Estimating an Impedance-to-Flow Parameter for Flood Peak Prediction in Semiarid Watersheds

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Abstract: The time of concentration equation used in Pima County, Arizona, includes a hydrologic parameter representing the impedance to flow for peak discharge estimation on small [typically less than 2.59 km^2 (1 mi^2)] semiarid watersheds. The impedance-to-flow parameter is similar in function to the hydraulic Manning's *n* roughness coefficient in the kinematic wave time of concentration equation; however, the impedance to flow is a hydrologic parameter representing all portions of a watershed rather than a hydraulic parameter representing friction loss during uniform flow. To relate the impedance-to-flow parameter to physical watershed characteristics, impedance-to-flow values were calculated for return period and observed events on five undeveloped rangeland watersheds and correlated with Manning's *n* roughness coefficients determined from particle size analysis and simulated flow conditions. Impedance to flow displayed a positive trend with observed peak discharge on each watershed. The results indicate that local impedance-to-flow values can be developed for time of concentration equations using observed rainfall and runoff data, as well as measurable field characteristics. The impedance-to-flow parameter allows for a physical basis in time of concentration estimation without the additional detail of a physically based model.

DOI: 10.1061/(ASCE)HE.1943-5584.0000177

CE Database subject headings: Hydrologic models; Travel time; Hydraulic roughness; Peak flow; Arizona.

Author keywords: Hydrologic models; Travel time; Hydraulic roughness; Peak flow; Impedance to flow.

Introduction

On small watersheds, rainfall is often assumed to be spatially and temporally uniform and discharge is often determined as a function of the time of concentration (T_c), which is defined as the "time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed" (Soil Conservation Service 1986). While many definitions of T_c employ the term "hydraulics," in practice T_c is often calculated by empirical equations where the hydraulics of flow are not specifically considered. An evaluation of 11 different T_c methods found that most include an empirical parameter and are subject to significant error for a given watershed (McCuen et al. 1984). Some exceptions to the use of empirical parameters in T_c methods are the various kinematic wave time of concentration calculations [e.g., Singh (1976)] that describe the hydraulic resistance to flow using Manning's "*n*" or Chezy "*C*," which are measures of energy loss in hydraulic models. Unfortunately, the kinematic wave T_c is typically limited to hillslopes and its range of applicability does not extend to the sub-basin or small watershed scale (McCuen and Spiess 1995).

In practice, calculating the actual hydraulic travel time is problematic. One option is to recognize that the impedance to flow on a watershed has a physical basis without specifically describing this impedance in hydraulic terms. The Pima County Hydrology Procedures (Zeller 1977) use a hydrologic impedance-to-flow parameter ("the basin factor") (n_b) to represent the conveyance from all portions of a watershed. The impedance-to-flow parameter is directly proportional to the T_c in the PC-Hydro peak discharge model (Arroyo Engineering, LLC 2007) (http://rfcd.pima.gov/software/) for small semiarid watersheds [recommended for use on watersheds <2.59 km^2 (1 mi^2)]. The appearance of the impedance-to-flow parameter in the Pima County time of concentration equation is similar to the Manning's *n* roughness coefficient in the kinematic wave time of concentration formulas (Morgali and Linsley 1965); however, the impedance to flow is a hydrologic parameter of the watershed rather than a hydraulic parameter representing friction loss during uniform flow.

Published Manning's *n* roughness coefficients were found to inadequately predict measured time of concentration values in the kinematic wave T_c equation by McCuen and Spiess (1995) unless distorted. This observation may be attributed in part to overland areas of a watershed that are not represented in the hydraulic resistance in a channel but can be included in a hydrologic impedance-to-flow parameter. The purpose of this paper is to present a method for developing a relationship between impedance-to-flow parameters appearing in hydrologic equations and the Manning's *n* roughness coefficient found in hydraulic equations.

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Note. This manuscript was submitted on February 19, 2009; approved on August 17, 2009; published online on August 24, 2009. Discussion period open until August 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Hydrologic Engineering***, Vol. 15, No. 3, March 1, 2010. ©ASCE, ISSN 1084-0699/2010/3-182–190/$25.00.

The impedance-to-flow parameter in Pima County, Arizona, is used to predict peak discharge at the "sub-basin scale" in the PC-Hydro model for semiarid watersheds with a drainage area up to 25.9 km^2 (10 mi^2) [recommended for less than 2.59 km^2 (1 mi^2)], a time of concentration less than 180 min, and negligible influence by detention or retention basins. The time of concentration is solved iteratively with the rainfall intensity from a modified form of the rational equation in the formula

$$T_c = \frac{n_b}{50}\frac{(L_c L_{ca})^{0.3}}{S_c^{0.4}}\frac{1}{(C_w i)^{0.4}} \tag{1}$$

where T_c=time of concentration (hours); n_b=length-weighted impedance-to-flow parameter representing the conveyance of the watershed; L_c=length of the longest watercourse (feet); L_{ca}=incremental length of longest water course, measured from the outlet to the point on the longest watercourse opposite the centroid of the watershed (feet); S_c=mean watershed slope of longest watercourse (ft/ft); C_w=runoff coefficient adjusted for the Natural Resource Conservation Service (NRCS) curve number (CN) and 1-h rainfall depth; i=rainfall intensity with duration equal to the time of concentration (in/h); and 50=conversion factor ($ft^{0.6}/in.^{0.4}\ h^{0.6}$). Eq. (1) was developed by Zeller (1977) from existing USDA methods and a study by Rostomov (1967). Eq. (1) is similar in format to the various kinematic wave T_c equations and the method developed in this study to estimate impedance to flow for Eq. (1) could be applied to develop impedance to flow for other T_c equations. The runoff coefficient in Eq. (1) is calculated as the ratio of the NRCS CN runoff depth to rainfall depth from 1 h of rainfall and the CN is adjusted to increase for 1-h rainfall depths over 38.1 mm (1.5 in) in the Pima County procedures; however, this study focuses on the impedance-to-flow parameter appearing in a given hydrologic equation and additional details about the Pima County T_c equation may be found at http://rfcd.pima.gov/software/. The impedance to flow in Eq. (1) may be assigned for segments of the flow path, and a weighted overall impedance-to-flow value may be used to calculate the T_c for each watershed. In practice, the impedance to flow (n_b) is a third unknown variable in the time of concentration formula.

