OVERLAND FLOW TIME OF CONCENTRATION ON VERY FLAT TERRAINS

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ABSTRACT

Two types of laboratory experiments were conducted to measure overland flow times on surfaces with very low slopes. One was a rainfall test using a mobile artificial rainfall simulator, and the other an impulse runoff test. Test plots were 6 feet (1.83 m) wide by 30 feet (9.14 m) long with slopes ranging from 0.24 to 0.48 percent. Surface types tested include bare clay, lawn (short grass), pasture (tall grass), asphalt and concrete. A regression analysis was used to construct models for predicting flow times. Predicted results by regressed models were compared with those by empirical models in the literature. It was found that the slope variable in the regressed model from rainfall test data is less influential than that in existing models. Furthermore, the exponent for the slope variable in the regressed model from impulse runoff test data is only one-tenth of those in existing models. Most empirical models underestimated overland flow time on surface of very low slopes. The slope variable becomes insignificant in governing overland flow time when slope is small. Antecedent soil moisture, not included in most empirical models, significantly affected time of concentration, which is included in the regressed models.

INTRODUCTION

Time of concentration is a primary basin parameter which represents the travel time from the hydraulically furthermost point in a watershed to the outlet. The accuracy of estimation of peak discharge is sensitive to the accuracy of the estimated time of concentration (*1*). Therefore, the importance of an accurate estimate of the time of concentration cannot be overlooked. For empirical models that estimate time of concentration, one of the major variables computed is a nominal value of slope for the watershed. Previous literature (*2*-*5*) has collected and listed most of the popular time of concentration formulas, all of which are empirical models and are compiled in Table 1. These models share the same general format formed by four variables:

- length of the watershed, *L*,
- surface roughness (usually Manning's roughness coefficient for overland flow), *n*,
- slope of the watershed, *S*, and
- rainfall intensity, *i*.

The general formula can be expressed as

$$t_c = kL^a n^b S^y i^z \qquad (1)$$

where t_c is the time of concentration, *k* is a constant and *a*, *b*, *y*, *z* are exponents. This equation exhibits a linear correlation of the logarithms of the variables involved.

As seen in Table 1, all models include the surface slope variable, *S*, raised to a negative power ranging from -0.2 to -0.5, that is, the slope variable is in the denominator. As such, the greater the surface slope, the less the time of concentration and vice versa. The problem occurs when such empirical models are to be used for estimating time of concentration on very flat terrains such as coastal plains. If existing empirical models are used, as the surface slope approaches zero, the time of concentration approaches infinity. Based on engineering judgment such long times of concentration are not representative of reality.

TABLE 1 Summary of Time of Concentration Models [a]

Publication and Year	Equation for time of concentration (minutes)	Remarks
Williams (1922) (*6*)	$t_c = 60LA^{0.4}D^{-1}S^{-0.2}$ L = basin length, mi A = basin area, mi^2 D = diameter (mi) of a circular basin of area S = basin slope, %	The basin area should be smaller than 50 mi^2 (129.5 km^2).
Kirpich (1940) (*7*)	$t_c = KL^{0.77}S^{-y}$ L = length of channel/ditch from headwater to outlet, ft S = average watershed slope, ft/ft For Tennessee, K = 0.0078 and y = -0.385. For Pennsylvania, K = 0.0013 and y = -0.5.	Developed for small drainage basins in Tennessee and Pennsylvania, with basin areas from 1 to 112 acres (0.40 to 45.3 hectares).
Hathaway (1945) (*8*), Kerby (1959) (*9*)	$t_c = 0.8275(LN)^{0.467}S^{-0.233}$ L = overland flow length, ft S = overland flow path slope, ft/ft N = flow retardance factor	Drainage basins with areas of less than 10 acres (4.05 hectares) and slopes of less than 0.01.
Izzard (1946) (*10*)	$t_c = 41.025(0.0007i + c)L^{0.33}S^{-0.333}i^{-0.667}$ i = rainfall intensity, in/hr c = retardance coefficient L = length of flow path, ft S = slope of flow path, ft/ft	Hydraulically derived formula; values of *c* range from 0.007 for very smooth pavement to 0.012 for concrete pavement to 0.06 for dense turf.
Johnstone and Cross (1949) (*11*)	$t_c = 300L^{0.5}S^{-0.5}$ L = basin length, mi S = basin slope, ft/mi	Developed for basins with areas between 25 and 1624 mi^2 (64.7 and 4206.1 km^2).
California Culvert Practice (1955) (*12*)	$t_c = 60(11.9L^3/H)^{0.385}$ L = length of longest watercourse, mi H = elevation difference between divide and outlet, ft If expressed as $T_c = kL^a n^b S^{-y} i^{-z}$ format: $t_c = KL^{0.77}S^{-0.385}$ K = conversion constant	Essentially the Kirpich (*7*) formula; developed for small mountainous basins in California.
Henderson and Wooding (1964) (*13*)	$t_c = 0.94(Ln)^{0.6}S^{-0.3}i^{-0.4}$ L = length of overland flow, ft n = Manning's roughness coefficient S = overland flow plane slope, ft/ft i = rainfall intensity, in/hr	Based on kinematic wave theory for flow on an overland area.
Morgali and Linsley (1965) (*14*), Aron and Erborge (1973) (*15*)	$t_c = 0.94L^{0.6}n^{0.6}S^{-0.3}i^{-0.38}$ L = length of overland flow, ft n = Manning roughness coefficient S = average overland slope, ft/ft i = rainfall intensity, in/hr	Overland flow equation from kinematic wave analysis of runoff from developed areas.
Federal Aviation Agency (1970) (*16*)	$t_c = 1.8(1.1 - C)L^{0.5}S^{-0.333}$ C = rational method runoff coefficient L = length of overland flow, ft S = surface slope, ft/ft	Developed from airfield drainage data assembled by U.S. Corps of Engineers.
U.S. Soil Conservation Service (1975, 1986) (*17*, *18*)	$t_c = (1/60)\sum(L/V)$ L = length of flow path, ft V = average velocity in feet per second for various surfaces	Developed as a sum of individual travel times. *V* can be calculated using Manning's equation.

