Application of Kinematic Wave Theory to Estimation of Runoff From Selected Areas of Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

by

David Edward Westhoff

May 1979
The thesis of David Edward Westhoff is approved:

Velle L. Gupta
Thesis Advisor

Department Chairman

Dean, Graduate School

University of Nevada

Reno

May 1979
ACKNOWLEDGEMENTS

I would like to thank my committee chairman and thesis director Dr. Vulli Gupta for his time and patience in directing this thesis effort. I would also like to thank Dr. Kenneth Kemp and Mr. Clare Mahannah for serving on the thesis committee and reviewing the manuscript.

To Dr. Clint Case, Mr. Jim Federici and Mr. and Mrs. Frank Ramos I extend my gratitude for their assistance.

And to my family, especially my parents, I am very grateful.

Financial aid was received through an assistantship from the Water Resources Center, Desert Research Institute. University of Nevada.
ABSTRACT

Application of the Kinematic Wave Theory to Estimating Runoff For Selected Areas of Nevada

David Edward Westhoff

This thesis presents the results from efforts to implement a method of estimating runoff based on physical laws. The methodology presented involves using the kinematic wave theory in conjunction with the Soil Conservation Service curve number method of estimating runoff.

The study involves relating peak flow rates, time of concentration, and design storm intensity to SCS curve number, return period, and lag modulus. The sites selected for study were Reno, Las Vegas, Tonopah, Wells and Moody Peak in Central Nevada.

The results of the study are a series of graphical aids for each site showing time of concentration vs. lag modulus for a given curve number and return period; design intensity vs. time of concentration for a given return period; and peak runoff rate per unit area vs. lag modulus for a given return period. The results therefore provide guidelines for surface water hydrologists in planning and design activities.
TABLE OF CONTENTS

Signature Page........................................... i
Acknowledgements...................................... ii
Abstract...................................................... iii
List of Figures.............................................. 1
List of Tables.............................................. 6
Introduction................................................. 7
   General.................................................... 7
   Scope and Objectives...................................... 8
   Precipitation............................................. 10
   Data Utilization......................................... 10
Literature Review........................................... 12
Framework of the Methodology......................... 13
   Kinematic Wave Theory................................... 13
   Curve Number............................................. 16
   Rainfall Intensity........................................ 17
   Lag Modulus.............................................. 21
   Time of Concentration................................... 22
   Summary.................................................. 23
Case Studies................................................ 23
Example..................................................... 91
Limitations.................................................. 91
Conclusions and Recommendations....................... 92
   Conclusions............................................... 92
   Recommendations......................................... 93
Bibliography............................................... 94
LIST OF FIGURES

Figure 1  Map showing location of sites studied.
Figure 2  Illustration showing the method of determining the rainfall intensity parameters a, b and c.
Figure 3  Lag modulus vs. time of concentration for Reno, return period 2 years.
Figure 4  Lag modulus vs. time of concentration for Reno, return period 5 years.
Figure 5  Lag modulus vs. time of concentration for Reno, return period 10 years.
Figure 6  Lag modulus vs. time of concentration for Reno, return period 25 years.
Figure 7  Lag modulus vs. time of concentration for Reno, return period 50 years.
Figure 8  Lag modulus vs. time of concentration for Reno, return period 100 years.
Figure 9  Design intensity vs. time of concentration for Reno.
Figure 10 Lag modulus vs. peak runoff rate for Reno, return period 2 years.
Figure 11 Lag modulus vs. peak runoff rate for Reno, return period 5 years.
Figure 12 Lag modulus vs. peak runoff rate for Reno, return period 10 years.
Figure 13 Lag modulus vs. peak runoff rate for Reno, return period 25 years.
Figure 14 Lag modulus vs. peak runoff rate for Reno, return period 50 years.
Figure 15 Lag modulus vs. peak runoff rate for Reno, return period 100 years.
Figure 16. Lag modulus vs. time of concentration for Las Vegas, return period 2 years.

Figure 17. Lag modulus vs. time of concentration for Las Vegas, return period 5 years.

Figure 18. Lag modulus vs. time of concentration for Las Vegas, return period 10 years.

Figure 19. Lag modulus vs. time of concentration for Las Vegas, return period 25 years.

Figure 20. Lag modulus vs. time of concentration for Las Vegas, return period 50 years.

Figure 21. Lag modulus vs. time of concentration for Las Vegas, return period 100 years.

Figure 22. Design intensity vs. time of concentration for Las Vegas.

Figure 23. Lag modulus vs. peak runoff rate for Las Vegas, return period 2 years.

Figure 24. Lag modulus vs. peak runoff rate for Las Vegas, return period 5 years.

Figure 25. Lag modulus vs. peak runoff rate for Las Vegas, return period 10 years.

Figure 26. Lag modulus vs. peak runoff rate for Las Vegas, return period 25 years.

Figure 27. Lag modulus vs. peak runoff rate for Las Vegas, return period 50 years.

Figure 28. Lag modulus vs. peak runoff rate for Las Vegas, return period 100 years.

Figure 29. Lag modulus vs. time of concentration for Tonopah, return period 2 years.