Study Area

The Santa Rita Experimental Range (SRER) was established in 1903, approximately 50 km south of Tucson, Ariz., in a semiarid grass-shrub ecosystem (Lane and Kidwell 2003). In 1975, the Agricultural Research Service (ARS) instrumented eight small watersheds within the SRER to measure rainfall, runoff, and sediment. The ARS-SRER watersheds are a compliment to the measurement network at the USDA-ARS Walnut Gulch Experimental Watershed (WGEW) near Tombstone, Ariz. and provide a more comprehensive measurement than the rain gauge network established on the SRER in 1940. Green and Martin (1967) found the SRER mean annual precipitation to range from 282 to 492 mm for 22 rain gauges from 1940 to 1965 with elevation ranging from 914 to 1,310 m. Precipitation at the SRER is seasonal with rainfall and runoff predominantly occurring from high-intensity short-duration convective thunderstorms during the summer months (July–September) and a secondary increase in rainfall during the winter months (December–February) from low-intensity long-duration frontal storms. Rainfall and runoff data are available online at http://www.tucson.ars.ag.gov/dap/.

Methods

Impedance-to-flow values were (1) estimated for return period events by frequency analysis and (2) calculated for observed events and used to perform a regression with peak discharge on five of the SRER watersheds using 33 years of rainfall and runoff data. Manning's n roughness coefficients for the SRER channels were estimated from particle size analysis and simulating flow conditions for "base n" values and summing roughness elements from channel surveys. Regression relationships were determined for the impedance-to-flow parameter with the Manning's n roughness coefficient.

Impedance to Flow Estimated by Frequency Analysis

Rainfall and runoff data were obtained for the period of record (1975–2007) from the Southwest Watershed Research Center Online Data Access Project (http://www.tucson.ars.ag.gov/dap/). Frequency analysis was performed for annual series event rainfall depth, event runoff depth, and peak discharge to estimate return period values. Statistical software (Minitab V 15.1) (Minitab, Inc. 2007) was used to fit the following nine distributions to each data set: normal, lognormal, weibull, exponential, two-parameter gamma, largest extreme value, three-parameter lognormal, and three-parameter loglogistic. The goodness of fit of each distribution to each hydrologic variable was evaluated using the Anderson and Darling (1954) and P-value test statistics. The Bulletin 17B method (U.S. Interagency Advisory Committee on Water Data 1982) of flood frequency analysis was used to evaluate the log-Pearson Type III distribution for peak discharge. The criteria for the most reasonable distribution to approximate return period values were that the distribution had (1) the lowest Anderson-Darling statistic of the fitted distributions; (2) the highest P value of the fitted distributions; and (3) a closer fit to observed data at higher return periods by graphical comparison. The 25-, 50-, and 100-year return period values were estimated using the distribution with the highest goodness-of-fit statistics across all watersheds for each hydrologic variable. The minimum record lengths required to predict 100- and 25-year return period values were estimated from Mockus (1960).

The return period runoff coefficients (C_{RP}) were calculated as the ratio of the return period runoff depth to return period rainfall depth, and therefore the runoff coefficient is assumed to have the same frequency as the rainfall and runoff depth. The average rainfall intensity necessary to produce the event or return period peak discharge was calculated from the modified form of the rational equation used in PC-Hydro for small watershed areas as

$$i = \frac{Q_{PRP}}{1.008 \times C_{RP} \times A} \tag{2}$$

where Q_{PRP}=return period peak discharge (cfs); i=rainfall intensity with duration equal to the time of concentration (in./h); A=drainage area (acres); C_{RP}=runoff coefficient calculated in this study from observed data as the ratio of return period event runoff depth to rainfall depth; and 1.008=conversion factor from (acre/in. h) to (cfs).

By definition, the average rainfall intensity has a duration equal to the time of concentration. This approach assumes that the return period of the runoff event is the same as the return period of the rainfall event, the rainfall is uniformly distributed over the watershed, and rainfall occurs with uniform intensity (Haan et al. 1994). The average rainfall intensity found from Eq. (2) was used with the return period intensity-duration frequency (IDF) curve to determine the duration of the rainfall that is equal to the time of concentration. The NOAA 14 Upper 90% confidence interval IDF curves (as used in Pima County) were used for the calculation of return period impedance-to-flow values. The return period impedance to flow was found from Eq. (3) with known watershed characteristics and variables described previously from Eq. (1) as

$$n_b = 50T_c \frac{S_c^{0.4}(C_{\mathrm{RP}}i)^{0.4}}{(L_c L_{ca})^{0.3}} \tag{3}$$

Impedance to Flow Calculated for Observed Events

In addition to the return period values, the observed impedance-to-flow values were calculated for the available data on the five SRER watersheds. The average rainfall intensity was calculated from Eq. (2) using observed peak discharge and a runoff coefficient calculated as the ratio of the observed runoff depth to observed rainfall depth. The event rainfall intensity-duration curve was used to iteratively solve for the observed time of concentration and observed impedance to flow value in Eq. (3).