	(The exponent of *S*, if converted from Manning's equation, will be -0.5.)	
Papadakis and Kazan (1986) (*2*)	$t_c = 0.66L^{0.5}n^{0.52}S^{-0.31}i^{-0.38}$ L = length of flow path, ft n = roughness coefficient S = average slope of flow path, ft/ft i = rainfall intensity, in/hr	Developed from USDA Agricultural Research Service data of 84 small rural watersheds from 22 states.
Chen and Wong (1993) (*19*), Wong (2005) (*20*)	$t_c = 0.595(3.15)^{0.33k}C^{0.33}L^{0.33(2-k)}S^{-0.33}i^{-0.33(1+k)}$ For water at 26°C C, k = constants (For smooth paved surfaces, C = 3, k = 0.5. For grass, C = 1, k = 0.) L = length of overland plane, m S = slope of overland plane, m/m i = net rainfall intensity, mm/hr	Overland flow on test plots of 1 m wide by 25 m long. Slopes of 2 and 5%.
TxDOT (1994) (*21*)	$t_c = 0.702(1.1 - C)L^{0.5}S^{-0.333}$ C = rational method runoff coefficient L = length of overland flow, m S = surface slope, m/m	Modified from Federal Aviation Administration (*16*).
NRCS (1997) (*22*)	$t_c = 0.0526[(1000/CN) - 9]L^{0.8}S^{-0.5}$ CN = curve number L = flow length, ft S = average watershed slope, %	For small rural watersheds.

[a] Base unit conversion: 1 mi = 1.61 km; 1 ft = 0.3048 m; 1 in = 25.4 mm.

METHODOLOGY

Rainfall Test

Rainfall test was conducted using a mobile artificial rainfall simulator (Figure 1) where test surfaces of low slope were prepared. The simulator included a hydroseeder with a 500-gallon (1890-liter) water tank and an 18 inch (0.46 m) high rain rack with spray nozzles mounted in a 5-foot (1.52-m) spacing. This rainfall simulator was designed to cover the entire test plot. The hydroseeder pump generated a flow ranging from approximately 15 to 41 gpm (0.0009 to 0.0026 m^3/s). With this range of flow rates, the precipitation rates generated by the spray nozzles ranged from 1.5 to 3.3 in/hr (38.1 to 83.8 mm/hr).

FIGURE 1 Rainfall test using artificial rainfall simulator.

Each test plot measured 6 feet (1.83 m) wide by 30 feet (9.14 m) long. This size allowed each rainfall test to run for more than 45 minutes using the maximum capacity 500-gallon (1890-liter) water tank. A 45-minute rainfall duration was used to ensure that each test would reach the time of concentration. Each rainfall test followed the procedure outlined below:

- surface soil moisture was measured (except on the concrete and asphalt surfaces),
- precipitation rate was determined,
- pump was started to begin test,

- runoff condition was observed at the lower end of the test plot,
- runoff rate was measured,
- hydroseeder pump was turned off after the runoff peaked for approximately ten minutes, and
- runoff rate was continually measured until the runoff ceased.

