of plus or minus 25 to 50 percent (assuming the cover type and condition are selected properly).

Quote:

The depth of calculated flow should not become too large. On long flow planes, the routing models may calculate depths that may be unrealistically large. The users must be aware of this and limit flow plane lengths. It appears that excessive depths would not be encountered if slope lengths are on the order of 150-300 feet (50-100 m).

Narrative:

This quote is similar to that of the other paper by Engman above. However, the depth should be estimated and length adjusted accordingly. Appropriate depths of overland or sheet flow are addressed in other reviewed papers.

**Parsons, D. A., Depths of Overland Flow, USDA-SCS, SCS-TP-82, July 1949.**

Quotes:

Runoff was measured from an area 6 feet wide by 47.5 feet long with sheet metal boundaries. The soil was Decatur clay loam from north Alabama. It was bare and had been considerably compacted.

One of the 50-foot tilting plots was also used in determination of overland flow depths on an excellent stand and growth of Korean lespedeza. The vegetation was green and nearly mature.

Narrative:

Several more types of cover and shorter plot lengths (and a few longer plots) were investigated. Results of this study are again primarily limited to short slopes and extending these results to long slopes is questionable.

Quote:

The formation of rills and gullies, in effect, shortens the distance, L, of overland flow. Instead of beginning at the upper boundary and increasing progressively until it reaches the lower boundary, the flow originates at the upper boundary, or divides between rills, and ends, in part, in concentrated flow uphill from the lower boundary. The concentrated flows in these channels may be much greater in depth than the average, but the relative area of the land that is covered by these flows is sufficiently small for this factor to be outweighed by the effect of shortening the distance of overland flow. The mere presence of rills or flow concentrations rather than their depth seems to be the more important influence.

Narrative:

The authors found some flow concentrations before the end of the 50 foot long plots. Data were analyzed as if all flow were overland (sheet) flow. Special analytical treatment of flow concentrations was not reported.

Quote:

When  $\rho = 1$ , the time of concentration,  $t_c$ , is

$$t_c = \frac{4}{3} * \frac{43200 D}{rf}$$

Narrative:

Based on their field experiments, the authors developed an equation for time of concentration ( $t_c$ ), which in the current context is travel time for sheet flow, based on slope parameters. These include average depth of flow ( $D$ ) in feet and runoff rate ( $rf$ ) in inches per hour. The units for  $t_c$  in the above equation are seconds. Interpretations of how  $D$  and  $rf$  are estimated are contained in the report. The average depth of overland flow is dependent on the slope, length, and roughness as well as the discharge or runoff rate. The meaning of the symbol  $\rho = 1$  is that the runoff rate has reached its maximum after a period of constant rainfall intensity. The authors used hydraulic theory to develop various relationships for laminar and turbulent flow and used Reynolds number and kinematic viscosity of water in their derivations.

**Ree, Wimberley, and Crow, Manning n and The Overland Flow Equation, Transactions of the ASAE, Volume 20, Number 1, pages 89-95, 1977.**

Quote:

The average length of overland flow was determined by dividing the watershed area by twice the total length of all waterways.

The delineation of drainageways on a contour map is highly subjective and is the product of the mapmaker's ideas and practices. Yet, the calculated length of overland flow depends completely on the value of the total drainageway length. Thus describing as exactly as possible how drainageways were determined becomes essential if results are to be meaningful.

Smooth contours were drawn, which fit the survey points chosen, to obtain a good representation of the topography using a 5-ft contour interval. The drainage pattern was drawn on the finished map extending the drainageways through the last contour, which indicated a draw or valley.

Watershed	Average Slope (percent)	Length of overland flow (meters)
W-1	4.43	69.5
W-3	5.13	61.9
W-4	6.66	60.0

Narrative:

The same equation was used to estimate overland (sheet) flow length as used in the above Status Report by Ree. The sheet flow lengths ranged from 200 to 230 feet. Like the authors state, defining the stream

locations is subjective. In the Status Report by Ree, streams were located using aerial photos, and in this study, they were defined on a hand produced topographic map. It would be interesting to see what sheet flow lengths would result from an aerial photo determination on the three watersheds. Examining the contour map of the 92 acre watershed W-3 reproduced in the paper, there are large areas within the watershed where no stream has been identified. It is entirely possible that some streams were missed which would cause the overland flow length to be shorter.