Figure 30. Lag modulus vs. time of concentration for Tohopah, return period 5 years.

Figure 31. Lag modulus vs. time of concentration for Tonopah, return period 10 years.
Figure 32  Lag modulus vs. time of concentration for Tonopah, return period 25 years.

Figure 33  Lag modulus vs. time of concentration for Tonopah, return period 50 years.

Figure 34  Lag modulus vs. time of concentration for Tonopah, return period 100 years.

Figure 35  Design intensity vs. time of concentration for Tonopah.

Figure 36  Lag modulus vs. peak runoff rate for Tonopah, return period 2 years.

Figure 37  Lag modulus vs. peak runoff rate for Tonopah, return period 5 years.

Figure 38  Lag modulus vs. peak runoff rate for Tonopah, return period 10 years.

Figure 39  Lag modulus vs. peak runoff rate for Tonopah, return period 25 years.

Figure 40  Lag modulus vs. peak runoff rate for Tonopah, return period 50 years.

Figure 41  Lag modulus vs. peak runoff rate for Tonopah, return period 100 years.

Figure 42  Lag modulus vs. time of concentration for Wells, return period 2 years.

Figure 43  Lag modulus vs. time of concentration for Wells, return period 5 years.

Figure 44  Lag modulus vs. time of concentration for Wells, return period 10 years.

Figure 45  Lag modulus vs. time of concentration for Wells, return period 25 years.

Figure 46  Lag modulus vs. time of concentration for Wells, return period 50 years.

Figure 47  Lag modulus vs. time of concentration for Wells, return period 100 years.

Figure 48  Design intensity vs. time of concentration for Wells.
Figure 49  Lag modulus vs. peak runoff rate for Wells, return period 2 years.

Figure 50  Lag modulus vs. peak runoff rate for Wells, return period 5 years.

Figure 51  Lag modulus vs. peak runoff rate for Wells, return period 10 years.

Figure 52  Lag modulus vs. peak runoff rate for Wells, return period 25 years.

Figure 53  Lag modulus vs. peak runoff rate for Wells, return period 50 years.

Figure 54  Lag modulus vs. peak runoff rate for Wells, return period 100 years.

Figure 55  Lag modulus vs. time of concentration for Central Nevada, return period 2 years.

Figure 56  Lag modulus vs. time of concentration for Central Nevada, return period 5 years.

Figure 57  Lag modulus vs. time of concentration for Central Nevada, return period 10 years.

Figure 58  Lag modulus vs. time of concentration for Central Nevada, return period 25 years.

Figure 59  Lag modulus vs. time of concentration for Central Nevada, return period 50 years.

Figure 60  Lag modulus vs. time of concentration for Central Nevada, return period 100 years.

Figure 61  Design intensity vs. time of concentration for Central Nevada.

Figure 62  Lag modulus vs. peak runoff rate for Central Nevada, return period 2 years.

Figure 63  Lag modulus vs. peak runoff rate for Central Nevada, return period 5 years.

Figure 64  Lag modulus vs. peak runoff rate for Central Nevada, return period 10 years.
Figure 65  Lag modulus vs. peak runoff rate for Central Nevada, return period 25 years.

Figure 66  Lag modulus vs. peak runoff rate for Central Nevada, return period 50 years.

Figure 67  Lag modulus vs. peak runoff rate for Central Nevada, return period 100 years.

Table 1  Rainfall intensity parameters \( a \), \( b \) and \( c \) for each site and return period for the equation

\[ I = \frac{a}{b^c} \]
LIST OF TABLES

Table 1: Geographical data for the study sites.

Table 2: Curve numbers for selected land uses, adopted from SCS Engineering Field Manual and SCS TP-149. Based on antecedent moisture condition II and \( I_a = 0.25 \).

Table 3: Rainfall intensity parameters \( a, b \) and \( c \) for each site and return period for the equation

\[
i = \frac{a}{(b+d)} c
\]
INTRODUCTION

GENERAL

Estimating the magnitude and timing of peak runoff rates of runoff from drainage basins is one of the most significant aspects of surface water hydrology in planning and design activities. The curve number or hydrologic soil complex method developed by the Soil Conservation Service (SCS) is a popular method of estimating runoff, particularly in rural and/or agricultural areas. Other empirical methods, however, do exist. Examples of these other methods are Cook's (4), Chow's (2), and the rational method (9).

The use of kinematic wave theory involves applying simplified, deterministic and physical laws to the estimation of magnitude and timing of peak runoff rates. When the SCS method is used in conjunction with kinematic wave theory, the methodology so developed may allow the use of the curve number method in urban as well as rural settings. This aspect has not been hitherto examined in detail. The investigation reported herein deals with the foregoing aspects as applied to selected sites in Nevada.

Some of the usual questions in rainfall-runoff linkages are:

1. What is the best method to estimate the peak runoff rate from a storm?
2. What will the timing of the peak be?
3. What design storm intensity should be used in the design of structures?
4. What will be the effect of land use changes on the runoff characteristics of a watershed?

Although this investigation does not attempt to answer all of the four preceding questions, an initial attempt was made to examine the feasibility and applicability of combining the concepts of the SCS method and kinematic wave theory.