Some observed events recorded on the SRER watersheds were found to require an average rainfall intensity higher than the observed rainfall data to produce the peak discharge, implying that portions of the watershed may have received more rainfall than the rain gauge or that the runoff coefficient based on the ratio of runoff depth to rainfall depth was not sufficient. These observed events were omitted from the discharge regression because the impedance to flow could not be calculated.

Field Methods

Real-time kinematic GPS with an estimated accuracy of 2–3 cm was used to survey the channel profiles and cross sections within each watershed. Composite sediment samples were collected at channel cross sections to a depth of approximately 7–10 cm to perform a particle size analysis for estimating base (grain roughness) Manning's n values. Particle size distributions and median particle sizes were determined for the composite sediment samples by dry sieving for the predominately sand samples (USDA 1979). The composite soil samples were oven dried, weighed, and sieved using screen sizes of 1, 0.5, 0.25, 0.105, and 0.050 mm and a pan.

Measurement and Estimation of Roughness from Field Conditions

The Manning's n roughness parameter represents the energy loss due to friction during uniform flow in open channels. The bed roughness consists of grain roughness and form roughness for mobile boundary channels (U.S. Army Corps of Engineers 1994) such as the sand channels of the SRER. The grain roughness accounts for the effective surface roughness height of the bed particle size and the form roughness accounts for dunes, antidunes, plain bed, or other bed features. The form roughness is dependant upon whether the flow is upper, transitional, or lower regime. The flow regime is verified by calculating the stream power as described in Aldridge and Garrett (1973). Phillips and Tadayon (2006) noted that flood peaks on sand channels generally occur during upper regime flow.

Cowan (1956) presented a method of adding roughness adjustments to the bed roughness or base Manning's n value as

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m \tag{4}$$

where n_0=Manning's n roughness coefficient base value for a straight, smooth, natural channel; n_1=adjustment value for surface irregularities; n_2=adjustment value for shape and size variations in channel cross section; n_3=adjustment value for obstructions; n_4=adjustment value for vegetation and flow conditions; and m=adjustment value for meandering of the channel. Phillips and Tadayon (2006) provided procedures for field estimation of the Manning's n roughness adjustments in Arizona.

Estimating the Base Manning's n Value

The method of Karim (1995) was used for determining the base Manning's n coefficient from particle size and a friction factor representing bed form roughness for a moving sediment bed as

$$n_0 = 0.032 D_{50}^{0.126}\left(\frac{f}{f_0}\right)^{0.465} \tag{5}$$

where D_{50}=median particle size (feet) and (f/f_0)=bed configuration parameter (λ), expressed as the ratio of the Darcy-Weisbach friction including bed forms (f) to the grain roughness friction (f_0). The friction factor was determined from relationships developed by Karim and Kennedy (1990) based on the relative bed form height (H/h)

$$\frac{f}{f_0} = 1.20 + 8.92\left(\frac{H}{h}\right) \tag{6}$$

where the relative bed form height, or ratio of bed form height (H) to flow depth (h), is defined as

$$\frac{H}{h} = -0.04 + 0.294\left(\frac{U_*}{w_f}\right) + 0.00316\left(\frac{U_*}{w_f}\right)^2 - 0.0319\left(\frac{U_*}{w_f}\right)^3 + 0.00272\left(\frac{U_*}{w_f}\right)^4 \tag{7}$$

for $0.15 < U_*/w_f < 3.64$, otherwise $H/h=0$. U_*=shear velocity (ft/s) and w_f=sediment fall velocity (ft/s) of particles with size D_{50}.

Analysis and Modeling of the SRER Watersheds

Each SRER watershed was delineated in a geographic information system (GIS) based on 1-m contour lines derived from a 1994 high resolution stereo image data set. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) (V 4.0 Beta) [U.S. Army Corps of Engineers, Hydrologic Engineering Center (HEC) 2002] was used to simulate flow conditions during return period discharge events. The HEC-RAS models were created from survey results and initially a constant Manning's n value of 0.035 was used for all cross sections. The models were run as steady flow simulations with a subcritical flow regime using the 25-year peak discharges. The downstream boundary condition was specified as critical depth due to the supercritical flumes on each watershed creating critical flow conditions for measurement of the discharge. The ratio of the shear velocity to the fall velocity in Eq. (7) was calculated from the HEC-RAS simulated conditions. The shear velocity was computed as

$$U_* = (ghS_w)^{0.5} \tag{8}$$

where g=acceleration due to gravity (ft/s^2); h=flow depth (ft); and S_w=energy grade line slope (ft/ft) (Sturm 2001). The fall velocity was computed as

Table 1. Drainage Area (A), Length of Longest Flowpath (L_c), Harmonic Mean Slope (S_c), Channel Manning's n, and 25-Year Hydraulic Radius (R_{25}) for the SRER Watersheds from Channel Surveys, GIS Analysis, and Simulated Flow Conditions

Gauge	A (ha)	L_c (m)	S_c (m/m)	Channel Manning's n	R_{25} (m)
SRER 1	1.635	265.7	0.0321	0.0453	0.1030
SRER 2	1.768	298.6	0.0353	0.0385	0.1293
SRER 3	2.756	301.3	0.0211	0.0440	0.1372
SRER 4	1.975	318.9	0.0322	0.0459	0.1695
SRER 5	4.019	349.3	0.0347	0.0561	0.1936

$$w_f = 8\upsilon[(1+0.0139d_*^3)^{0.5}-1]/d_s \tag{9}$$

where υ=fluid kinematic viscosity (ft^2/s); $d_*=d_s[\text{SG}-1)g/\upsilon^2]^{1/3}$; d_s=sieve diameter usually measured as the geometric mean of sieve sizes just passing and retaining a sand grain (ft); and SG=specific gravity taken as 2.65 (Sturm 2001). The shear velocity and fall velocity were used to calculate the relative bed form height [Eq. (7)] and the friction factor [Eq. (6)] to estimate the Manning's n base value [Eq. (5)].

