FIELD TEST ON CONVERSION OF NATURAL WATERSHED INTO KINEMATIC WAVE RECTANGULAR PLANE

James C.Y Guo

Professor and Director, Civil Engineering, U of Colorado Denver, E-mail: James.Guo@UCDenver.edu

Abstract

Conversion of a natural watershed into its equivalent kinematic wave rectangular plane has long been a concern in the practice of stormwater numerical simulations. Based on the principles of mass and energy, the actual watershed and its virtual kinematic wave plane can be related by the watershed shape factor that involves the waterway length and slope, and watershed area. In this study, two dimensionless watershed shape functions are derived to use parabolic function and trigonometric Sine curve for watershed conversion. These two watershed shape functions produce good agreements with the maximum overland flow length method for hypothetical square watersheds. Also, these two watershed shape functions are able to re-produce similar kinematic wave plane widths as reported in a calibrated model. Furthermore, in this study, these two watershed shape functions are tested by nine observed rainfall events and three levels of modeling details. These 54 case studies reveal that the parabolic shape function consistently produces better agreements with the observed runoff hydrographs. Also, a model with more drainage details results in more concentrated flows or higher peak flows. On the contrary, a model with a low resolution tends to decrease the peak flow because of the significant surface detention volume spread in the overland flow.

Key Words: Kinematic Wave, SWMM, Watershed Shape, Stormwater, Overland Flow

INTRODUCTION

The numerical procedure for the kinematic wave overland flow (KWOF) method requires the conversion of an irregular watershed into its equivalent rectangular sloping plane on which the storm hydrograph can be simulated using the unit-width overland flow multiplied by the plane width (Lighthill and Whitham 1955, Wooding 1965, Singh 1966). Among all necessary watershed parameters, the plane width is a pre-knowledge for runoff numerical modeling when using the KWOF method (Guo 1998). However, in the development of kinematic wave theories, the width of KW sloping plane is not defined clearly. As a result, there has been a wide variability in how a plane width is assessed. For instance, as recommended (UDSWMM Manual 2000), the plane width is twice the channel length. The comparison study between the EPA Storm Water Management Model Version 5 (Rossman 2005) and the Colorado Urban Hydrograph Procedure (CHUP 2005) suggests that the ratio of 2.2 be used between waterway length and KW plane width. As reported (Guo and Urbonas 2009), such a ratio can vary from 2.0 for the watershed symmetric to its collector channel to 1.0 for the watershed skewed with a side channel. Based on the calibration study of a watershed in Ontario, Canada, a ratio of 1.67 was adopted between the waterway length and its KW plane width (Proctor and Redfern 1976). The EPA SWMM5 user manual (Rossman 2005) suggests that an initial estimate of the plane width be given by the watershed area divided by the average maximum overland flow length and then the model needs a calibration to confirm the selections of KW plane width and other parameters. As reported, the model-calibration approach was successful in the study of Fox Hollow Watershed, Centre County, PA (Zhang and Hamlett 2006). All these reports amount to the fact that a reliable application of the KWOF method depends on the model calibration against the historic data or modeler’s experience with the watershed. It implies that the KWOF method is only applicable to an existing
watershed and it has no warranty when predicting stormwater movement for a proposed future condition.

Urban master drainage planning is a common practice to outline the best strategy to mitigate the future flood potentials before the regional development. When using EPA SWMM5 and HEC HMS (2010) computer models to predict flood flows for the future alternatives, the selection of plane width for each subarea used in the computer model has become a fundamental challenge. Since the width of the virtual rectangular KW plane is related to the channel length of the actual irregular watershed, it was an attempt to derive a KW parabolic shape function that could directly help the engineer calculate the plane width based on the watershed shape defined as the ratio of width to length (Guo and Urbana 2009). Although this KW parabolic shape function was successfully tested for its consistency among several hypothetical watersheds, its application to real watersheds needs to be verified. Secondly, a question was raised among reviewers and users as to if a periodical function such as, Sine and Cosine, may be better than the parabolic function for watershed shape conversion. In this study, a new periodical KW shape function was derived using trigonometric sine function. Both the periodical sine curve and the parabolic KW shape function are then tested for real watersheds under the observed rainfall cases. The comparison with the observed runoff hydrographs provides a basis to evaluation the applicability of these two KW shape functions. It is expected that the KW shape function tested in this paper will serve as a guide on the selection of KW plane width when developing EPA SWMM5 and HEC HMS computer models for purpose of regional master drainage planning.