SCOPE AND OBJECTIVES

The primary objective of this study is to develop a methodology relating peak flow rates, time of concentration and design storm intensity to SCS curve number, lag modulus and return period. The scope is limited to applying the kinematic wave theory to selected sites in Nevada, namely Reno, Las Vegas, Tonopah, Wells and a site near Moody Peak in Central Nevada. The sites are shown in Figure 1. The study will be conducted for return periods of 2, 5, 10, 25, 50 and 100 years and storm durations of 5 to 1440 minutes.

In order to fulfill the above objectives, the concepts developed by Overton and Tsay (13) will be partially utilized at the selected sites.
 Virtually all of Nevada falls into a climatic classification of dry. That is, potential evapotranspiration exceeds precipitation. The only exceptions are isolated sites in the mountains. Nevada's precipitation is most significantly affected by the barrier created by the mountain system to the West. The Sierra Nevada and Pacific ranges force the moisture-carrying winds of the Pacific Ocean to rise, cool, and deposit their moisture in the mountains. Thus, mostly dry winds enter. Still, most of Nevada's precipitation is a result of moisture from the Pacific Ocean. In general, precipitation increases with elevation in Nevada. Historically, the northern half of the state has more days of precipitation while the southern half has storms of higher intensity. Geographical data for each study area is shown in Table 1.

Figure 1. Map showing location of sites studied.
PRECIPITATION

Virtually all of Nevada falls into a climatic classification of dry. That is, potential evapotranspiration exceeds precipitation. The only exceptions are localized sites in the mountains. Nevada's precipitation is most significantly affected by the barrier created by the mountain system to the West. The Sierra Nevada and other Pacific ranges force the moisture-carrying winds off of the Pacific Ocean to rise, cool, and deposit their moisture in the mountains. Thus, mostly dry winds enter Nevada. Still, most of Nevada's precipitation is a result of moisture from the Pacific Ocean (6).

In general, precipitation increases with elevation and latitude in Nevada (6). Historically, the northern half of the state has more days of precipitation while the southern half has storms of higher intensity. Geographical data for each study site is shown in Table 1.

DATA UTILIZATION

The precipitation data for this study was taken from NOAA Atlas 2, vol. 7 (10). The Atlas contains isopluvial maps of Nevada for storm durations of 6 and 24 hours and return periods of 2, 5, 10, 25, 50 and 100 years with procedures for determining the precipitation depths for other storm durations. Therefore, precipitation data is available for the entire state, even areas that have no rain gages.
TABLE 1. Geographical data for the study sites.

<table>
<thead>
<tr>
<th>SITE</th>
<th>ELEVATION, FT.</th>
<th>LAT.,°N</th>
<th>LONG.,°W</th>
</tr>
</thead>
<tbody>
<tr>
<td>RENO</td>
<td>4404</td>
<td>39.50°</td>
<td>119.78°</td>
</tr>
<tr>
<td>LAS VEGAS</td>
<td>2162</td>
<td>36.08°</td>
<td>115.17°</td>
</tr>
<tr>
<td>TONOPAH</td>
<td>6033</td>
<td>38.05°</td>
<td>117.15°</td>
</tr>
<tr>
<td>WELLS</td>
<td>5626</td>
<td>41.12°</td>
<td>114.97°</td>
</tr>
<tr>
<td>CENTRAL NEVADA</td>
<td>6560</td>
<td>39.0°</td>
<td>116.0°</td>
</tr>
</tbody>
</table>
The application of physical principles to the study of overland flow was initially done by Keulegan in 1945 (7). In his paper, the equations of continuity and momentum applicable to the movement of water were derived and the steady-state velocity profile was approximated.

Wooding (17, 18, 19) applied the kinematic wave theory to solving problems in a V-shaped catchment. Brakensiek (1) applied a finite-difference scheme to solving the equations of continuity and momentum and then estimating the runoff hydrograph of a watershed.

Woolhiser and Liggett (20) developed the kinematic flow number 'K' which can be used to determine the validity of using kinematic wave approximations. They also concluded that most field cases of overland flow are closely approximated by the kinematic solutions. Overton (11) used the kinematic equations to compute lag times for idealized watersheds.

Overton and Tsay (13) utilized the kinematic wave equations in conjunction with the SCS curve number method of estimating runoff. They developed a methodology for estimating time of concentration and peak flow rates for Knoxville, Tennessee.
A good reference on all aspects involving the applications of kinematic wave theory is by Overton and Meadows (12).

FRAMEWORK OF THE METHODOLOGY

The methodology utilized in this study is based on certain concepts and their interrelationships. These concepts are kinematic wave theory, SCS curve number, rainfall intensity, lag modulus, and time of concentration.

KINEMATIC WAVE THEORY

Wave movement may consist of two types, kinematic and/or dynamic. Both may be present in any natural wave (5). The bed slope, $S_o$, is usually the most significant slope term. Therefore, the kinematic wave usually predominates over the dynamic wave, although the dynamic wave component is present. The Froude number is the ratio of the stream velocity to the wave velocity such that

$$Fr = \frac{v}{\sqrt{gy}}$$  \hspace{1cm} (1)

where

$Fr$ = Froude number, dimensionless
$v$ = wave velocity, ft./sec.
$g$ = gravitational acceleration, ft./sec.$^2$
$y$ = depth of flow, ft.