The Manning's n roughness adjustments assigned in the field using tables from Phillips and Tadayon (2006) were added to the base Manning's n value at each cross section. The roughness adjustments were estimated in July and August 2007 during the summer thunderstorm season to represent conditions when flooding was most likely to occur on the SRER watersheds.

Results and Discussion

Statistical Distributions for Hydrologic Variables

The best-fit distributions for the SRER watersheds were found to be the three-parameter lognormal for annual series event rainfall depth and the gamma distribution for event runoff depth. The log-Pearson Type III distribution was selected for the peak discharge as used in common practice. The length of the historic data record was found to be inadequate for estimating 100-year peak discharge on SRER watersheds 2, 5, and 6 and therefore 25-year impedance-to-flow values were primarily used in the study. In addition, the period of record was found to be inadequate to estimate 25-year peak discharge for SRER Watershed 6 and therefore SRER 6 was not used in the frequency analysis.

SRER Watershed Characteristics

The SRER watersheds used in the study have drainage areas ranging from 1.64–4.02 ha and relatively steep slopes along the flow path (2–3%) (Table 1). The drainage areas of the watersheds are relatively small and may limit applicability to larger watersheds; however, (1) the watersheds have significant lengths of record (33 years); (2) the smaller drainage area allows assumptions in rainfall uniformity to be reasonable; and (3) the results from the smaller watersheds can provide qualitative results for impedance to flow on larger areas.

Manning's n Values from Field Measurement and Simulated Flow Conditions

The steep slopes of the SRER watersheds often created critical flow depth conditions at cross sections in the HEC-RAS models, producing Froude numbers that were in the transitional range defined by Karim (1995) and base Manning's n values relatively low compared to published values for coarse sand (Phillips and Tadayon 2006) at some locations. Upper regime flow was used for base Manning's n values due to the uncertainty in predicting roughness in the transitional regime described by Karim (1995) (Table 2). Manning's n and 25-year hydraulic radii were found for each watershed as a length-weighted mean from cross sectional values

$$\overline{X_w} = \left(\sum_{i=1}^{k} w_i x_i\right) \Big/ \left(\sum_{i=1}^{k} w_i\right) \tag{10}$$

where x_i=Manning's n or hydraulic radius value for cross section i; w_i=length along flow path nearest to cross section i (meter); and k=total number of cross sections on the flow path. The flow path beyond the farthest cross section from the flume was not included in the weighted mean calculation for each watershed.

Comparison of Manning's n Roughness Coefficients with Published Values

The Manning's n roughness coefficients for the SRER channel systems are compared in Fig. 1 with the Gibson Arroyo in Ajo, Ariz. (Aldridge and Garrett 1973) and Skunk Creek near Phoenix, Ariz., with nine verification measurements from Phillips and Ingersoll (1998) at various stages of vegetation growth. The Manning's n value for the Gibson Arroyo is published as 0.038–0.040 with scoured banks and dense brush (Aldridge and Garrett 1973), and the Skunk Creek values ranged from 0.031 after maintaining vegetation to 0.052 when vegetation had regrown (Phillips and Ingersoll 1998).

Return Period and Observed Impedance-to-Flow Values

The 25-year frequency analysis impedance-to-flow values are regarded as more accurate than the discharge regression values because the frequency analysis method used the best-fit statistical distribution for each hydrologic variable to estimate impedance to flow (Table 3). The difference in impedance to flow between the frequency analysis and discharge regression methods for SRER 3 may be attributed to the low coefficient of determination (R^2) in the discharge regression for the observed event impedance to flow on SRER 3.

The regression of impedance to flow with observed peak discharge displays the qualitative trend of impedance to flow to increase with higher peak discharge events. Normalizing the observed event impedance-to-flow values on all SRER watersheds by the watershed slope and length characteristics in Eq. (3), $(50S_c^{0.4})/(L_c L_{ca})^{0.3}$, equals $T_c(C_w i)^{0.4}$ and displays the qualitative tendency for the overall impedance to flow to increase with peak discharge (Fig. 2). This is one aspect of how the hydrologic impedance to flow of a watershed differs from the hydraulic rough-

Table 2. Length along Flowpath, Base Manning's n, Channel Manning's n, and 25-Year Hydraulic Radii (R_{25}) for Each Cross Section (CS) of the Five SRER Watersheds