Quote:

The Manning n value data for this study were obtained from tests on grass-lined unit channels at the laboratory. These are flat-bottomed channels (0.91 m wide and 29.26 m long) with a 5 percent bottom slope.

Narrative:

Again, the study is based on a flow length of about 100 feet. Results are applicable for that length.

Quote:

Fig. 1 (Photograph) An example for a good cover condition in watershed W-3. The average overland flow equation for this condition is  $q = 1.48 D^{1.22}$ . The equivalent Manning n for a flow depth of 1 cm is 0.31.

Narrative:

The authors make limited reference to the depth of overland flow such as in this caption to the photograph labeled Figure 1. 1 cm depth is approximately 0.03 foot. In Figure 6, a plot of discharge versus depth shows depths of 1 cm and less.

**Emmett, W., The Hydraulics of Overland Flow on Hillslopes, USGS Professional Paper 662-A, US Government Printing Office, 1970.**

Quotes:

Seven field sites in west central Wyoming were selected for verification of laboratory data. The field sites were 7 feet wide, about 45 feet long, and approximately represented four slope angles.

The flume used in this investigation was constructed with a plywood bed... The width was 4 feet and the length was 16 feet. Flume slope was adjustable by hydraulic jacks at the lower end....

Narrative:

Length of overland flow experiments is again limited to under 50 feet. The slopes of the seven field sites ranged from 2.9 to 33 percent.

Quote:

On nearly flat slopes, microrelief features on the order of only 0.1 foot appeared to dictate the paths of the flow concentrations. However, on steeper slopes, small microrelief features did not appreciably alter the down-slope gradient and their influence on concentrations of flow was masked.

As explained earlier, the flow rarely occurred as a uniform sheet of water and the majority of water travelled downslope in several lateral concentrations of flow; however, these concentrations were not considered rill flow.

Report content:

Figures 11 through 15 show plots with average flow depth of 0.05 foot or less for the field tests. Table D includes average flow depths of 0.04 foot or less (with most under 0.02 foot) for laboratory experiments. Manning n values ranged from less than 0.01 up to 0.10 for the laboratory tests and from 0.10 to greater than 2.0 with most falling between 0.20 and 1.0 for the natural ground.

Narrative:

Depth of flow was not uniform across the slope because the natural ground surface and laboratory soil surface was not smooth. The slope of the plots was also not uniform in the longitudinal direction. This caused differences in depth as flow proceeded downslope. This is typical of natural surfaces in many areas. Table C shows results of depth measurements at one of the field sites measured at one foot intervals across the slope and 2 foot intervals downslope. The range of flow depth was 0.0 to 0.09 feet (with most depths between 0.01 and 0.06 feet) indicating magnitude of microrelief. The surface in the natural ground tests was fine to moderate grain size (D50 values were from 0.09 to 0.48 mm) and vegetation cover ranged from 8 to 35 percent. Equations were applied with respect to the average depth of flow across the slope. The depths were shallow enough that what flow concentrations were present, they were not deep enough to classify them as rills.

**McCuen and Spiess, Assessment of Kinematic Wave Time of Concentration, unpublished manuscript, November, 1993.**

Quote:

Current practices use the flow length, L, as the limiting criterion when using a kinematic wave equation to calculate travel time. According to the 1986 TR-55 documentation, the flow length in Eq. 3 must be less than 300 feet. Some localities believe 300 feet is too long and limit L to 100 feet. However, there does not appear to be documented evidence that shows these limits are justified.

The use of flow length alone as a limiting factor for the kinematic wave equation can lead to circumstances where the kinematic wave assumptions are no longer valid. Overprediction will generally occur for lengths with high Manning's n values and/or flat slopes. For instance, lengths of grassed surfaces of much less than 100 feet may have significant depression storage, as may flat areas. In such a case, the kinematic wave equation will overpredict the sheet-flow travel time.