When $Fr > 1$, the wave velocity is less than the stream
velocity, and the wave cannot move upstream. Such is the case for kinematic waves. However, for dynamic waves, $Fr < 1$, therefore dynamic waves can travel upstream as well as downstream. The usual case is for the main body of the wave to travel as a kinematic wave with a dynamic wave moving ahead and a dynamic wave moving upstream. Both dynamic waves are rapidly attenuating (5).

The equations governing flow in wide rectangular channels are the conservation of mass (Equation 2) and the conservation of momentum (Equation 3).

$$\frac{\partial Q}{\partial X} + \frac{\partial q}{\partial t} = q \tag{2}$$

$$V\frac{\partial V}{\partial X} + \frac{\partial q}{\partial t} + g \frac{\partial y}{\partial X} = g (S_o - S_f) - V \frac{q}{y} \frac{Q}{W} \tag{3}$$

In equations 2 and 3,

- $Q$ = discharge, cfs/ft. width
- $X$ = space coordinate, ft.
- $y$ = depth of flow, ft.
- $t$ = time, seconds
- $g$ = gravitational accelerations, ft/sec.$^2$
- $V$ = average flow velocity, ft/sec.
- $q$ = lateral inflow, cfs/ft. width/ft. length
- $S_o$ = bed slope
- $S_f$ = friction slope
- $W$ = channel width, ft.
Derivation of the above equations may be found in Stoker (14).

Kinematic waves govern the flow of long waves in shallow water when the inertia and pressure terms in Equation 3 are insignificant. The gravitational and frictional components balance each other, hence there is little or no acceleration. Under equilibrium conditions Equations 2 and 3 may be expressed as

\[ S_0 = S_f \] (4)
\[ Q = qX \] (5)

Kinematic flow is unsteady uniform flow. In this report, the flow will be considered as gradually varied so the unsteady aspects will not be accentuated.

Woolhiser and Liggett (20) developed the kinematic flow number \( K \) which can be used to determine the validity of using the kinematic wave approximations. As shown by Overton and Meadows (12).

\[ K = 10^5 n^{1.2} S_o^{.4} L^{.2} (i_e)^{.8} \] (6)

where

\( K = \) kinematic flow number, dimensionless
\( n = \) Manning's roughness coefficient
\( S_o = \) bed slope
\( L = \) length of plane
\( i_e = \) effective rainfall intensity, in/hr
The kinematic wave equations give good results when \( K \geq 10 \). In most cases of overland flow this condition is met (20).

**CURVE NUMBER**

The U.S. Soil Conservation Service developed an equation that can be used to estimate runoff from a storm (15). From experimental watersheds, the relationship of runoff to rainfall was found to be

\[
Q = \frac{(P - Ia)^2}{(P - Ia) + s}
\]

where

\[
Q = \text{accumulated direct runoff, inches}
\]

\[
P = \text{accumulated rainfall, inches}
\]

\[
Ia = \text{initial abstractions such as surface storage and infiltration, inches}
\]

\[
s = \text{potential maximum retention, inches}
\]

A relationship between \( Ia \) and \( s \) was also developed

\[
Ia = 0.2s
\]

then

\[
Q = \frac{(P - 0.2s)^2}{P + 0.8s}
\]

The SCS curve number and \( s \) are related by

\[
CN = \frac{1000}{10 + s}
\]

or

\[
S = \frac{1000 - 10}{CN}
\]

Substituting for \( S \) in Equation 8 we have
\[
Q = \left( P + \frac{800}{CN} - 8 \right)
\]
\[
(P - \frac{200}{CN} + 2)^2
\]

Which is the basic equation for estimating runoff via the SCS method.

As \((P - \frac{200}{CN} + 2) = P - Ia\), it is assumed (16) that runoff can occur only if \((P - \frac{200}{CN} + 2)\) is greater than 0, that is if the volume of precipitation is greater than the volume of initial abstractions.

The effective rainfall intensity, \(i_e\), is the rainfall rate utilized in overland flow. It may be found by

\[
i_e = 60 \frac{Q}{D}
\]

where

- \(i_e\) = effective rainfall intensity, in/hr.
- \(Q\) = accumulated direct runoff, inches
- \(D\) = storm duration, minutes

In general, curve number is a reflection of the degree of urbanization. As urbanization increases, curve number increases, volume of runoff increases, effective intensity increases, and time of concentration decreases.

Table 2 shows curve numbers for various land uses.

RAINFALL INTENSITY

Rainfall intensity may be approximated by the following equation
\[ i = \frac{a}{(b+D)^c} \]  

(14)

where

\[ i = \text{rain intensity, in/hr., for duration (b+D)} \]
\[ D = \text{storm duration, minutes} \]
\[ a, b, c = \text{rainfall parameters that vary with location and return period} \]

The meaning of \( a, b \) and \( c \) may be seen from Figure 2. When rainfall intensity, \( i \), is plotted vs. storm duration, \( D \), on log-log graph paper, a straight line results when the proper value is added to \( D \). This value is \( b \) (3). The slope of the resulting line is \( c \) and \( a \) is the intensity at \((b+D) = 1\).