DERIVATION OF SINE SHAPE FUNCTION

The KWOF method is widely utilized to predict storm hydrographs from natural watersheds (HEC HMS 2010, EPA SWMM5 2005). As illustrated in Figure 1, the natural watershed has to be converted into its equivalent rectangular KW plane. The conservation of runoff volume between these two flow systems is essentially the equality of the surface drainage area because the amount of rainfall excess remains the same.

\[ A = X_w L_w \]  \hspace{1cm} (1)

in which \( A \) = watershed tributary area, \( X_w \) = length of overland flow on KW sloping plane, and \( L_w \) = width of KW sloping plane. Between these two flow systems, the potential energy in terms of the vertical fall along the waterway must be conserved as:

\[ S_o L = S_w (X_w + L_w) \]  \hspace{1cm} (2)

In which \( L \) = natural waterway length, \( S_o \) = watershed slope and \( S_w \) = KW plane slope.
Figure 1 Conversion of Natural Watershed into KW Rectangular Sloping Plane

Consider the natural waterway length to be the characteristic length for both flow systems. Eq’s (1) and (2) can be normalized as:

\[ \frac{A}{L^2} \approx \frac{B}{L} = \frac{X_w}{L} \frac{L_w}{L} \]  

(3)

In which B = average watershed width. In this study, the watershed shape factor is defined as the ratio of B/L or A/L^2.

\[ \frac{S_o}{S_w} = \frac{X_w}{L} + \frac{L_w}{L} \]  

(4)

Eq (3) represents the geometric relationship between these two watershed systems in Figure 1. The ratio, L_w/L, is termed the KW shape factor (Guo and Urbonas 2009).

As indicated in Eq (3), the KW shape factor, L/L_w, is related to A/L^2. For convenience, in this study, the watershed shape factors are derived as:

\[ X = \frac{A}{L^2} \]  

(5)

\[ Y = \frac{L_w}{L} \]  

(6)
In which \( X = \) watershed shape factor for actual system, and \( Y = \) KW shape factor for the KW sloping plane. The general functional relationship between these two shape factors is described as:

\[ Y = f(X) \]  \hspace{1cm} (7)

In which \( f(X) = \) mathematical functional relationship. This mathematic function needs to satisfy three special cases as follows (Guo and Urbonas 2009):

**Case 1:** When the natural watershed is extremely small, then the KW shape factor will approach zero as:

\[ X \approx Y \approx 0 \quad \text{when} \quad A \rightarrow 0 \]  \hspace{1cm} (8)

**Case 2:** As illustrated in Figure 2, the square-shaped watershed provides a unique relationship between the actual watershed and virtual KW plane as follows:

\[ Y = 1 \quad \text{when} \quad X = 1 \quad \text{for square watershed with a side channel} \]  \hspace{1cm} (9)

\[ Y = 2 \quad \text{when} \quad X = 1 \quad \text{for square watershed with a central channel} \]  \hspace{1cm} (10)

![Figure 2 KW Conversion of Square Shaped Watershed](image)

The two cases in Figure 2 represent two extreme locations of channel alignment. In most cases, the collector channel divides the watershed into two uneven sub-areas. In this study, the area skewness coefficient, \( Z \), is incorporated into the KW shape function as:

\[ Y = (1.5 - Z) f(X) \quad \text{for all watersheds} \]  \hspace{1cm} (11)

\[ Z = \frac{A_m}{A} \]  \hspace{1cm} (12)

in which \( Z = \) area skewness coefficient between 0.5 and 1.0, and \( A_m = \) dominating area that is the larger one between the right and left sub-areas separated by the collector channel. As illustrated in Figure 3, \( Z = 1.0 \) for a watershed with a side channel along its boundary while \( Z = 0.5 \) for a watershed symmetric to its central channel.
Case 3: As a common practice, a watershed is often divided into smaller sub-basins before the numerical simulation. The sub-basin’s shape shall not be too wide or too slender. Mathematically, it implies that the first derivative of Eq 11 vanishes when Y reaches its allowable maximum as:

\[ \frac{dY}{dX} = 0 \quad \text{at} \quad X = K \]  
(13)

In which K = maximal value for X. As recommended, the value of X is not to exceed 4 when dividing a watershed into sub-basins (CUHP 2005). In this study, it is proposed that Eq 11 can be formulated as:

\[ Y = (1.5 - Z)[a \sin(bX) + c] \quad \text{(Trigonometric function)} \]  
(14)

