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Development and Verification of a Kinematic Wave Model for Overland Flow

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Abstract. Development and experimental verification of a kinematic wave model which simulates surface runoff is presented in this paper. The model was derived from basic kinematic wave theory. The verification of the model was performed using actual data of sets of experiments that were conducted on an experimental catchment. The experiments were conducted for both permeable and impermeable planes, a variety of rainfall intensities and durations, and different plane slopes. Ten experiments were performed to verify the model's predictive capabilities. Results have shown good agreement between experimental and model values for both permeable and impermeable surfaces as well as for complex storms. The study also serves as further verification of the validity of the kinematic wave equations for overland flow and presents a model, which could be utilized in the prediction of overland runoff from catchment and can be used in the estimation of kinematic parameters.

1. Introduction

Overland flow is defined as the movement of water over the land surface to the stream channel. It is supplied by rainfall and depleted by infiltration. When the rate of rainfall is greater than the rate of infiltration of water into the ground, the excess will accumulate to flow over the surface as an overland flow.

The overland flow problem has been studied by many researchers and wide range of methods have been applied to solve this problem. The most applicable approximation used to solve overland flow problem is the kinematic wave approach. This approach is an approximation of the dynamic unsteady equations of Saint Venant that govern overland flow movement[1].

There have been several studies on the development of kinematic wave method. Lighthill and Whitham[2] introduced the kinematic wave theory, after introducing various assumptions to the dynamic wave technique, and utilized it in describing flood movement in long rivers. They also developed kinematic wave equations for overland flow. Henderson and Wooding[3] have simplified the method of Lighthill and Whitham in an actual application to natural watersheds, while Kibler and Woolhiser[4] provided a kinematic cascade approach to simulate unsteady overland flow on a cascade plane. The kinematic wave approach has been widely applied in many practical studies[5-8].

Using kinematic wave approach, the problem of overland flow is best solved by the method of characteristics. Examples of these solutions are presented by Wooding[9], and Woolhiser and Liggett[10]. Parlange *et al.*[11] and Rose *et al.*[12] have presented exact and approximate solutions for kinematic overland flow on a plane. The approximate solution of Rose *et al.* applies only to a very special case, namely, one particular water surface profile shape and a non-converging and a non-diverging overland flow plane. An exploration of Rose's approximate solution has been carried out by Moore[13]. He expanded Rose's solution to approximate the behaviour of converging and diverging surfaces by defining the nature of the outflow hydrograph and the shape of the water surface profile for constant and time-varying rainfall excess.

Modeling of overland flow using the kinematic wave approximation has been carried out by many researchers. As an example, Marcus and Julien[14] developed two-dimensional distributed finite element and finite difference models to simulate storm events on arid watersheds. Also, Palacios-Velez and Cuevas-Renaud[15] developed watershed model based on Triangular Irregular Network (TIN) concepts. The model calculates the infiltration and routes the resultant runoff by a numerical solution of the kinematic wave equations.

Studying infiltration with overland flow has been conducted by several authors. The recent works of Lee *et al.*[16], Onodera[17], Stone *et al.*[18]; and Ritter[19] are good examples of such studies.

Experimental verification of the kinematic wave solutions has been performed by many researchers. Singh and Ram[20] have developed a method to obtain solutions to the kinematic wave equations for border irrigation. Experimental data on freely draining borders were utilized for comparison and evaluation of that method. Hall *et al.*[21] gave background and attempted using a rainfall simulator (experimental catchment area) to create artificially the conditions under which hydrological processes occur. Bell *et al.*[22] used an experimental catchment area to investigate the performance of numerical models of overland flow and also to verify the kinematic wave approximation. Luce and Cundy[23] tested modifications of a kinematic-wave model on overland flow with Philip's infiltration.

The present investigation is aimed at the development of a kinematic wave model that can be used for overland flow. The major difference between the proposed model and previous ones is that the assumption of an initially dry plane is not necessary. The proposed model is verified by comparing its predictions to experimental values. Experimental results were obtained by conducting several laboratory tests on an experimental catchment. The experiments were performed for both permeable and impermeable planes, different rainfall intensities and duration and with different plane slopes.