When storm duration is set equal to time of concentration, \( t_c \), the resulting intensity is the design intensity, \( i_D \), for the given conditions. The total volume of precipitation under design conditions is then

\[ P = \frac{(i_D)(t_c)}{60} \]

(15)

where

\[ P = \text{accumulated rainfall, inches} \]
\[ i_D = \text{design intensity, in/hr.} \]
\[ t_c = \text{time of concentration, minutes} \]

Substituting Equation 15 into Equation 12 and the resulting expression for \( Q \) into Equation 13 results in the following expression under design conditions:
TABLE 2. Curve numbers for selected land uses, adopted from SCS Engineering Field Manual and SCS TP-149. Based on antecedent moisture condition II and \( I_a = 0.2S \).

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Hydrologic Soil Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Open spaces, lawns, cemeteries, etc</td>
<td></td>
</tr>
<tr>
<td>grass on 75% or more of the area</td>
<td>39</td>
</tr>
<tr>
<td>grass on 50 to 75% of the area</td>
<td>49</td>
</tr>
<tr>
<td>Commercial and business areas</td>
<td></td>
</tr>
<tr>
<td>(85% impervious)</td>
<td>89</td>
</tr>
<tr>
<td>Industrial districts</td>
<td></td>
</tr>
<tr>
<td>(72% impervious)</td>
<td>81</td>
</tr>
<tr>
<td>Residential</td>
<td></td>
</tr>
<tr>
<td>Ave. lot size</td>
<td></td>
</tr>
<tr>
<td>1/8 acre or less</td>
<td>77</td>
</tr>
<tr>
<td>1/4 acre</td>
<td>61</td>
</tr>
<tr>
<td>1/3 acre</td>
<td>57</td>
</tr>
<tr>
<td>1/2 acre</td>
<td>54</td>
</tr>
<tr>
<td>1 acre</td>
<td>51</td>
</tr>
<tr>
<td>Parking lots, roofs, driveways, etc.</td>
<td>98</td>
</tr>
<tr>
<td>Streets and roads</td>
<td></td>
</tr>
<tr>
<td>paved with curbs and storm sewers</td>
<td>98</td>
</tr>
<tr>
<td>gravel</td>
<td>76</td>
</tr>
<tr>
<td>dirt</td>
<td>72</td>
</tr>
<tr>
<td>Row crops</td>
<td></td>
</tr>
<tr>
<td>straight row</td>
<td>72</td>
</tr>
<tr>
<td>contoured</td>
<td>70</td>
</tr>
<tr>
<td>Small grain</td>
<td></td>
</tr>
<tr>
<td>straight row</td>
<td>65</td>
</tr>
<tr>
<td>contoured</td>
<td>63</td>
</tr>
<tr>
<td>Pasture or range</td>
<td></td>
</tr>
<tr>
<td>no mechanical treatment</td>
<td>68</td>
</tr>
<tr>
<td>contoured</td>
<td>47</td>
</tr>
</tbody>
</table>
Figure 2. Illustration showing the method of determining the rainfall intensity parameters $a$, $b$, and $c$.  

Actual duration, $D$, vs. intensity

Adjusted duration, $(b+D)$, vs. intensity
\[ i_e = \left\{ \begin{align*} 
&\left\{ \frac{60}{t_c} \left( \frac{i_D t_c}{60} - \frac{200}{CN} + 2 \right) \right\}^2 \\
&\left\{ \frac{i_D t_c}{60} + \frac{800}{CN} - 8 \right\} 
\end{align*} \right. \]  

(16)

where

\[ i_e = \text{effective rainfall intensity, in/hr.} \]
\[ t_c = \text{time of concentration, minutes} \]
\[ i_D = \text{design intensity, in/hr.} \]
\[ CN = \text{curve number} \]

and \( i_e \) is the same as the runoff rate per unit area.

LAG MODULUS

The time of concentration of a watershed may be found by the following equation (10).

\[ t_c = \frac{.928 \left( \frac{nL}{V_s} \right)^{.6}}{(i_e)^{.4}} \]  

(17)

where

\[ t_c = \text{time of concentration, minutes} \]
\[ n = \text{Manning's roughness coefficient} \]
\[ L = \text{slope length, feet} \]
\[ s = \text{slope, dimensionless} \]
\[ i_e = \text{effective rainfall intensity, in/hr.} \]
L, n and s are the physical characteristics of a watershed. They may be combined into a single quantity, μ, the lag modulus (13), such that

\[ \mu = 0.928 \left( \frac{nL}{\sqrt{s}} \right)^{0.6} \]  \hspace{1cm} (18)