And

\[ Y = (1.5 - Z)[aX^2 + bX + c] \quad \text{(Parabolic function)} \]  
(15)

Substituting Eqs (14) into Eq’s (8), (11), and (13) yields

\[ Y = (1.5 - Z)\left[2 \sin\left(\frac{\pi X}{8}\right)\right] \quad \text{for} \quad 0 \leq X \leq 4 \]  
(16)

Repeat the same process, Eq (15) becomes

\[ Y = (1.5 - Z)(2.286X - 0.286X^2) \quad \text{for} \quad 0 \leq X \leq 4 \]  
(17)

Figure 4 presents a comparison between the parabolic function and Sine curve for KW plane width. When X<1.5, there is not any difference between these two KW shape functions, but the difference grows when X increases.
In this study, the first test is conducted on five square watersheds of 100 feet by 100 feet. As shown in Figure 5, the collector channel in each square is aligned with a different path. The three methods are used and then compared in this test, including the parabolic function, Sine curve, and maximum overland flow length method (MOFL). The maximum overland flow length is the distance of the flow path from the upper watershed boundary to the collector channel. Maximum lengths from several different overland flow paths should be averaged. These paths should depict the slow flows through pervious surfaces, rather than the rapid flows over paved surfaces. To apply the MOFL method, the overland flow is defined in the direction perpendicular to the channel alignment. The KW plane width is then equal to the ratio of watershed area to maximum overland flow length as:

\[ L_{wm} = \frac{A}{L_{max}} \]  

(18)

where \( L_{wm} \) = KW plane width determined by MOFL method in [L], and \( L_{max} \) = maximum overland flow length in [L]. Eqs (16) and (17) can be used to directly calculate the KW plane widths. Table 1 is the summary of detailed computations using these three methods. For the first two special cases, these three methods produce the same exact solutions. For the rest of cases, the differences among these three methods are negligible. It implies that for these five hypothetic square watersheds, both parabolic and periodical KW shape functions derived in this study can select good KW plane widths in case of no experience about the site or no data for model calibration.
Figure 5 Channel and Overland Flows in Hypothetical Square Catchments

Table 1 KW Plane Widths Determined for Square Watersheds of 100-ft by 100-ft

<table>
<thead>
<tr>
<th>Case ID</th>
<th>Channel Length L (ft)</th>
<th>Area Z</th>
<th>Shape X=A/L^2</th>
<th>Parabolic Plane Width Y=Lw/L (ft)</th>
<th>Sine Curve Plane Width Lw (ft)</th>
<th>Max Overland Flow Lmax (ft)</th>
<th>Flow Method Lwm (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
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<td>2.00</td>
<td>200.0</td>
<td>200.0</td>
<td>50.0</td>
</tr>
<tr>
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<td>171.0</td>
<td>169.0</td>
<td>65.0</td>
</tr>
<tr>
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<td>0.80</td>
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<td>138.0</td>
<td>135.0</td>
<td>75.0</td>
</tr>
</tbody>
</table>

TEST OF PARABOLIC SHAPE FUNCTION ON CALIBRATED WATERSHED

The next test is to extend the comparison from the hypothetical cases into a real case that involves the watershed located in the City of Miami, Florida. As reported, this watershed in Figure 6 has a tributary area of 14.7 acres which was divided into 13 sub-basins. The KW plane widths were calibrated by several observed rainfall-runoff events and then examined for other events independently (Bedient and Huber 1997). Table 2 presents the calibrated plane widths, L_{mw}, for this watershed determined using the averaged maximum overland flow length method.

Based on the aerial photo from Google Earth, this watershed is a high-density residential area with roadside ditches to serve as the side channel. As a result, Z=1 for all sub-basins. Table 2 is the summary of the watershed parameters. Again, the parabolic KW shape function almost reproduces the calibrated plane widths without on-site experience. As can be seen, the differences between L_{w} and L_{mw} are negligible. As shown in Figure 6, the EPA SWMM5 computer model was developed in this study to reproduce the observed runoff hydrographs when applying the parabolic KW shape function to plane widths. Details can be found elsewhere (Cheng 2010). This case study further confirms that the parabolic shape function provides reasonably good guidance to select the KW plane widths for use in the EPA SWMM5 models.
Table 2 Plane Widths Predicted by Parabolic Shape Function for Miami Watershed.
In this study, the derived periodic and parabolic KW shape functions are further tested for the observed rainfall and runoff events recorded at two rain gages and one stream gage, USGS 06711570, installed in Harvard Gulch located in the City of Denver, Colorado. The Harvard Gulch Watershed is one of the matured urban watersheds managed under a long term rainfall and runoff monitor programs. The drainage system consists of grassy waterway, concrete channels, and closed conduits. The details of its hydrologic parameters are well documented as public information (FHAD 1979, Zarriello 1998, OSP 2010). Referring to Figure 7, the tributary area is approximately 728 acres (or 295 ha.) and has been developed into a mixed land use among commercial, high-density apartments, low-density residential, parks and open space.