Impulse Runoff Test

Impulse runoff test measured runoff travel time without artificial rainfalls. Both pervious and impervious surfaces were tested. For pervious surface testing, test plots were maintained saturated prior to testing. The notion was to minimize the effect of antecedent soil moisture and infiltration, and focus on the effects of surface type, flow rate and slope on travel time. Meanwhile, time of concentration was measured as the time for water to travel from the farthest point of the plot to the outlet.

As with the rainfall test, researchers used a hydroseeder as the mobile water source. A large reservoir stored water that was filled by the hydroseeder. This reservoir, during an impulse runoff test, was placed on the upstream side of the test plot and as water was added beyond the reservoir capacity, water was allowed to overflow its weir (Figure 2). The hydroseeder pump generated a flow ranging from approximately 15 to 41 gpm (0.0009 to 0.0026 m^3/s). The size of each test plot again measured 6 feet (1.83 m) wide by 30 feet (9.14 m) long, as in the rainfall test. Each impulse runoff test followed the procedure outlined below:

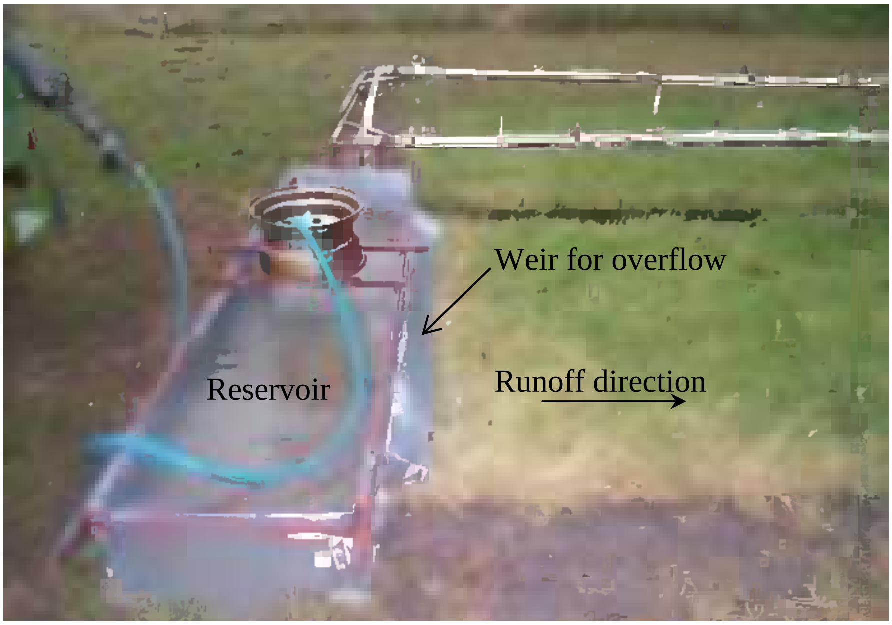


FIGURE 2 Reservoir used for impulse runoff test.

- prior to each test, pervious test plots, including bare clay and pasture were watered to create a saturated condition,
- flow rate was determined,

- pump was started to begin the test,
- travel time was recorded when water overtopped the weir, and
- travel time was continually measured until the water reached the outlet.

Tested Surfaces and Number of Tests

Five surface types were tested in this study. The details of each test type are described below:

- Bare clay (two plots). The texture for the soil tested in this research was 21% sand, 31% silt and 48% clay. The slope of these two bare clay plots was 0.43%.
- Lawn (two plots). The lawn was formed using common Bermuda grass (*Cynodon dactylon*). A grass height of less than 2 inches (5.1 mm) was maintained by mowing. The slopes of these two lawn plots were 0.48% and 0.24%, respectively.
- Pasture (two plots). The lawn was also formed using common Bermuda grass (*Cynodon dactylon*). Grasses of 6 inches (0.15 m) or taller were maintained to simulate pasture conditions. The slopes of these two pasture plots were 0.48% and 0.24%, respectively.
- Concrete (one plot). The plot was built on an old airport taxiway. The slope of this plot was 0.35%.
- Asphalt (one plot). An asphaltic cold mix was applied on top of an old airport taxiway to simulate the asphalt surface. The slope of this plot was again 0.35%.