TIME OF CONCENTRATION

Time of concentration is the time required for water to travel from the hydrologically most remote part of a watershed to the outlet of the watershed. When the storm duration is equal to or greater than the time of concentration the entire watershed is contributing to the discharge at the outlet and the flow rate is at its peak. It has been shown (11) that time of concentration may be estimated via the following equation

\[ t_c^{0.6} = \frac{\mu}{60 \left( \frac{a}{60(b+t_c)} \right)^c + \frac{200}{CN} + 2}^{0.4} \]  \hspace{1cm} (19)

where
\[ t_c = \text{time of concentration, min.} \]
\[ \mu = \text{lag modulus} \]
\[ a, b, c = \text{rainfall intensity parameters} \]
\[ CN = \text{SCS curve number} \]
SUMMARY

To summarize the above concepts:

1. The kinematic wave approximations are valid if $K > 10$.

2. Runoff occurs if precipitation exceeds initial abstractions.

3. The volume of runoff may be found from Equation 12.

4. The effective rainfall intensity or runoff rate may be found from Equation 16.

5. Time of concentration may be found from Equation 19.

CASE STUDIES

Precipitation data from NOAA Atlas 2, vol. 7 (10) was utilized to determine storm intensities for each of the 5 study sites for storm durations from 5 to 1440 minutes and return periods of 2, 5, 10, 25, 50, and 100 years. This information was used to evaluate the rainfall intensity parameters $a$, $b$, and $c$. These parameters are listed in Table 3. A chi-square test performed on the resulting equations showed the error to have less than 1% significance.

The Newton-Raphson method of successive approximations (8) was used to solve Equation 19 for time of concentration. For a given site and return period, $a$, $b$, and $c$
are known. For curve number values at which \( (P - \frac{200}{CN} + 2) > 0 \), the lag modulus is varied and time of concentration is determined. The results for Reno are shown in Figures 3-8, for Las Vegas in Figures 16-21, for Tonopah in Figures 29-34, for Wells in Figures 42-47, and for Central Nevada in Figures 55-60.

From Equation 14, the design intensity can be found by setting \( D = t_c \). For each location and return period, \( t_c \) was varied and \( i_D \) was computed. The results for Reno are shown in Figure 9, for Las Vegas in Figure 22, for Tonopah in Figure 35, for Wells in Figure 48, and for Central Nevada in Figure 61.

Equation 16 can be used to find the effective rainfall intensity or peak runoff rate per unit area. The results for Reno are shown in Figures 10-15, for Las Vegas in Figures 23-28, for Tonopah in Figures 36-41, for Wells in Figures 49-54, and for Central Nevada in Figures 62-67.

The total peak runoff rate may be found by

\[
Q_p = (i_e) (A) \tag{20}
\]

where

- \( i_e \) = effective rainfall intensity (from the proper chart), in/hr.
- \( A \) = area, acres
- \( Q_p \) = peak runoff rate, cfs

as 1 cfs = 0.9917 acre-inch/hr.
TABLE 3. Rainfall intensity parameters $a$, $b$ and $c$ for each site and return period for the equation

\[ i = \frac{a}{(b+D)c} \]