Watershed	CS	Length (m)	Base Manning's n	Channel Manning's n	R_{25} (m)
SRER 1	1	9.93	0.0287	0.0387	0.0953
	2	17.33	0.0291	0.0641	0.0721
	3	35.40	0.0277	0.0352	0.0807
	4	60.71	0.0285	0.0465	0.1260
	5	95.32	0.0273	0.0473	0.1204
SRER 2	1	7.91	0.0294	0.0304	0.1061
	2	30.68	0.0288	0.0338	0.1165
	3	60.18	0.0298	0.0318	0.1398
	4	87.26	0.0289	0.0489	0.1385
	5	105.15	0.0295	0.0645	0.1617
SRER 3	1	9.68	0.0291	0.0441	0.1113
	2	26.90	0.0285	0.0335	0.1233
	3	59.34	0.0297	0.0397	0.1584
	4	101.39	0.0287	0.0487	0.1309
	5	134.01	0.0293[a]	0.0493	0.1504
	6	160.35	0.0299	0.0499	0.1392
	7	166.76	0.0296	0.0446	0.1159
	8	170.08	0.0275	0.0375	0.1106
SRER 4	1	8.31	0.0291	0.0381	0.1655
	2	40.40	0.0296	0.0366	0.1808
	3	69.38	0.0304	0.0524	0.1812
	4	79.66	0.0294[a]	0.0529	0.1799
	5	111.58	0.0284	0.0534	0.1632
	6	134.99	0.0212	0.0482	0.1683
	7	149.99	0.0277	0.0537	0.1656
	8	153.14	0.0171	0.0251	0.1231
	9	160.04	0.0285	0.0385	0.1083
SRER 5	1	5.17	0.0295	0.0335	0.1476
	2	33.46	0.0300	0.0650	0.2002
	3	85.35	0.0298	0.0518	0.2314
	4	132.25	0.0298	0.0698	0.1884
	5	178.10	0.0296	0.0416	0.1506

[a]Unconsolidated soil could not be collected at these cross sections and base Manning's n values were interpolated from the adjacent cross sections.

ness of the channel. Considering flow paths on all portions of a watershed [less than 2.59 km^2 (1 mi^2) in this study), higher discharges may encounter greater resistance due to increased flow outside the rill or low order channel, while the hydraulic roughness in a channel may be expected to decrease with higher discharge due to a higher flow depth. The increase in impedance to flow with higher discharge is particularly applicable to semiarid watersheds with ephemeral channels such as the SRER that do not have the capacity to convey high return period flows within the channel banks. The variance of the observed event impedance to flow from the regression line suggests that impedance to flow is not solely a function of peak discharge and the impedance-to-flow values are accounting for other factors (i.e., transmission losses and rainfall variability) not included in the simplified approach to peak discharge estimation.

Impedance to flow is expected to increase with peak discharge

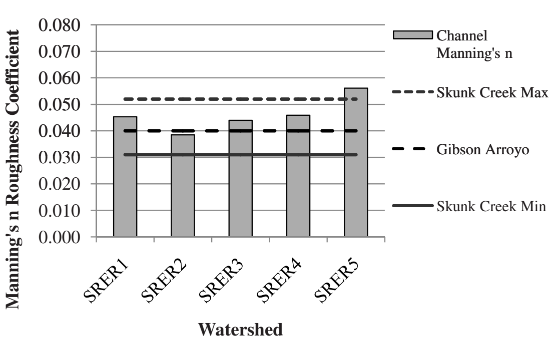

Fig. 1. Comparison of the assigned channel Manning's n roughness coefficients for the SRER watersheds with published values for Arizona

Table 3. 25-Year Impedance-to-Flow Values (n_{b25}) for the Frequency Analysis (FA) and Discharge Regression (DR) Methods

Watershed	FA n_{b25}	DR n_{b25}
SRER1	0.0335	0.0394
SRER2	0.0248	0.0219
SRER3	0.0268	0.0639
SRER4	0.0340	0.0296
SRER5	0.0581	0.0614

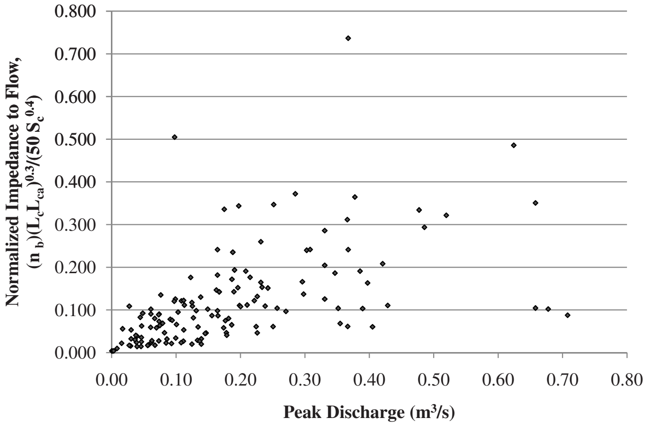

Fig. 2. Impedance to flow normalized by watershed characteristics versus observed peak discharge events on six of the SRER watersheds

for a given watershed based on the regression with observed events. Therefore, the best estimates of 100-year peak discharge for the SRER watersheds were used to develop a ratio to estimate 100-year impedance to flow from 25-year impedance to flow. SRER Watersheds 1, 3, and 4 were the only watersheds with a record adequate to estimate the 100-year peak discharge. Solving for the 100-year impedance-to-flow values required to produce the 100-year peak discharge for SRER 1, 3, and 4 provides ratios of 100- to 25-year impedance to flow (Table 4). The mean of the impedance-to-flow ratios is 1.087, and is the best available information for estimating 100-year impedance to flow from this study.

Correlation of Impedance-to-Flow Values

The impedance to flow for the frequency analysis and observed discharge regression methods were correlated with watershed characteristics (variables described previously) and rainfall intensity. The correlation coefficients for the 25-year impedance-to-flow values with the channel Manning's n, 25-year hydraulic radius (R_{25}), and 25-year 10-min rainfall intensity (i_{25}) were 0.965, 0.733, and 0.809, respectively. Peak discharge was not used in the correlation because the function of the impedance to flow is to calculate T_c for peak discharge estimation.