The test number for different surfaces is presented in Table 2. The data and the range of that specific data category collected in this study are summarized in the following list:

- Slope: 0.24 – 0.48%
- Rainfall intensity (for rainfall tests): 1.5 to 3.3 in/hr (38.1 to 83.8 mm/hr)
- Runoff flow rate (for impulse runoff tests): 15 – 41 gpm (0.0009 to 0.0026 m^3/s)
- Antecedent soil moisture (on bare clay, lawn and pasture): 8 – 54%
- Infiltration rate: 0.0358 – 0.0598 in/hr (0.91 – 1.52 mm/hr)
- Soil texture: 21% sand, 31% silt and 48% clay (for bare clay, lawn and pasture plots)
- Raindrop size: 0 – 0.07 inch (0 – 1.8 mm) in diameter

TABLE 2 Number of Tests

Tested surfaces	Rainfall test	Impulse runoff test
Bare clay	11	15
Lawn	13	Not tested
Pasture	12	13
Concrete	10	5
Asphalt	7	16

RESULTS AND DISCUSSION

Rainfall Test

A typical hydrograph of the rainfall test observed in this study is shown in Figure 3. A rainfall test began at time zero when the artificial rainfall simulator was turned on. Initially, there was a no-flow period at the outlet. "Time of beginning" was recorded when the first flow was observed at the outlet. As the flow reached to a plateau and fluctuated within 5% of the flow rate, the rate was considered as the peak, which determined the "time to peak." Because time of concentration should only involve hydraulic travel time, the initial loss process (initial abstraction) was not considered as part of time of concentration. Therefore, time of concentration in the rainfall test was determined as the "time to peak less time of beginning of runoff."

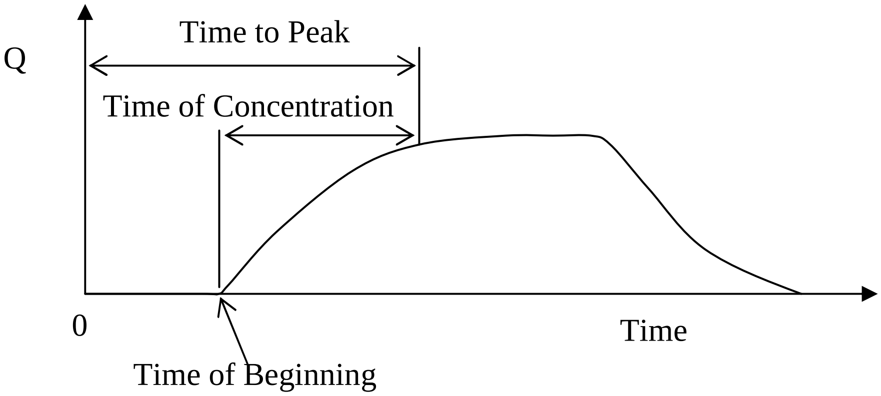


FIGURE 3 Typical hydrograph in a rainfall test.

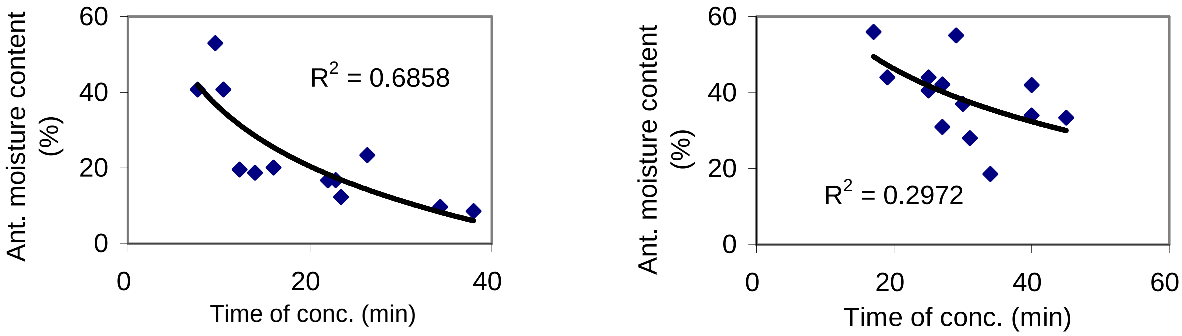
The results of rainfall tests are presented in Table 3. A linear regression analysis on the rainfall test data was conducted to construct a model to predict time of concentration. From a preliminary analysis, it was found that the antecedent soil moisture negatively affected the time of concentration (Figure 4). Therefore, the antecedent soil moisture variable, θ, was added to Equation (1) to create the new model as:

$$t_c = kL^a n^b \theta^x S^y i^z \qquad (2)$$

where θ is the antecedent soil moisture in % and x is an exponent of θ. In the new model, the watershed length L is 30 feet (9.14 m) which is the length of test plots. For the exponent of length L, the mean value, 0.5, of several models compiled by Papadakis and Kazan (*2*) was used. Similarly, regression analysis was conducted to construct models for time of beginning, t_b, and time to peak, t_p, using the same initial model shown in Equation (1).