Narrative:

This is the prime study focusing on the limits (including sheet flow length) in the use of the Manning-kinematic equation for computing sheet flow travel time. Background is given concerning research on the length of sheet flow and development of the Manning-kinematic travel time equation. Eq. 3 mentioned in the above quote is the sheet flow travel time equation which is contained in TR-55 (1986 printing). The approach in this study is to consider the theory and assumptions of kinematic flow and actual field measurements to develop practical limits on the use of the Manning-kinematic travel time equation similar (but not the same) as in the NRCS TR-55 computer program.

According to the authors, length alone is not an appropriate as a criterion. The authors mention Manning n and slope as additional factors to be considered.

Quote:

Times of concentration and watershed characteristics from 59 field and laboratory experiments were analyzed to determine a suitable limit for the kinematic equation. The data used in this analysis represented a wide range of watershed sizes, slopes, and ground conditions.

Narrative:

The authors considered data for paved and unpaved surfaces. Range in length was from 12 to 3033 feet. Range in Manning n was 0.0073 to 0.4. Slopes ranged from 0.001 to 0.162 ft/ft.

Quotes:

The composite parameter  $nL/\sqrt{S}$ , where the variables are as described in Eq. 1, will be developed and assessed in this paper as an accurate and useful criterion when estimating travel times using the kinematic wave equation. This criterion is a conceptually more rational limit than both the flow length and the product  $iL$  (where  $i$  is the rainfall intensity) because it incorporates main properties of sheet flow. Also, the criterion  $nL/\sqrt{S}$  can differentiate a 100-foot flow length with a steep slope and low Manning's  $n$  and the same length with a flat slope and high Manning's  $n$ , each of which have the same flow length, but quite different flow conditions.

In summary, the  $nL/\sqrt{S}$  criterion provided better goodness of fit statistics than the length. While the statistics for  $iL$  as a criterion were comparable to those of  $nL/\sqrt{S}$ , the latter is preferred because it is composed of variables that are related to the physical processes that underlie kinematic flow. Thus  $nL/\sqrt{S}$  is a more rational criterion than  $iL$  for limiting the use of Eq. 2 in estimating sheet-flow travel times. The analysis for an upper limit for  $nL/\sqrt{S}$  of 100 provided the best overall results and suggested an upper limit of about 100.

Narrative:

Equations 1 and 2 mentioned in the above quote are general kinematic time of concentration equations developed from theory. The term "time of concentration" is used with reference to the uniform slope length. If this slope length were the sheet flow length for a watershed which also had shallow concentrated and channel flows the term would be interpreted as "sheet flow travel time".

$$T_c = C_1 (nL/\sqrt{S})^{C_3} / i^{C_2} \quad (1)$$

$$T_c = 0.93 (nL/\sqrt{S})^{0.6} / i^{0.4} \quad (2)$$

$T_c$  is the time of concentration in minutes,  $i$  is the rainfall intensity (in/hr),  $L$  is the length of sheet flow (ft),  $n$  is Manning's roughness coefficient,  $S$  is the slope (ft/ft), and  $C_1$ ,  $C_2$ ,  $C_3$  are coefficients.

The authors investigated whether a limit based on sheet flow length ( $L$ ), the value  $iL$  (product of intensity in inches per hour and sheet flow length), or  $nL/\sqrt{S}$  fit the data the best. They decided on the term  $nL/\sqrt{S}$ . If this limit were set at 100, an example of the application follows. For a surface of dense grass,  $n = 0.24$ , and slope of 0.02 ft/ft, the maximum length of sheet flow would be 59 ft (corresponding to a value of  $nL/\sqrt{S}$  of 100). Inserting these values into the TR-55 sheet flow travel time equation and assuming the 2-year 24 hour rainfall is 3 inches, the travel time would be 0.16 hour.