The rain gages and stream gage operated in this watershed provide a continuous record for 18 years. After an extensive review of more than 150 events, it was found that most of the observed events could not even satisfy the basic principle of volume conservation, or the runoff volume under the direct runoff hydrograph is greater than the rainfall volume under the recorded hyetograph. Such a volumetric discrepancy is often caused by the rain under-catch at the rain gages due to wind and vegetation canopy effects (Guo et al. 2001). As recommended in EPS SWMM manual, four major water volumes in storm water simulation shall satisfy the principle of continuity as:

\[ D_v = V_F - V_R \]

(19)
In which $D_v = \text{depression volume in [L]}$, $V_P = \text{rainfall volume in [L]}$, $V_F = \text{infiltration volume in [L]}$, and $V_R = \text{direct runoff volume in [L]}$. All these volumes are computed as unit depth per watershed area. The infiltration volume can be estimated by the Horton formula for Type C and D soils. The unknown depression volume is set to be within 0.1 to 0.7 inch based on many field investigations (UDFCD 2001). Using Eq 19 as a screening criteria, there were only 9 events identified for modeling tests. These selected events had a total rainfall depth greater than 1.0 inch. Table 3 summarizes these 9 events identified in this study.

<table>
<thead>
<tr>
<th>Time</th>
<th>Rainfall Depth</th>
</tr>
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<tbody>
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<td>8/4/1988</td>
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</tr>
<tr>
<td>7/20/1991</td>
<td>0.20</td>
</tr>
<tr>
<td>7/23/1992</td>
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<tr>
<td>9/18/1993</td>
<td>0.64</td>
</tr>
<tr>
<td>7/25/1998</td>
<td>0.51</td>
</tr>
<tr>
<td>8/17/00</td>
<td>0.56</td>
</tr>
<tr>
<td>7/8/2001</td>
<td>0.13</td>
</tr>
<tr>
<td>9/12/2002</td>
<td>0.13</td>
</tr>
<tr>
<td>6/18/2003</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Table 3 Rainfall Events Selected for Harvard Gulch Watershed Tests

The computer model, EPA-SWMM5, is employed to simulate these 9 recorded rainfall and runoff events. The watershed was divided into 23 smaller sub-areas with an average size about 30 acres each. As shown in Table 4, the KW plane widths are determined using the parabolic and periodical shape functions. Minor differences are detected between these two functions. Aided with Eq (4), the slopes on the KW planes are determined to preserve the potential energy along the waterways in the two flow systems. The KW plane widths for the sub-basins in Table 4 were directly computed with deterministic formulas. No specific calibration or empirical adjustment was involved. These parameters were then entered into the EPA SWMM5 computer model to predict the storm hydrographs at the location of USGS Stream Gage, ID 671157. Figure 8 presents the predicted and observed hydrographs for the 7/21/1991 rainfall event. In comparison, the Sine shape function underestimates the peak flow while the parabolic shape function produces good...
agreement with the observed. This tendency is consistently revealed throughout these 9 rainfall events (Cheng 2010).

### Watershed Parameters

<table>
<thead>
<tr>
<th>Subarea</th>
<th>A</th>
<th>L’</th>
<th>Z</th>
<th>%</th>
<th>X=A/L²</th>
<th>Sine Curve</th>
<th>Parabolic</th>
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<td></td>
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<td>feet</td>
<td>%</td>
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<td></td>
<td>%</td>
<td>%</td>
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Note: 1 ha = 2.47 acres, 1 meter = 3.25 feet

Table 4 Hydrologic Parameters for 23 Sub-basins Harvard Gulch Watershed
TESTS OF WATERSHED SHAPE FUNCTIONS ON MODELING DETAILS