2. Development of Proposed Model

2. Theoretical Background

Overland flow is spatially varied, nonuniform, free surface flow. The kinematic flow relations are based on the continuity and momentum equations, commonly referred to as Saint-Venant equations. The continuity equation on a plane surface is defined as:

$$\frac{\partial vy}{\partial x} + \frac{\partial y}{\partial t} = r_e \tag{1}$$

Where y is depth of flow, v is local average velocity, r_e is excess rainfall rate, x is space coordinate measured in the direction of flow, and t is time.

The momentum equation is simplified by assuming a balance between gravitational and frictional forces. That balance implies that the derivatives of the energy and velocity terms in the momentum equation are negligible in comparison with gravity and friction effects. The simplified momentum equation is thus reduced to

$$S_0 = S_f \tag{2}$$

where S_0 is bed slope and S_f is friction slope.

Equation (2) is a simple form of the momentum and known as the kinematic wave approximation to momentum equation.

Substitution of Manning's equation into Equation (2) will produce the following parametric relationship of velocity and depth of flow[9]

$$v = \alpha m y^{m-1} \tag{3}$$

where α is roughness and slope coefficient, and m is flow type parameter. For turbulent flow, α and m are always expressed as:

$$\alpha = \frac{S_0^{1/2}}{n} \quad ; \quad m \text{ between } 5/3 \text{ and } 8/3$$

where n is Manning's roughness coefficient. For laminar flow, α and m are normally given by

$$\alpha = \frac{gS_0}{3\upsilon} \quad ; \quad m = 3$$

where υ is the fluid kinematic viscosity and g is the gravitational constant. Substituting Equation (3) into Equation (1) yields

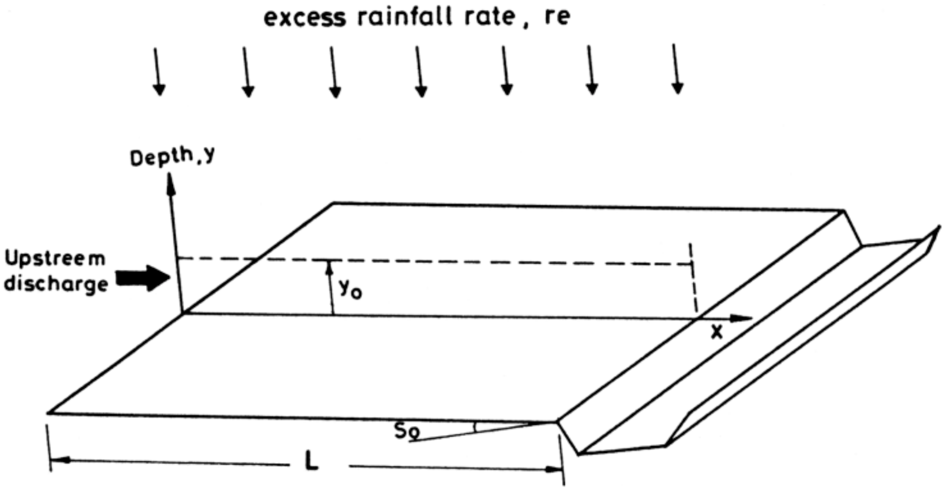
$$\frac{\partial y}{\partial t} + \alpha m\, y^{m-1} \frac{\partial y}{\partial x} = r_e \tag{4}$$

Equation (4) is the kinematic wave equation.

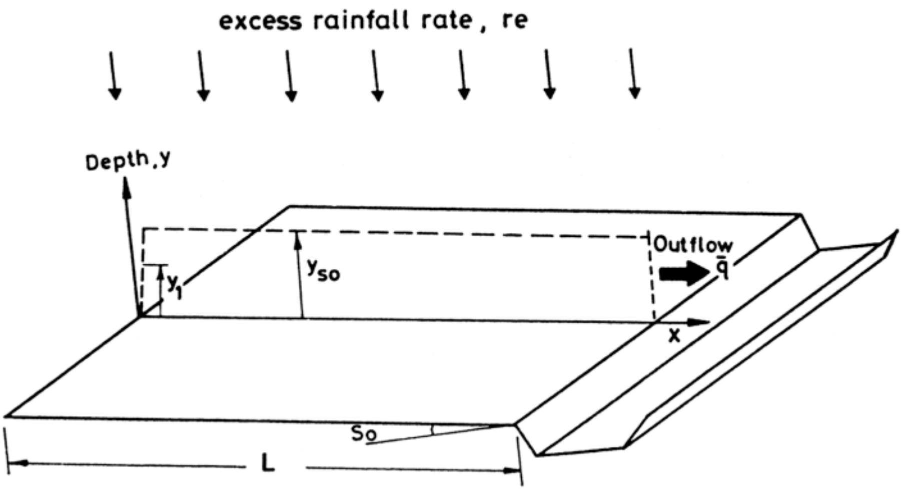
2.2 Formulation of the Model

The proposed model was developed to obtain solution of Equation (4). It is applicable for general overland flow situation where the overland plane does not have to be initially dry. In this study, Equation(4) is solved analytically using the method of characteristics with the following initial and boundary conditions, as shown in Fig. 1(a)