The high correlation coefficient with the channel Manning's n roughness (0.965) for the five watersheds suggests that the impedance to flow is measurable from physical watershed characteristics because the Manning's n roughness values were determined from particle size analysis and roughness components. However, the Manning's n coefficients were not equivalent in magnitude to the impedance to flow. The R_{25} correlated with the impedance-to-flow values have limited use because of the limited range of R_{25} for the watersheds and the requirement of a discharge to estimate R_{25}. The impedance to flow was positively correlated with the 10-min rainfall intensity (i_{25}) for the watersheds, which may be attributed to the positive correlation of i_{25} with the observed peak discharge. The watershed area, slope, and length of flow path are recognized as being indicators of the impedance to flow, but could not be used in the correlation because the variables were used to calculate the impedance-to-flow values.

Table 4. 100-Year Impedance-to-Flow Values for SRER Watersheds with Adequate Record to Estimate the 100-Year Return Period Event

Watershed	n_{b25}	Q_{p100} (m^3/s)	n_{b100}	n_{b100}/n_{b25}
SRER 1	0.0335	0.526	0.0407	1.214
SRER 3	0.0268	1.027	0.0202	0.754
SRER 4	0.0340	0.656	0.0441	1.294

Regression

Regressions were performed using the Manning's n roughness coefficients of the channel. The 25-year impedance to flow on the SRER watersheds as a function of the length-weighted channel Manning's n was found as

$$n_{b25\ \text{year}} = 2.004(n) - 0.0566 \quad (11)$$

where $n_{b25\ \text{year}}$=25-year return period impedance-to-flow value and n=length-weighted Manning's n roughness coefficient of the channel. This empirical equation is an example specific to the impedance-to-flow parameter appearing in the Pima County T_c equation and a separate relation must be developed from local watershed conditions for impedance-to-flow parameters appearing in other hydrologic equations. Eq. (11) has a calibration coefficient of determination (R^2) of 0.932 for the undeveloped SRER watersheds and is intended for natural channels in semiarid watersheds with a representative Manning's n roughness coefficient $>$ 0.038 (Fig. 3).

By calculating prediction intervals (Walpole et al. 2002) for the impedance to flow on the SRER watersheds, a conservative value may be used for design and the error bounds of Eq. (11) can be considered. The 5% prediction interval displays the impedance-to-flow value estimated as less than a future data point with 95% probability based on the SRER watersheds. The regression equation to estimate the 5% prediction interval 25-year impedance to flow ($n_{b25,\ 5\%}$) from the SRER watersheds is

$$n_{b25,\ 5\%} = 1.929n - 0.0627 \quad (12)$$

where n=length-weighted Manning's n roughness coefficient of the channel and the calibration coefficient of determination (R^2) is 0.995. Eq. (12) is limited to the same applications as Eq. (11). A smaller impedance-to-flow value yields a higher peak discharge value, and the lower bound prediction interval will provide a more conservative impedance-to-flow value for design.

Jackknife Validation

A validation was performed for the SRER regression using "delete-1 jackknifing" (McCuen 2005) to display the prediction capabilities for Eq. (11) from the SRER data set (Table 5). In jackknife validation, an observed data point is removed from the data set and a new regression equation is created from the remaining n-1 data points (where n is the sample size). The missing point is predicted from the new regression equation and the error is calculated. The data point is replaced in the data set and this process is repeated with new data points until the error has been calculated for n predictions. The jackknife statistics are calculated from the error of the prediction points. Jackknifing provides a more accurate representation of prediction capabilities than the calibration statistics. The explained variation (R^2) of 0.563 for Eq. (11) indicates that impedance to flow on the SRER watersheds may be predicted from the Manning's n roughness coefficient; however, significant error remains in estimating the impedance to flow.

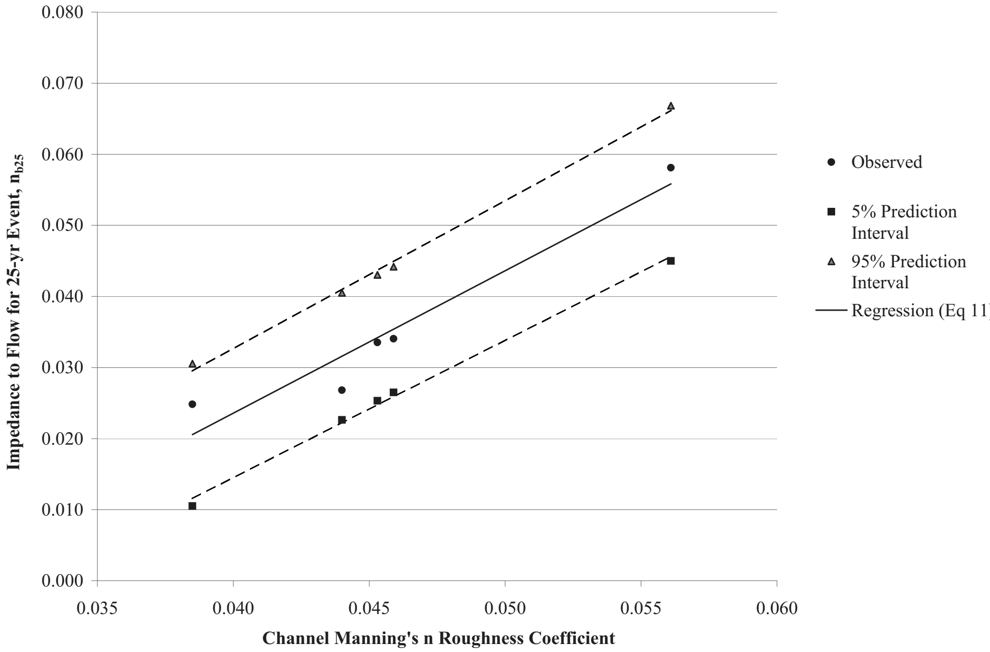

Fig. 3. Regression of 25-year impedance-to-flow values with the channel Manning's *n* roughness coefficient for the SRER watersheds