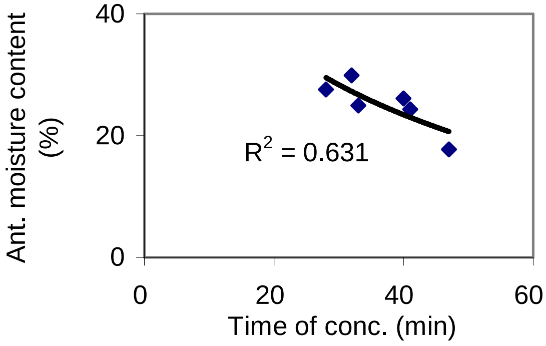
TABLE 3 Rainfall Test Results

	Time of beginning (min)	Time to peak (min)	Antecedent soil moisture (%)	Rainfall intensity (mm/hr)	Slope (%)
Bare clay 1	6	14	41	47	0.43
Bare clay 2	15	27	20	50	0.43
Bare clay 3	6	20	19	54	0.43
Bare clay 4	2	12	53	85	0.43
Bare clay 5	5	15	41	58	0.43
Bare clay 6	22	45	12	43	0.42
Bare clay 7	14	37	17	38	0.42
Bare clay 8	15	37	17	41	0.42
Bare clay 9	10	36	23	41	0.42
Bare clay 10	38	71	9	40	0.42
Bare clay 11	27	61	10	41	0.42
Lawn 1	9	34	41	38	0.48
Lawn 2	14	54	42	38	0.48
Lawn 3	9	34	44	53	0.48
Lawn 4	9	38	55	46	0.48
Lawn 5	9	36	31	78	0.48
Lawn 6	13	32	44	87	0.48
Lawn 7	7	24	56	83	0.48
Lawn 8	11	55	33	54	0.24
Lawn 9	14	47	19	49	0.24
Lawn 10	10	40	28	56	0.24
Lawn 11	18	57	34	47	0.24
Lawn 12	8	34	42	47	0.24
Lawn 13	10	39	37	52	0.24
Pasture 1	18	50	30	49	0.48
Pasture 2	23	63	26	33	0.48
Pasture 3	11	39	28	75	0.48
Pasture 4	16	49	25	51	0.48
Pasture 5	44	91	18	40	0.48
Pasture 6	18	60	24	42	0.48
Pasture 7	49	95	23	54	0.24
Pasture 8	8	46	38	65	0.24
Pasture 9	15	44	34	53	0.24
Pasture 10	16	51	30	41	0.24
Pasture 11	26	61	30	44	0.24
Pasture 12	17	47	34	39	0.24
Concrete 1	4	12	N.A.	38	0.35
Concrete 2	2	18	N.A.	35	0.35
Concrete 3	2	15	N.A.	32	0.35
Concrete 4	1	16	N.A.	36	0.35
Concrete 5	3	10	N.A.	53	0.35
Concrete 6	2	10	N.A.	56	0.35
Concrete 7	2	14	N.A.	43	0.35
Concrete 8	3	12	N.A.	41	0.35
Concrete 9	3	9	N.A.	44	0.35
Concrete 10	1	11	N.A.	32	0.35
Asphalt 1	1	10	N.A.	38	0.35
Asphalt 2	1	10	N.A.	41	0.35
Asphalt 3	4	14	N.A.	37	0.35
Asphalt 4	1	10	N.A.	45	0.35
Asphalt 5	1	12	N.A.	43	0.35
Asphalt 6	3	10	N.A.	47	0.35
Asphalt 7	2	12	N.A.	49	0.35



(a) bare clay

(b) lawn



(c) pasture

FIGURE 4 The relationship between antecedent moisture content and time of concentration (rainfall tests).

The best-fit models for time of concentration (t_c), time of beginning (t_b) and time to peak (t_p) are summarized in Table 4. Signs and values of exponents for each variable in all three models are generally similar to each other. When compared with existing models, exponents of variables n, θ and i are close to those of existing models and they are all statistically significant (p-value < 0.001). However, exponents of the slope variable, S, were found insignificant and their absolute values are less than those ($\approx$ 0.33) from existing models. It appears that S has the least influence on the time of concentration because the absolute values of the exponents for S are the least among all variables. This could result from the relatively few slopes tested in the study (0.24%, 0.35%, 0.43% and 0.48%). Or, if the slope data number is not the cause, the insignificant effect of S might indicate that when slope is very small, the effect from variables n, θ and i become dominant on the time of concentration.