$$y = y_0 \ at \ t \leq 0; \ y = y(t) \ at \ x = 0$$



(a)



(b)

FIG. 1. Overland plane: (a) Actual, (b) Equivalent.

The first condition reflects the difference between the proposed model and other models. Many kinematic wave models assume initial dry plane (*i.e.,* $y_0 = 0$) while in this model that condition is accounted for at the beginning of each time step. The second condition means that there is an upstream discharge entering the plane from the upstream boundary. However, it is known that the method of characteristics is rather complicated with transient boundary conditions. To overcome this difficulty, the upstream mean discharge is converted to an additional supply depth distributed uniformly over the plane at the beginning of each time step. This assumption reduces the boundary condition to no-flow at upstream boundary, and the initial condition to uniform supply depth as

$$y_{s0} = y_0 + \frac{\overline{Q}\,\Delta t}{A} \tag{5}$$

where y_{s0} is the initial (supply) depth at the beginning of each time step, y_0 is initial flow depth deduced from previous time step calculations, $\overline{Q}$ is the mean upstream discharge coming during time interval Δt, and A is the plan area of the plane. Hence, Equation (4) is solved with the following initial and boundary conditions, as shown in Fig. 1(b)

$$y = y_{s0} \quad at \quad t \leq 0 \quad ; \quad y = 0 \quad at \ \mathrm{x} = 0$$

The characteristics (parametric) equations developed from Equation (4), with previous conditions, are

$$\frac{dy}{dt} = r_e \tag{6}$$

$$\frac{dx}{dt} = \alpha m y^{m-1} \tag{7}$$

The quantities of interest to be evaluated are the mean outflow discharge at the downstream end of the plane per unit width of the plane $\overline{q}_L$, and the mean depth over the plane at the end of the time step, $\overline{y}_L$. Equations (6) and (7) are used to obtain these quantities. Due to different excess rainfall conditions, two cases are defined:

Case I: When $r_e > 0$

Integrating and rearranging terms of Equation (7) gives the time required for a particle having depth y_1 “signal” at upstream boundary to reach the outlet of the plane as

$$t_L = \frac{1}{r_e}[(\frac{r_e L}{\alpha} + y_1^m)^{1/m} - y_1] \tag{8}$$

where y_1 ($0 < y_1 < y_{s0}$) is the depth emanating from upstream boundary at beginning of each time step. In particular, for $y_1 = y_{s0}$ and $y_1 = 0$, the travel times deduced from Equation (8) are respectively denoted t_{Lm} (for minimum) and t_{ss} (for steady state). Naturally t_{ss}, time to steady state, is greater than t_{Lm}.

Depending on time step interval T, three subcases are considered. In the simplest case when T is $< t_{Lm}$, then the mean depth at the outlet, $\overline{y}_L$, over the time interval T is obtained from Equation (6) as

$$\bar{y}_L = y_{s0} + r_e\, T/2 \tag{9}$$

In the second case when $t_{Lm} < T < t_{ss}$, more complex computations lead to a value for $\bar{y}_L$ as

$$\bar{y}_L = \frac{y_{s0}}{2}\left(\frac{T + t_{Lm}}{T}\right) + \frac{y_a}{2}\left(\frac{T - t_{Lm}}{T}\right) + \frac{r_e T}{2} \tag{10}$$

where y_a is the depth "signal" that reaches the outlet at time T and is the solution of

$$L = \frac{\alpha}{r_e}[(y_a + r_e T)^m - y_a^m] \tag{11}$$

In the third situation with $T > t_{ss}$, the flow pattern reaches steady state. The value of $\bar{y}_L$ is then

$$\bar{y}_L = \frac{y_{s0}}{2}\frac{(t_{ss} + t_{Lm})}{T} + r_e t_{ss} - \frac{r_e\, t_{ss}^2}{2T} \tag{12}$$