Return Period Peak Discharge Estimation from Impedance to Flow

Using the length-weighted channel Manning's *n* with Eq. (11) to estimate 25-year impedance to flow and estimating 25-year peak discharge using the T_c from Eq. (3) finds relative agreement with the frequency analysis 25-year peak discharge (Table 6) as expected from Eq. (11). Using the mean of the available ratios (Table 4), the 100-year impedance to flow was estimated from the 25-year impedance to flow in this study as

$$n_{b100\ \text{year}} = 1.087 n_{b25\ \text{year}} \tag{13}$$

Eq. (13) is an example approximation of the 100-year impedance to flow that is intended for use only with the impedance-to-flow parameter appearing in the Pima County T_c equation because this is a location-specific empirical value. A separate relation must be developed from local watershed conditions for impedance-to-flow parameters appearing in other hydrologic equations and for other locations. The 100-year peak discharge was estimated using the 100-year impedance to flow with Eq. (1) on the SRER watersheds where the length of record is adequate to predict 100-year peak discharge (Table 7).

Table 5. Goodness-of-Fit Statistics for Calibration (C) and Jackknife Validation (J) for the Impedance-to-Flow Regression; Bias (e), Relative Bias (e/y), Standard Error (S_e), Standard Error Ratio (S_e/S_y), Explained Variation (R^2), Correlation Coefficient (R), and Sample Size (n)

Statistic	C	J
e	-3.00×10^{-8}	-2.89×10^{-3}
e/y (%)	−0.0001	−8.8606
S_e	0.0035	0.0088
S_e/S_y	0.270	0.821
R^2	0.932	0.563
R	0.965	0.751
n	5	5

Table 6. 25-Year Peak Discharge from 25-Year Impedance-to-Flow Values

Watershed	Q_{p25} (m^3/s)	n_{b25}	Estimated Q_{p25} (m^3/s)	Relative error (%)
SRER 1	0.354	0.0342	0.351	−0.89
SRER 2	0.475	0.0206	0.496	4.44
SRER 3	0.689	0.0316	0.654	−5.00
SRER 4	0.484	0.0354	0.479	−1.06
SRER 5	0.749	0.0558	0.774	3.37

Example Impedance-to-Flow Estimation

An impedance-to-flow value was estimated in the field for an independent sub-basin located in the WGEW for comparison with the regression developed at the SRER. The 149-km^2 WGEW includes Tombstone, Ariz., and was established by the USDA in 1953 (Renard et al. 2008). The WGEW is considered to be representative of Chihuahuan desert with black grama desert shrub vegetation and is approximately 90 km east of the SRER and 110 km southeast of Tucson, Ariz. The subbasin used in this study is the undeveloped WGEW 103 located at latitude 31.7438° N and longitude 110.0530° W with a drainage area of 3.70 ha.

To estimate an impedance-to-flow value for WGEW 103, a Manning's *n* value was estimated in the field at assigned cross

Table 7. Estimation of 100-Year Peak Discharge from Estimated 100-Year Impedance-to-Flow Values

Watershed	Q_{p100} (m^3/s)	Estimated n_{b100}	Estimated Q_{p100} (m^3/s)	Relative error (%)
SRER 1	0.526	0.0372	0.536	1.85
SRER 3	1.027	0.0343	0.975	−5.06
SRER 4	0.656	0.0385	0.684	4.19

Table 8. Length-Weighted Manning's n Value Assigned for WGEW 103 from the Channel Bed and Additional Roughness Adjustments

Cross section	Channel						Channel n	Length assigned to cross section (m)	(Channel n)×(length)/(total length)
	Base n_0	Irregularities n_1	Geometry n_2	Obstructions n_3	Vegetation n_4	Meandering m			
1	0.028	0.003	0.003	0.002	0.015	1.0	0.051	19.27	0.0086
2	0.028	0.003	0.001	0.004	0.015	1.0	0.051	22.86	0.0102
3	0.028	0.001	0.001	0.002	0.020	1.0	0.052	17.74	0.0081
4	0.028	0.005	0.001	0.002	0.010	1.0	0.046	16.75	0.0068
5	0.028	0.005	0.002	0.002	0.010	1.0	0.047	23.23	0.0096
6	0.028	0.004	0.002	0.001	0.012	1.0	0.047	14.12	0.0058
							Sum	113.97	0.0491

sections from the channel bed and additional roughness adjustments using USGS publications for southern Arizona (Table 8). A base Manning's n value of 0.028 was assigned for the coarse sand channel bed at WGEW 103 from USGS publications for southern Arizona and the base n values assigned at the SRER. The length of the channel was measured as 114 m and the length-weighted channel Manning's n assigned for WGEW 103 was 0.0491 from Eq. (10). Using the length-weighted Manning's n for WGEW 103 with Eq. (12) to estimate impedance to flow at the 5% prediction interval for design, the 25-year event impedance-to-flow parameter was estimated from field conditions as 0.0320 and the 100-year value was estimated from Eq. (13) as 0.0348.