TABLE 4 Regressed Models (Rainfall Test)

	N	R^2	Constant	*b* (for *n*)	*x* (for θ)	*y* (for *S*)	*z* (for *i*)
t_c	53	0.86	0.553 (0.115)*	0.320 (< 0.001)	-0.277 (< 0.001)	-0.172 (0.192)	-0.646 (< 0.001)
t_b	53	0.85	0.196 (0.753)	0.326 (< 0.001)	-0.942 (< 0.001)	-0.016 (0.947)	-0.415 (0.119)
t_p	53	0.92	0.692 (0.026)	0.305 (< 0.001)	-0.474 (< 0.001)	-0.139 (0.228)	-0.631 (< 0.001)

* *p-value* in parenthesis.

The final regressed model for time of concentration can be expressed as:

$$t_c = 0.553L^{0.5}n^{0.32}\theta^{-0.277}S^{-0.172}i^{-0.646} \qquad (3)$$

This model was compared with some existing models developed from both overland flow data [Kerby (*9*), Izzard (*10*), Henderson and Wooding (*13*) and Chen and Wong (*19*)] and watershed data [Papadakis and Kazan (*2*) and NRCS (*22*)]. Values used for variables in each model are presented in Table 5. The comparison result is plotted in Figure 5. It is apparent that all compared models underestimate the time of concentration for tested conditions. Note that Izzard's model predict the time reasonably well with the majority underestimated and minority overestimated.

TABLE 5 Variable Values Used for Model Comparison (Rainfall Test)

	Kerby model	Izzard model	Chen and Wong model	Papadakis and Kazan / Henderson and Wooding models	NRCS model
	N (flow retardance factor)	c (retardance coefficient)	C and k (constant)	n (Manning roughness n)	Curve number
Bare clay	0.1	0.02	Not provided	0.0425	89
Lawn	0.3	0.046	C = 1, k = 0	0.24	78
Pasture	0.4	0.06	Not provided	0.41	80
Concrete	0.02	0.012	C = 3, k = 0.5	0.012	98
Asphalt	0.02	0.007	C = 3, k = 0.5	0.014	98

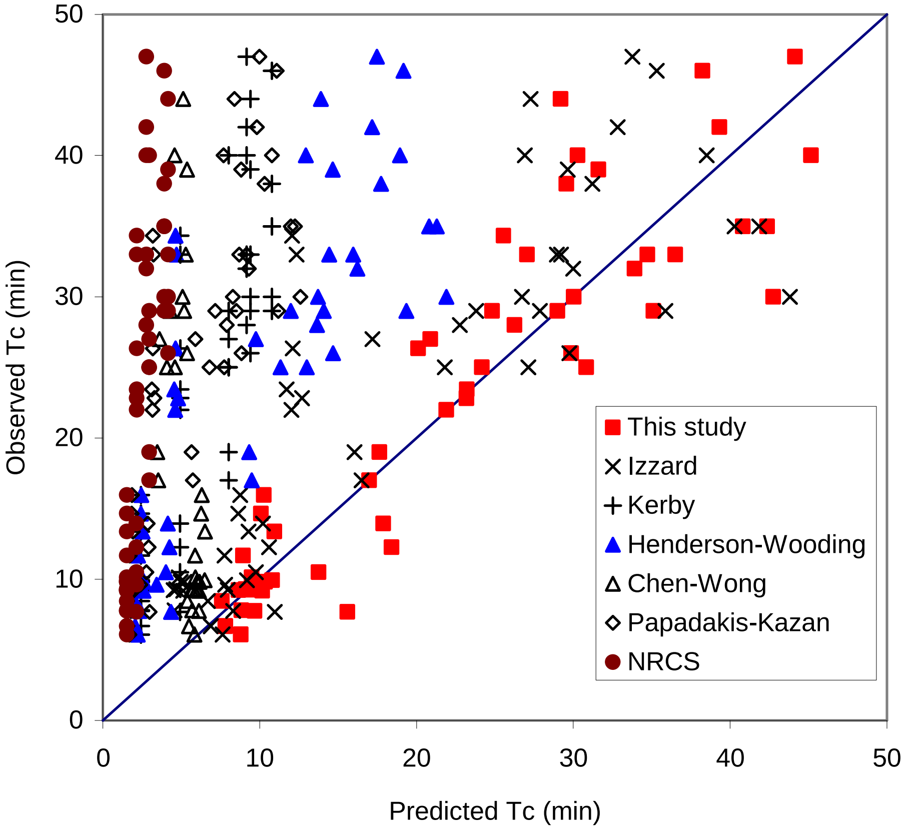


FIGURE 5 Observed vs. predicted time of concentration in the rainfall test by seven models: this study, Papadakis and Karan (*2*), Kerby (*9*), Izzard (*10*), Henderson and Wooding (*13*), Chen and Wong (*19*) and NRCS (*22*).