In all the three previous situations, mean outflow rate per unit plane width is given by the rating curve as

$$\bar{q}_L = \alpha(\bar{y}_L)^m \tag{13}$$

and the mean depth over the plane at the end of the time step is obtained by mass balance as

$$y_0^v = y_{s0} + r_e\, T - \bar{q}_L\, \frac{T}{L} \tag{14}$$

Case II: When r_e = 0

In this situation (hydrograph recession) a ponded condition exists at the beginning of time step (*i.e.*, $y_{s0} > 0$) but may not prevail by the end of the time step. However, one first determines the time of disappearance of plateau of depth y_{s0}, which is

$$t_{LM} = \frac{L}{\alpha m\, y_{s0}^{m-1}} \tag{15}$$

In the case $T \le t_{LM}$ the mean outlet depth and discharge are

$$\bar{y}_L = y_{s0} \text{ and } \bar{q}_L = \partial\, \bar{y}_L^m \tag{16}$$

and depth of flow over the plane at end of time step is zero.

In the $T > t_{LM}$, one evaluates a mean value of $\bar{y}_L$ for the time interval from 0 to t_{LM}, which is y_{s0} and a mean value over the interval t_{LM} to T, which is

$$\bar{y}_L = \frac{m-1}{m-2}\left[\frac{1}{T - t_{LM}}\right]\left[\frac{L}{\partial m}\right]^{\frac{1}{m-1}}\left[T^{\frac{m-2}{m-1}} - t_{LM}^{\frac{m-2}{m-1}}\right] \tag{17}$$

and the mean outflow specific discharge is evaluated as

$$\bar{q}_L = \frac{1}{T}[t_{LM}\ \alpha y_{s0}^m + (T - t_{LM})\,\alpha \bar{y}_L^m] \tag{18}$$

Equation (17) does not apply in the special cases m = 1 or 2. For m = 1, the solution is much simpler as $\bar{y}_L = y_{s0}$ in the interval of time 0 to t_{LM} and zero afterwards. The mean outflow rate in that case is simply

$$\bar{q}_L = \frac{t_{LM}}{T}\,\alpha y_{s0}^m \tag{19}$$

and the depth of flow over the plane at end of time step is zero.

The proposed model just presented does not account for infiltration, routing components and lateral flow

3. Model Verification

An experimental set up was utilized to collect data, which then was used to test the mathematical model's ability and accuracy in predicting outflow discharge from an overland plane. The two sets of results (experimental and theoretical) were compared.

3.1 Experimental Set Up

The rainfall-runoff experimental facility which is called "Basic Hydrology System" at the Hydraulics and Hydrology Laboratory at the Civil Engineering Department, King Saud University, was used as the model catchment. This facility simulates flow from a watershed with or without infiltration. Characteristics such as surface roughness, imperviousness, and geometry can be changed to represent a wide variety of natural catchments. In addition, simulated rainfall can be generated at various intensities and durations. The catchment basin is represented by a shallow tank made of fiberglass reinforced resin, which is 2 m long × 1 m wide × 40 cm deep. It can be filled with any type of soil. Rainfall is provided by a row of spray nozzles above the tank and runoff is led to a measuring system at one end of the apparatus. The water supply to the equipment is provided by an electrical centrifugal pump. Water passes through the strainer and flowmeter which measures the rate of flow, and hence to three inlet control valves. Two of these valves are for controlling the rate of flow to the basin and the third is for controlling the flow to the nozzles. Nozzle control valve is used for adjusting the rate of flow to the desired quantity and then left undistributed while other supply valves are firmly closed. When the basin has been filled with sand, the surface profile for the run-off experiments can be formed with the template provided by drawing it along the instrument rails mounted on the channel walls. Flow measurement is carried out using graduated measuring channel which should be adjusted to the horizontal position by adjustment of the fitted levelling screws. Water falls from measuring channel into the sump which completes the cycle.

4. Experimental Procedure

In order to achieve the objectives of the study, two types of experiments were carried out. Each type consists of different experiments for various catchment and storm characteristics. The first type was run by taking into account the effect of infiltration, where the second type was carried out by isolating the surface runoff from the effect of infiltration.

4.1 First Type of Experiments

This set of experiments were performed by changing catchment slope and rainfall rate. The desired slope was obtained by drawing the template along the instrument rails. The difference in elevation between the two ends of each rail was 2 cm (to get slope 1/100) and 1 cm (to get slope of 1/200). Rainfall rate was adjusted by using the flowmeter. Three values of constant rainfall rate were used which are 6, 8 and 10 lit/min.