Quote:

The SCS Kinematic Wave Equation. Equation 3 has the same structure as the generalized model of Equation 1. However, it has different coefficients and uses the 2-year 24-hour rainfall depth rather than the intensity for the time of concentration (Welle and Woodward, 1986). The use of a depth that is not dependent on the time of concentration is desirable because it simplifies the solution procedure by eliminating the need to iterate. However, the exponents of 0.8 and 0.5 in Eq. 3, rather than 0.6 and 0.4 in Eq. 2, produce an equation that must be dimensionally balanced through the coefficients. The SCS equation could not be tested with our data because the 2-year 24-hour depth was not obtainable for many of the data samples, obviously for the laboratory data. Thus the limit for  $nL/\sqrt{S}$  of 100 cannot be applied to the SCS equation, and use of this limit may result in inaccurate estimates of  $T_c$  with Equation 3. The larger exponent of 0.8 for the  $nL/\sqrt{S}$  term suggests that the limiting value for Eq. 3 would be less than the limit of 100 for Eq. 2. Equating the two  $nL/\sqrt{S}$  terms of Eqs. 2 and 3 with their respective exponents of 0.6 and 0.8

yields a limit of 31.6 for the SCS kinematic wave equation. However this was not tested and it ignores the differences in the two rainfall terms. Further study of this is needed.

Narrative:

The authors have some reservations on application of a limit of 100 on the value of  $nL/\sqrt{S}$  for use in the SCS (NRCS) kinematic wave travel time equation. Equations 2 and 3 give reasonably close results for travel time especially in the NRCS Type 2 rainfall distribution region. If Manning  $n$  is 0.24, slope is 0.02 ft/ft,  $L = 59$  feet, and 2-year 24 hour rainfall is 3 inches, the travel time using Eq. 3 (NRCS equation) is 0.16 hour. Since Eq. 2 uses intensity instead of 2-year 24-hour rainfall, intensity needs to be estimated for a duration equal to the travel time. At the location of Cincinnati, Ohio, where the 2-year 24-hour rainfall is 3 inches (TP-40 atlas), the 2-year 5-minute rainfall is 0.44 inches (intensity of 5.3 inches per hour) and the 2-year 15-minute rainfall is 0.85 inches (intensity of 3.4 inches per hour). The short duration rainfalls were read from maps in the NOAA NWS Hydro – 35 publication. Since 0.16 hour is approximately 10 minutes, interpolating the intensity gives approximately 4.35 inches per hour. Substituting this intensity of 4.35 inches per hour along with  $n = 0.24$ ,  $S = 0.02$ , and  $L = 59$  feet into Eq. 2 produces a travel time of 0.14 hour. Further study of the author's reservations could be made but this example indicates the limit is applicable to the NRCS kinematic wave travel time equation.

### Summary of Investigations

Although this investigation did not include an exhaustive search of the literature, enough references were studied in order to get a general overview of status of knowledge and practice concerning sheet flow characteristics. A number of additional references were studied but not included in this review because they did not add significant technical information or insights. Most of the studies considered the major aspects of sheet flow; length, slope, roughness, and a number of related factors; soil, vegetation, rainfall intensity, geomorphology, etc. Most also considered theory of hydraulics and kinematic or flow routing. That no definitive results are stated, does not reflect on the quality of the research but on the complexity of the problem. The studies focusing on depth of sheet flow give general guidelines on what is realistic in the field. Defining the point where small flow concentrations become what may be called shallow concentrated flow is a key to analyzing this problem. Complications in defining this point include variations in soil type, vegetation (or lack of it), slope, and rainfall intensity.

Defining conditions used in the various experiments is important because, especially when gathering data and developing various models, one needs to be careful not to extrapolate the results beyond the conditions where they were measured and developed.

The experiments on unpaved areas clearly focused on relatively short sheet flow lengths. Experiments on paved areas focused on a wider range of lengths. Whether these support a limit on sheet flow length of 100 feet is not definitive but, especially for unpaved areas, it appears reasonable until further research can be completed. One commonality of the studies was the shallow depth being considered, generally less than 0.1 foot. Studies of Manning  $n$  indicated roughness values were significantly greater for sheet flow than for channel flow.

The concept of linking hydraulic and hydrologic theory to measured data will lead to the best formulation of models to analyze sheet flow and also the best guidelines for using them in engineering practice.

Further investigation of sheet flow characteristics is needed. A method to consider length, slope, depth, and roughness is practical and feasible. With all the variability across the country with respect to soil, land use, climate, geomorphology, etc, there is no substitute for investigating sheet flow characteristics of the watershed in the field.