Evaluation at the WGEW

To provide additional validation for the regression developed for the impedance-to-flow parameter in the hydrologic time of concentration equation used in Pima County, the 25- and 100-year impedance to flow was calculated from rainfall and runoff data collected by the USDA-ARS for WGEW 103 for comparison. A frequency analysis was performed on the WGEW 103 annual series event rainfall depth, event runoff depth, and peak discharge. The 100- and 25-year event rainfall depths were 79.6 and 69.5 mm from a three-parameter lognormal distribution. The 100- and 25-year event runoff depths were 32.7 and 24.4 mm from the gamma distribution. The 100- and 25-year peak discharges were 0.973 and 0.759 m^3/s from the log-Pearson Type III distribution. The 100- and 25-year runoff coefficients were calculated as the ratio of return period event runoff depth to event rainfall depth as 0.411 and 0.351, respectively. Solving Eq. (2) for the required rainfall intensity to produce the return period peak discharge gave a 100-year value of 230.2 mm/h and a 25-year value of 210.0 mm/h. Using the NOAA14 Upper 90% IDF curve at the watershed location with the required 100- and 25-year rainfall intensities, the T_c was calculated as 8.6 min for the 100-year event and 5.9 min for the 25-year event because the T_c is equal to the rainfall duration by definition in the modified form of the rational formula [Eq. (1)].

The watershed area, slope, and longest flow path were measured from topographic data in a GIS. The watershed area was measured as 3.70 ha. The harmonic mean slope was measured as 0.0131 m/m. The longest flow path length and the length to the watershed centroid were measured as 357.7 and 178.8 m, respectively. By converting to English units and solving Eq. (3) for the impedance-to-flow parameter specific to the Pima County T_c equation, the WGEW 103 impedance to flow for the 100-year event was found as 0.0380 and the 25-year event was found as 0.0237.

The difference between the field estimated impedance to flow and the value calculated from rainfall and runoff indicates that the empirical regression developed for Pima County was less accurate at WGEW 103 (Table 9); however, the results support the conclusion that the impedance to flow increases with return period and the Manning's n coefficient and hydrologic impedance to flow are not equivalent. The 25-year impedance to flow (0.0237) calculated for WGEW 103 is significantly lower than typical Manning's n values assigned for natural channels (Phillips and Tadayon 2006), and in this respect the impedance to flow estimated from Eq. (12) (0.0320) provides an improvement over using the Manning's n value (0.0491) in this hydrologic equation [Eq. (1)]. The purpose of this study is not to provide an impedance-to-flow equation but to provide guidance concerning the role of impedance to flow in hydrologic equations and a method for developing impedance-to-flow relationships. The relative error in estimating the 25-year impedance to flow for WGEW 103 may be attributed in part to the sensitivity of the calculated impedance to flow to the runoff coefficient in the Pima County methods, or the inherent error in estimating Manning's n values in the field from published literature. In addition, the relative error may be attributed to the development of the SRER regression for the Sonoran desert watersheds while the WGEW 103 is considered to be representative of Chihuahuan desert and rainfall intensity and rainfall distributions vary between the two regions. The impedance-to-flow value assigned from field conditions provided a better approximation of the calculated 25-year impedance to flow than the Manning's n value in this study, and the impedance to flow assigned from field conditions may provide reasonable results for a simplified method for peak discharge. The evaluation of the SRER regression at WGEW 103 displays the empirical nature of impedance to flow in hydrologic equations and the necessity of developing an adjustment to the Manning's n roughness coefficient for application in hydrologic equations using local watershed conditions.

Conclusions

An impedance-to-flow parameter considers all portions of a watershed and provides a physical basis for calculating T_c without

Table 9. Example Estimation and Evaluation of Impedance to Flow for WGEW 103

Return period (year)	Field estimated n_b [Eq. (12)]	Calculated n_b	Relative error (%)
100	0.0348	0.0380	−8.4
25	0.0320	0.0237	35.4

the additional detail in a physically based model. This study indicates that the hydrologic impedance to flow is related to the hydraulic parameter, the Manning's *n* roughness coefficient, but it is not equivalent. Impedance-to-flow values were calculated from hydrologic data and correlated with field measurements on five undeveloped rangeland watersheds in Pima County, Ariz. The study has produced several conclusions:

- Impedance to flow was found to increase with peak discharge for observed events. At a watershed scale, higher discharges may encounter greater resistance due to increased flow outside the rill or low order channel;
- Impedance to flow has a measurable field component. It was measured in this study from the Manning's *n* roughness coefficient using particle size analysis and roughness adjustments; and
- The Manning's *n* roughness and the watershed impedance to flow were not equivalent. The impedance to flow is an empirical hydrologic parameter, while Manning's *n* is a hydraulic parameter that typically behaves differently (e.g., Manning's *n* often decreases rather than increases with increasing depth).

The study of the impedance-to-flow parameter for the SRER watersheds in Pima County, Ariz., has broader implications due to the necessity described by McCuen and Spiess (1995) to distort published values of the Manning's *n* roughness coefficient in the kinematic wave time of concentration formulas to match measured times of concentration on hillslopes and small watersheds. This study indicated that the impedance to flow for T_c calculations on sub-basins and small watersheds can be estimated based on field conditions. Since the impedance-to-flow values are more empirical than the Manning's *n* roughness, estimates must be developed based on local conditions. However, once developed, an impedance-to-flow parameter can be an accurate means of estimating T_c from measurable field conditions.

Acknowledgments

The writers thank the anonymous reviewers of this article, the United States Department of Agriculture—Agricultural Research Service, the University of Arizona, and the Pima County Regional Flood Control District for making this study possible. The writers express their gratitude to Michael Zeller, P.E., for developing the Pima County Hydrology Procedures and providing insightful comments on this study.

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