The selection of these values is based on capability of the instrument. The range of slope which can be used is from zero to 1/100 and the range of rainfall rate that can be used is from zero to 14 liter per minute. In each experimental run, the observed ponding time was recorded (This will be used for estimating infiltration).

4.2 Second Type of Experiments

In this type of experiments, the surface of sand is completely covered by a thin metal sheet and along its perimeter is sufficient amount of plastic clay is used to close any openings through which water might infiltrate. Before placing the metal sheet, the sand is adjusted to the desired slope.

One value of slope (1/100) was used in this type with which three values of constant rainfall rate (6, 8 and 10 lit/min) were used. In order to check the effect of the variability of excess rainfall rate, an experiment of complex storm of nine minutes duration was carried out. During the first three minutes, excess rainfall rate was set to be 6 lit/min. The rate was then increased to 10 lit/min. during the following three minutes. For the last three minutes, the rate was reduced to 8 lit/min.

5. Results

5.1 Estimation of Infiltration

Before computing outlet discharge, it was necessary to estimate infiltration rate during each time step. Green and Ampt method was used for estimating infiltration rate. It is assumed that all rainfall from time zero to ponding time is used only for increasing initial water content of the soil up to saturated water content. At ponding time infiltration rate equals rainfall rate. Using this initial condition and the value of the saturated hydraulic conductivity (9.6 cm/hr) and capillary drive (12 cm), the difference between initial and final water content was calculated. That value of water content difference was used to calculate cumulative infiltration at end of each time step. Infiltration rate during each time was calculated by dividing the difference between cumulative infiltrations at the beginning and at the end of any time step by the duration of the time step.

5.2 Estimation of Parameters

By checking Reynolds number of flow in all experiments, it was found that turbulent flow describes the flow more accurately. The parameter m was taken equal to 2 since for turbulant flow, the range for *m* is between 5/3 and 7/3. Parameter α was estimated using Manning's equations with a conversion factor as

$$\alpha = \frac{3.6*10^7}{(100)^{5/3}} \frac{S_0^{1/2}}{(n)}$$

where α is in units of $(\text{cm} \cdot \text{hr})^{-1}$.

5.3 Calculation of Outlet Discharge

For each time step, the calculated infiltration rate was subtracted from the rainfall rate to get the effective rainfall rate. With this value of effective rainfall rate the proposed mathematical model was used to compute outlet discharge.

A computer program was developed to compute the outlet discharge. Input data were the calculated infiltration rate, catchment length, duration of storm, time step, initial depth of water flow and values of parameters *m* and α.

Observed and computed outlet discharges are plotted versus time for rainfall rates of 6, 8 and 10 lit/min. These hydrographs are shown in Fig. 2 and 3 for slopes 1/100 and 1/200 respectively.