Impulse Runoff Test

The results of impulse runoff tests are presented in Table 6. A linear regression analysis of the impulse runoff test data was also conducted to construct a model to predict time of concentration. In this case, time of concentration is the travel time from the farthest side of the test plot to the outlet. The initial regression model was modified from Equation (1) as:

$$t_c = k \cdot L^a n^b Q^w S^y \qquad (4)$$

where t_c is the time of concentration in minutes, *k* is a constant, *L* is the watershed length in feet [30 feet (9.14 m) in this study], *n* is Manning's roughness coefficient for overland flow, *Q* is the flow rate in gpm, *S* is the watershed slope and *a*, *b*, *w*, *y* are exponents. Again, the exponent (*a*) of variable *L* was set as 0.5, which is the mean value compiled by Papadakis and Kazan (*2*) from several existing models.

TABLE 6 Impulse Runoff Test Results

	Travel time (min)	Flow rate (m^3/sec)	Slope (%)
Bare clay 1	1.28	0.0011	0.43
Bare clay 2	1.17	0.0018	0.43
Bare clay 3	0.70	0.0023	0.43
Bare clay 4	1.02	0.0013	0.43
Bare clay 5	1.31	0.0017	0.43
Bare clay 6	1.20	0.0016	0.43
Bare clay 7	0.73	0.0026	0.43
Bare clay 8	1.80	0.0019	0.42
Bare clay 9	1.72	0.0015	0.42
Bare clay 10	2.27	0.0012	0.42
Bare clay 11	1.72	0.0018	0.42
Bare clay 12	2.25	0.0020	0.42
Bare clay 13	2.23	0.0017	0.42
Bare clay 14	2.42	0.0015	0.42
Bare clay 15	2.67	0.0011	0.42
Pasture 1	5.60	0.0013	0.24
Pasture 2	4.88	0.0013	0.24
Pasture 3	5.00	0.0013	0.24
Pasture 4	4.07	0.0013	0.24
Pasture 5	5.50	0.0013	0.24
Pasture 6	6.92	0.0016	0.24
Pasture 7	5.53	0.0014	0.24
Pasture 8	7.00	0.0015	0.48
Pasture 9	6.28	0.0009	0.48
Pasture 10	5.53	0.0015	0.48
Pasture 11	4.33	0.0013	0.48
Pasture 12	4.07	0.0019	0.48
Pasture 13	5.83	0.0019	0.48
Concrete 1	1.32	0.0015	0.35
Concrete 2	1.28	0.0015	0.35
Concrete 3	1.33	0.0013	0.35
Concrete 4	1.35	0.0010	0.35
Concrete 5	1.23	0.0009	0.35
Asphalt 1	1.02	0.0011	0.35
Asphalt 2	1.10	0.0012	0.35
Asphalt 3	1.12	0.0007	0.35
Asphalt 4	1.33	0.0012	0.35
Asphalt 5	1.02	0.0017	0.35
Asphalt 6	1.30	0.0011	0.35
Asphalt 7	1.02	0.0026	0.35
Asphalt 8	1.42	0.0012	0.35
Asphalt 9	1.22	0.0008	0.35
Asphalt 10	1.08	0.0009	0.35
Asphalt 11	1.07	0.0015	0.35
Asphalt 12	1.07	0.0015	0.35
Asphalt 13	1.15	0.0016	0.35
Asphalt 14	1.18	0.0020	0.35
Asphalt 15	1.23	0.0023	0.35
Asphalt 16	1.63	0.0012	0.35

The final model is presented in Table 7. It can be observed that exponents of n and Q are statistically significant whereas the exponent of S is insignificant, similar to the rainfall test result. Furthermore, the exponent for the slope variable in the regressed model from impulse runoff test data is only one-tenth of those in existing models. Again, the slope variable becomes insignificant in governing overland flow time when slope is small.