<table>
<thead>
<tr>
<th>SITE</th>
<th>RETURN PERIOD</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reno</td>
<td>2</td>
<td>7.0</td>
<td>3.0</td>
<td>.70</td>
</tr>
<tr>
<td>Reno</td>
<td>5</td>
<td>7.5</td>
<td>2.0</td>
<td>.64</td>
</tr>
<tr>
<td>Reno</td>
<td>10</td>
<td>8.4</td>
<td>2.0</td>
<td>.62</td>
</tr>
<tr>
<td>Reno</td>
<td>25</td>
<td>14.5</td>
<td>3.0</td>
<td>.70</td>
</tr>
<tr>
<td>Reno</td>
<td>50</td>
<td>17.5</td>
<td>3.0</td>
<td>.71</td>
</tr>
<tr>
<td>Reno</td>
<td>100</td>
<td>26.0</td>
<td>5.0</td>
<td>.76</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>2</td>
<td>17.0</td>
<td>5.0</td>
<td>.81</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>5</td>
<td>23.0</td>
<td>7.0</td>
<td>.82</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>10</td>
<td>22.0</td>
<td>5.0</td>
<td>.78</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>25</td>
<td>19.0</td>
<td>5.0</td>
<td>.71</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>50</td>
<td>27.0</td>
<td>5.0</td>
<td>.76</td>
</tr>
<tr>
<td>Las Vegas</td>
<td>100</td>
<td>27.0</td>
<td>4.0</td>
<td>.73</td>
</tr>
<tr>
<td>Tonopah</td>
<td>2</td>
<td>7.5</td>
<td>5.0</td>
<td>.70</td>
</tr>
<tr>
<td>Tonopah</td>
<td>5</td>
<td>16.0</td>
<td>5.0</td>
<td>.76</td>
</tr>
<tr>
<td>Tonopah</td>
<td>10</td>
<td>24.0</td>
<td>5.0</td>
<td>.82</td>
</tr>
<tr>
<td>Tonopah</td>
<td>25</td>
<td>32.0</td>
<td>5.0</td>
<td>.85</td>
</tr>
<tr>
<td>Tonopah</td>
<td>50</td>
<td>37.0</td>
<td>5.0</td>
<td>.84</td>
</tr>
<tr>
<td>Tonopah</td>
<td>100</td>
<td>50.0</td>
<td>5.0</td>
<td>.86</td>
</tr>
<tr>
<td>Wells</td>
<td>2</td>
<td>6.8</td>
<td>3.0</td>
<td>.69</td>
</tr>
<tr>
<td>Wells</td>
<td>5</td>
<td>10.5</td>
<td>3.0</td>
<td>.71</td>
</tr>
<tr>
<td>Wells</td>
<td>10</td>
<td>23.0</td>
<td>5.0</td>
<td>.82</td>
</tr>
<tr>
<td>Wells</td>
<td>25</td>
<td>22.2</td>
<td>5.0</td>
<td>.78</td>
</tr>
<tr>
<td>Wells</td>
<td>50</td>
<td>23.0</td>
<td>5.0</td>
<td>.76</td>
</tr>
<tr>
<td>Wells</td>
<td>100</td>
<td>35.0</td>
<td>5.0</td>
<td>.83</td>
</tr>
<tr>
<td>Central NV</td>
<td>2</td>
<td>7.6</td>
<td>3.0</td>
<td>.66</td>
</tr>
<tr>
<td>Central NV</td>
<td>5</td>
<td>13.8</td>
<td>3.0</td>
<td>.72</td>
</tr>
<tr>
<td>Central NV</td>
<td>10</td>
<td>19.0</td>
<td>5.0</td>
<td>.75</td>
</tr>
<tr>
<td>Central NV</td>
<td>25</td>
<td>19.0</td>
<td>3.0</td>
<td>.72</td>
</tr>
<tr>
<td>Central NV</td>
<td>50</td>
<td>26.0</td>
<td>5.0</td>
<td>.75</td>
</tr>
<tr>
<td>Central NV</td>
<td>100</td>
<td>31.0</td>
<td>5.0</td>
<td>.76</td>
</tr>
</tbody>
</table>
Figure 3. Lag modulus vs. time of concentration for Reno, return period 2 years.
Figure 4. Lag modulus vs. time of concentration for Reno, return period 5 years.
Figure 5. Lag modulus vs. time of concentration for Reno, return period 10 years.
Figure 6. Lag modulus vs. time of concentration for Reno, return period 25 years.
Figure 7. Lag modulus vs. time of concentration for Reno, return period 50 years.
Figure 8. Lag modulus vs. time of concentration for Reno, return period 100 years.
Figure 9. Design intensity vs. time of concentration for Reno.
Figure 10. Lag modulus vs. peak runoff rate for Reno, return period 2 years.
Peak runoff rate per unit area, in./hr.

Figure 17. Lag modulus vs. peak runoff rate for Reno, return period 5 years.
Figure 12. Lag modulus vs. peak runoff rate for Reno, return period 10 years.
Figure 13. Lag modulus vs. peak runoff rate for Reno, return period 25 years.
For 750 year return period, the module vs. peak runoff rate is shown as a curve. The module, in ft² per acre, is plotted on the y-axis, and the peak runoff rate, in ft³ per sec, is plotted on the x-axis. The curve indicates the relationship between the two variables.
Figure 15. Lag modulus vs. peak runoff rate for Reno, return period 100 years.
Figure 16. Lag modulus vs. time of concentration for Las Vegas, return period 2 years.
Figure 17. Lag modulus vs. time of concentration for Las Vegas, return period 5 years.
Figure 18. Lag modulus vs. time of concentration for Las Vegas, return period 10 years.
Figure 19. Lag modulus vs. time of concentration for Las Vegas, return period 25 years.
Figure 20. Lag modulus vs. time of concentration for Las Vegas, return period 50 years.
Figure 21. Lag modulus vs. time of concentration for Las Vegas, return period 100 years.
Figure 22. Design intensity vs. time of concentration for Las Vegas.
Figure 23. Lag modulus vs. peak runoff rate for Las Vegas, return period 2 years.
Figure 24. Lag modulus vs. peak runoff rate for Las Vegas, return period 5 years.
Figure 25. Lag modulus vs. peak runoff rate for Las Vegas, return period 10 years.
Figure 26. Lag modulus vs. peak runoff rate for Las Vegas, return period 25 years.
Figure 27. Lag modulus vs. peak runoff rate for Las Vegas, return period 50 years.
Figure 28. Lag modulus vs. peak runoff rate for Las Vegas, return period 100 years.
Figure 29. Lag modulus vs. time of concentration for Tonopah, return period 2 years.
Figure 30. Lag modulus vs. time of concentration for Tonopah, return period 5 years.
Figure 31. Lag modulus vs. time of concentration for Tonopah, return period 10 years.
Figure 32. Lag modulus vs. time of concentration for Tonopah, return period 25 years.
Figure 33. Lag modulus vs. time of concentration for Tonopah, return period 50 years.
Figure 34. Lag modulus vs. time of concentration for Tonopah, return period 100 years.
Figure 35. Design intensity vs. time of concentration for Tonopah.
Figure 36. Lag modulus vs. peak runoff rate for Tonopah, return period 2 years.
Figure 37. Lag modulus vs. peak runoff rate for Tonopah, return period 5 years.
Figure 38. Lag modulus vs. peak runoff rate for Tonopah, return period 10 years.
Figure 39. Lag modulus vs. peak runoff rate for Tonopah, return period 25 years.
Figure 40. Lag modulus vs. peak runoff rate for Tonopah, return period 50 years.
Figure 41. Lag modulus vs. peak runoff rate for Tonopah, return period 100 years.
Figure 42. Lag modulus vs. time of concentration for Wells, return period 2 years.
Figure 43. Lag modulus vs. time of concentration for Wells, return period 5 years.