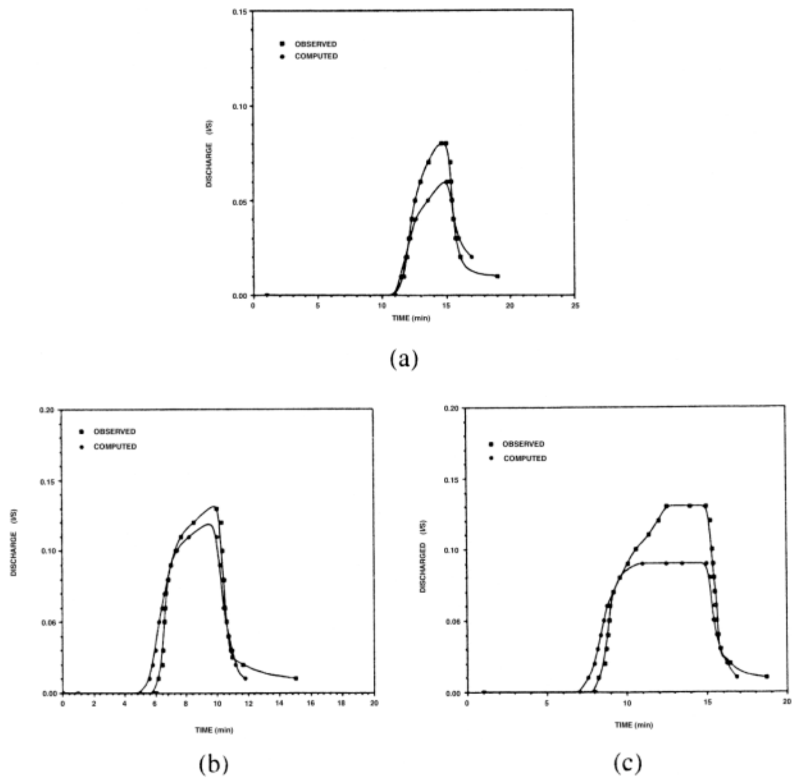


Fig. 2. Outflow hydrographs for Type I, slope (1/100): (a) r_e = 6 lit/min, (b) r_e= 8 lit/min, (c) r_e = 10 lit/min.

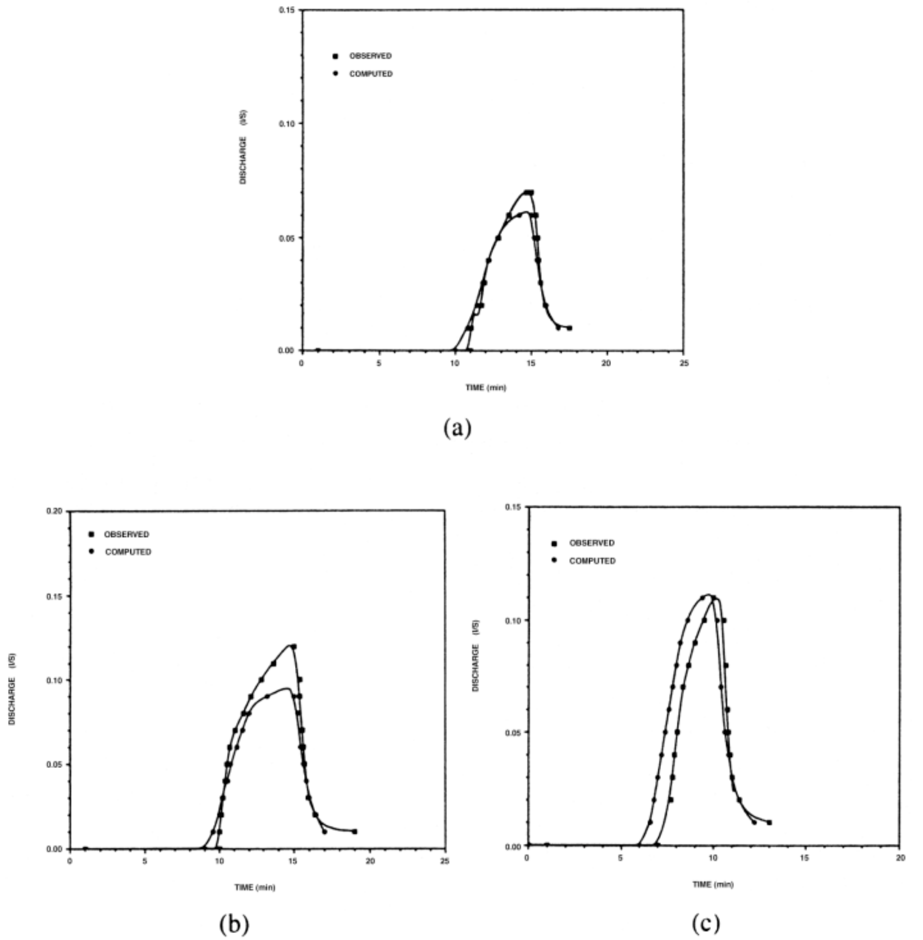


Fig. 3. Outflow hydrographs for Type I, slope (1/200): (a) r_e = 6 lit/min, (b) r_e= 8 lit/min, (c) r_e = 10 lit/min.

5.4 Experiments with no Infiltration (Type II)

For this type of experiments, only one value of slope which is 1/100 was used with the three values of rainfall rates; namely 6, 8 and 10 lit/min. Also an experiment with a complex storm was carried out in order to verify the effect of variable rainfall rate an outlet hydrograph.

5.5 Estimation of Parameters

Parameters m and α has to be estimated to use them in theoretical calculations. Parameter m was taken as 2 since flow was characterized as turbulent flow by computing Renold's number.