As stated in SWMM4 User’s manual (Huber and Dickson 1988), the level of watershed’s modeling details using the KWOF method leads to a variation in runoff predictions. In this study, the two KW shape functions are tested for 3 levels of modeling details. They are Model A using 23 sub-basins or approximately 30 acres per sub-basin, Model B using 4 sub-basins or approximately 180 acres for each sub-basin, and Model C using a single sub-basin of 730 acres. For instance, Figures 9 and 10 present the predicted hydrographs for 7/20/1991 event. This case reveals that the larger size the sub-basins, the lower peak flow the watershed produces. This tendency reflects the fact that each sub-basin is numerically treated as a shallow reservoir. The longer the overland flow, the higher the surface detention and the lower the peak flow.
In this study, these three models, A, B, and C are tested for both parabolic and periodical shape functions under 9 observed rainfall events or a matrix of 54 cases (3x2x9=54) generated for comparison. For the purpose of comparison, the Nash-Sutcliffe efficiency index is adopted for case comparisons (Nash and Sutcliffe 1970). The coefficient of model-fit efficiency is defined as:

\[
E = \frac{\sum_{i=1}^{N} (Q_{oi} - Q_{o})^2 - \sum_{i=1}^{N} (Q_{oi} - Q_{si})^2}{\sum_{i=1}^{N} (Q_{oi} - Q_{o})^2} 
\]  

(20)

Figure 10 Hydrographs from Single Sub-basin under 7/20/1991 Rainfall Event in Harvard Gulch Watershed

Where E= model-fit efficiency, \( Q_{oi} \) =observed runoff at i-th time step; \( Q_{si} \)=simulated runoff at i-th time step; \( Q_{o} \)=average observed runoff, and \( N \)=number of hydrograph ordinates. Using Eq 20, the 54 cases are evaluated as shown in Table 5. Both the parabolic and Sin shape functions provide good guidance to conduct the KWOF method using EPA SWMM. In general, a model with a higher resolution on drainage details tends to produce more concentrated flows. Based on the comparison of 54 cases, it is concluded that the shape functions derived in this study do not replace the effort in watershed’s modeling details. The longer the plane width is, the higher the peak flow will be.
Table 5 Summary of Model-fit Efficiency for 54 Cases

<table>
<thead>
<tr>
<th>Rainfall event</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
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CONCLUSION

1. The two KW shape functions were presented in this study for the purpose of converting a natural watershed into its KW rectangular plane. Both parabolic and sine functions provide same plane widths when the watershed shape factor, X, less than 1.5. The difference between these two functions increases as the watershed shape factor, X, becomes greater than 1.5. In this study, the watershed shape factor, X, is set not to exceed 4.0. In case of wide watersheds, Eq’s 16 and 17 can be revised with a pre-selected K in Eq 13. In general, it is advisable to maintain X≤4 for engineering practices.

2. The comparison with a calibrated model published in the previous report verifies that the watershed shape functions provide reasonably good guidance to re-produce the on-site experience on the selection of KW plane widths. Based on 54 case studies, the parabolic shape function produces a higher model-fit efficiency at all levels of modeling details than the Sine shape function. Mathematically, both Eq’s (3) and (4) implies that the shape function is related to L², or the parabolic function fits the field data better than the periodical.

3. In this study, it was also confirmed that both parabolic and periodic shape functions for plane width do not replace the effort in watershed’s modeling details. In comparison, a higher level of details in watershed model, the more concentrated flows will be generated. The numerical sensitivity in peak flow prediction is directly related to the surface detention volume under the overland flow profile. In comparison, a smooth surface and a longer plane width produce a higher peak flow while a rougher surface or/and a shorter plane width result in a more surface detention volume.

REFERENCES


II. NOTATIONS
A = watershed tributary area,
$A_m$ = dominating area or the larger half
$B$ = average watershed width
$D_v$ = depression volume in [L],
$E$ = model-fit efficiency,
$f(X)$ = mathematical functional relationship.
$K$ = maximal value for X
$L_{wm}$ = KW plane width determined by MOFL method in [L]
$L_{max}$ = maximum overland flow length in [L]
$L$ = natural waterway length
$L_w$ = width of KW sloping plane.
$N$ = number of hydrograph ordinates
$Q_{Oi}$ = observed runoff at i-th time step;
$Q_{Si}$ = simulated runoff at i-th time step;
$Q_O$ = average observed runoff,
$S_o$ = watershed slope
$S_w$ = KW plane slope
$V_p$ = rainfall volume in [L],
$V_f$ = infiltration volume in [L],
$V_R$ = direct runoff volume in [L]
$X$ = watershed shape factor for actual watershed
$X_w$ = length of overland flow on KW sloping plane
$Y$ = KW shape factor for the KW sloping plane
$Z$ = area skewness coefficient between 0.5 and 1.0