Curve number

Lag modulus, min.
Curve number 70

Figure 44. Lag modulus vs. time of concentration for Wells, return period 10 years.
Figure 45. Lag modulus vs. time of concentration for Wells, return period 25 years.
Figure 46. Lag modulus vs. time of concentration for Wells, return period 50 years.
Figure 47. Lag modulus vs. time of concentration for wells, return period 100 years.
Figure 48. Design intensity vs. time of concentration for Wells.
Figure 49. Lag modulus vs. peak runoff rate for Wells, return period 2 years.
Figure 50. Lag modulus vs. peak runoff rate for Wells, return period 5 years.
Figure 51. Lag modulus vs. peak runoff rate for Wells, return period 10 years.
Figure 52. Lag modulus vs. peak runoff rate for Wells, return period 25 years.
Figure 53. Lag modulus vs. peak runoff rate for Wills, return period 50 years.
Figure 54. Lag modulus vs. peak runoff rate for Wells, return period 100 years.
Figure 55. Lag modulus vs. time of concentration for Central Nevada, return period 2 years.
Figure 56. Lag modulus vs. time of concentration for Central Nevada, return period 5 years.
Figure 57. Lag modulus vs. time of concentration for Central Nevada, return period 10 years.
Figure 58. Lag modulus vs. time of concentration for Central Nevada, return period 25 years.
Figure 59. Lag modulus vs. time of concentration for Central Nevada, return period 50 years.
Figure 60. Lag modulus vs. time of concentration for Central Nevada, return period 100 years.
Figure 64. Design intensity vs. time of concentration for Central Nevada.
Figure 62. Lag modulus vs. peak runoff rate for Central Nevada, return period 2 years.
Figure 63. Lag modulus vs. peak runoff rate for Central Nevada, return period 5 years.
Figure 64. Lag modulus vs. peak runoff rate for Central Nevada, return period 10 years.
Figure 65. Lag modulus vs. peak runoff rate for Central Nevada, return period 25 years.
Figure 66. Lag modulus vs. peak runoff rate for Central Nevada, return period 50 years.
Figure 67. Lag modulus vs. peak runoff rate for Central Nevada, return period 100 years.
EXAMPLE

To utilize the curves, the curve number and lag modulus of a watershed must be determined from field observations or estimated for a future land use. From the desired location and curve number the time of concentration may be found from the appropriate chart. With the time of concentration and return period, the design intensity can be found from the appropriate graph or Equation 14. With a given lag modulus, curve number and return period, the peak runoff rate can be found from the appropriate chart and Equation 20.

For example, say a watershed in Reno is found to have a curve number of 90, a lag modulus of 50 and the desired return period is 50 years. From Figure 7, the time of concentration is found to be 88 minutes. From Figure 9 or Equation 14, the design intensity is seen to be 0.7 in/hr., and from Figure 14 the peak runoff rate is 0.25 inches/hr per acre.

LIMITATIONS

The limitations of the methodology presented are as follows:

1. The kinematic wave theory gives poor results if the $K$ value from Equation 6 is less than 10 because the kinematic approximation is not valid under such circumstances.
2. The graphs presented are based on uniform precipitation over the entire watershed. Hence, it is limited to small watersheds.

3. The use of the graphs should be limited to precipitation in the form of rainfall.

4. The methodology presented should not be used to evaluate the potential flash flood hazard of a watershed as the method is least accurate for storms of short duration.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions can be drawn from the study:

1. Development of a methodology relating (i) design intensity, (ii) time of concentration and (iii) peak flow rates to SCS curve number, lag modulus and return period.

2. Presentation of a method of evaluating the effects of land use changes on a watershed via the SCS curve number.

3. Presentation of a methodology useful in both urban and rural situations.

4. Working curves for the study sites are provided to aid the practicing hydrologist.

In addition, it has been said that "The question of the validity of the kinematic flow model for various types of applications becomes better defined as more comparisons
are made (and reported upon) between model results and prototype measurements" (21). This study is one of the initial steps in such endeavors.

RECOMMENDATIONS

Due to the importance of the need for estimating the timing and volumes of peak flow, and based on the study contained herein, the following recommendations are made:

1. That the theoretical data presented here be compared with actual runoff data, preferably for small watersheds.

2. That the study be conducted for other areas, especially those projected for significant land use changes, such as urbanization.

3. A comparative study involving the various known methods for estimating peak rates of runoff, including the method reported herein, must be conducted to establish the relative merits and applicability of each of the methods.