An equation different to Manning's equation was used to estimate parameter α. In order to create flow with no infiltration, a thin metal sheet was used which differs from a natural channel. This equation is based on measuring the time, t_x, taken by a water drop at distance x from outlet of the plane to arrive to the outlet, namely:

$$\alpha = \frac{L - x}{r_e^{m-1} \; t_x} \tag{20}$$

A certain amount of dye was added to the water at distance of 1.5 meter from the outlet and the time the dye took to arrive to the outlet was recorded. Then for each value of excess rainfall rate, a value of α was calculated using Equation (20). The average of these values was used as the value of α to be used in the model. Table 1 shows these calculations.

TABLE 1. Calibration of α for Type II experiments.

r_e (lit/min)	Observed Measured t_x (min)	α $(cm \cdot hr)^{-1}$
6	0.667	67500
8	0.533	79102
10	0.450	88793

Average value of α = 78465 $(cm \cdot hr)^{-1}$

5.6 Constant Rainfall Rate

The proposed model was used to calculate outlet discharge where infiltration was always set equal to zero. The same program was used to compute outlet discharge for this case by entering zero for the value of infiltration rate at each time step.

Results of outflow hydrographs for rainfall rates of 6, 8 and 10 lit/min and slope 1/100 are presented graphically on Fig. 4.

5.7 Complex Storm

A little modification was done to the program used in previous sections to make it capable of computing outflow discharge for the complex storm. This is achieved by considering the variation in excess rainfall instead of constant rate.

Outlet discharge versus time for the complex storm is shown in Fig. 5.

6. Discussion

For Type I experiments and for slope (1/100), observed and computed hydrograph were shown in Fig. 2. Good match between the observed and computed hydrographs can be seen from this figure. For the second slope (1/200), observed and computed hydrographs were shown in Fig. 3. Also acceptable agreements between two hydrographs were achieved. For both slopes, however, the model slightly under predicts the peak discharge.

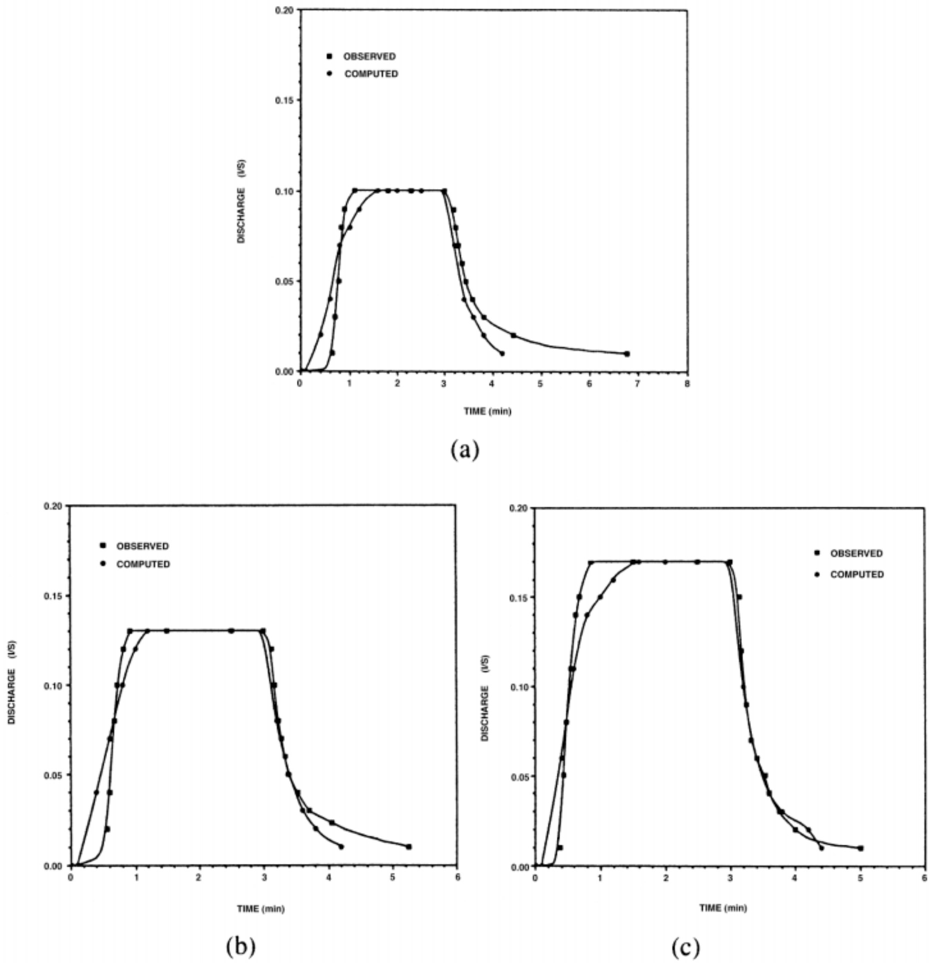


Fig. 4. Outflow hydrographs for Type II, slope (1/100): (a) r_e = 6 lit/min, (b) r_e= 8 lit/min, (c) r_e = 10 lit/min.