The observed times of concentration were also plotted against those predicted by the new and existing models in Figure 6. Values used for variables in each model are presented in Table 8. It can be observed that Kirpich's (*7*) and NRCS' (*22*) underestimate the observed times of concentration while TxDOT's (*21*) overestimates them. Note that the left lower cluster of data in Figure 6 indicates the test results on smooth surfaces (bare clay, asphalt and concrete) while the higher clusters indicate the results on pasture. Based on the comparison result, existing models cannot correctly predict time of concentration on flat surfaces.

TABLE 7 Regressed Model (Impulse Runoff Test)

	N	R^2	Constant	b (for n)	w (for Q)	y (for S)
t_c	49	0.86	0.779 (0.185)*	0.453 (< 0.001)	-0.537 (< 0.001)	-0.037 (0.848)

* *p-value* in parenthesis.

TABLE 8 Variable Values Used for Model Comparison (Impulse Runoff Test)

	Kirpich model K	TxDOT model C (runoff coefficient)	NRCS model Curve number
Bare clay	0.0078	0.2	89
Pasture	0.0078	0.15	80
Concrete	0.0078	0.925	98
Asphalt	0.0078	0.875	98

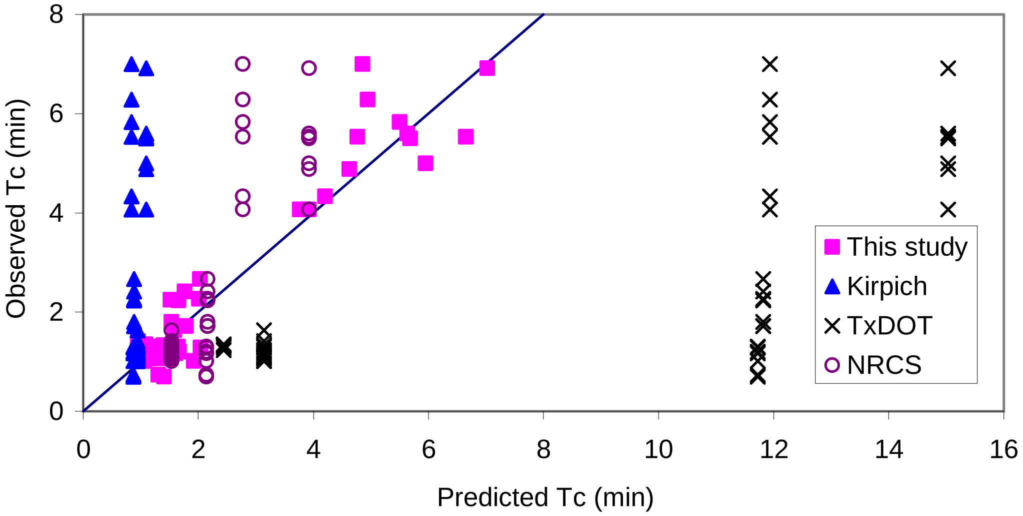


FIGURE 6 Observed vs. predicted time of concentration in the impulse runoff test by four models: this study, Kirpich (*7*), TxDOT (*21*) and NRCS (*22*).

Limitations

The limitations associated with the laboratory experiment are summarized as follows:

- Data were only collected from laboratory experiments. Field studies are needed to verify the laboratory results.
- Only a few flat slopes were tested.
- The antecedent soil moisture has a significant effect on the time of concentration However, changes of soil moisture during tests were not monitored.

CONCLUSIONS

Existing empirical models of estimating time of concentration were mostly developed from data of common watersheds. The ability of these models to predict time of concentration on very flat terrains has not been fully analyzed. This study used a controlled laboratory environment to measure times of concentration on test plots of 6 feet (1.83 m) wide by 30 feet (9.14 m) long with slopes of less than 0.5%. Artificial rainfall tests and impulse runoff tests were conducted. The results indicate that the slope variable becomes insignificant in governing overland flow time when slope is small. In addition, antecedent soil moisture negatively affected the time of concentration and was as influential as surface roughness, rainfall intensity and flow rate to the time of concentration of flat terrains. This finding suggests that soil moisture should be considered in design and a moderate value be chosen for risk balancing.

The findings of this study indicate that a direction for future work would be through field-scale instrumentation and observation of a number of watersheds with low slopes. The rationale for performing the laboratory study was the lack of appropriate data as well as the desire to develop a relationship between time of concentration and the explanatory variables without having to collect several years of data. In light of the realization that antecedent soil moisture can have an impact on time of concentration, some representative soil moisture content data would also be useful.

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