In Type I experiments, it is found that the model is valid better for the higher value of rainfall rate. This is may be due to the effect of infiltration which has small effect as rainfall rate increases.

For Type II experiments and as expected, validation of the model for this type is much better than that for the first type. Also for this type the validation does not depend on the rainfall rate which means that this effect was due to estimation of infiltration. Observed and computed hydrographs for slope (1/100) which were shown in Fig. 4 have shown an excellent agreement. Also in this type, effect of variability of rainfall rate on the validation of the model was tested. The model has good matching between computed and observed hydrographs for the case of variable rainfall rate as shown by the results in Fig. 5.

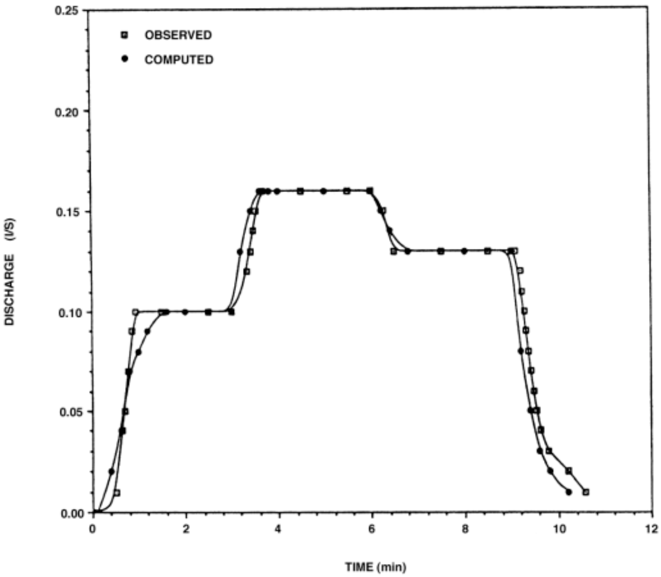


Fig. 5. Outflow hydrograph for complex storm for Type II, S = 1/100.

7. Conclusions

On the basis of the results of this study, the following conclusions can be drawn:

1) Data from experiments indicate that the proposed kinematic form for turbulent flow derived using Manning's relationship is valid and that the presented model equations can be useful tools in the estimation of kinematic parameters.

2) Experimental results suggest that the kinematic model is appropriate for runoff hydrograph prediction.

3) A good match between observed and computed hydrographs of overland flow in the case of permeable watershed were shown. However, the best match was obtained in the case of impermeable watershed where pure overland flow exists.

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تطوير نموذج للتدفق ا لسطحي مبنى على الموجات الكينماتية والتحقق منه معمليًا

صالح عبد اللّه الحسون و عبد العزيز سليمان الطرباق
قسم الهندسة المدنية ، كلية الهندسة ، جامعة الملك سعود
الريـــــاض - المملكة العربية السعودية

المستـخلص . تم في هذا البحث تطوير نموذج رياضي المعملي للتدفق السطحي ، مبني على الموجات الكينماتية ، ومن ثم التحقق منه . وقد اشتق النموذج المستعمل من نظرية الموجات الكينماتية ، أما التحقق منه فقد استخدمت فيه نتائج تجارب معملية . وقد أجريت هذه التجارب على أسطح منفذة للمياه ، وأخرى غير منفذة ، وبميول مختلفة ، وبمعدلات ومدد أمطار مختلفة ، وكان الهدف الرئيسي لهذه التجارب هو جمع معلومات يمكن استخدامها للتحقق من دقة النموذج الرياضي . وتؤكد نتائج البحث صحة نظرية الموجات الكينماتية للتدفق السطحي ، كما تبين هذه النتائج أن النموذج المطور يمكن استعماله لتقدير كميات التدفق السطحي والحصول على قيم دقيقة لتلك الكميات .