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The influence of the pattern of moving rainstorms on overland flow

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Abstract

This study emphasizes the importance of spatial rainfall intensity patterns of moving rainstorms on overland flow. A simple numerical model, based on the non-linear kinematic wave, was used for comparing the results for hypothetical storms moving up and down an impervious plane surface. Simulations were undertaken by varying the storm pattern, length, speed and direction. No account was made for time varying losses, such as infiltration, evaporation, etc. The results indicate significant differences in peak discharges and hydrograph shapes for moving storms of various patterns. The sensitivity of runoff to storm patterns decreases as storm speed increases.

Keywords: Rainfall pattern; Kinematic wave; Overland flow; Storm movement

1. Introduction

The hydraulic characteristics of overland flow are strongly related to the characteristics and spatial variability of rainfall. The areal coverage of rainfall storms may vary with their type. Some rainfall storms concentrate in a small area while others spread over considerable large areas. Heavy rainfall in small areas is caused mainly by convective thunderstorms. Rainfall intensity has a large correlation with the vertical stability of the air and also has a close relation with orographic conditions [14]. Also, rainfall is frequently generated by moving storms. The problem of storm movement affecting flows (shape of the hydrograph and peak discharges) has been recognized for a long time (e.g., [6,13,22,24]). The influence of a moving storm on the hydraulics of underlying overland flow is dependent on its direction, speed, length and pattern. Wind also affects the mean drop size, drop incidence angle and drop speed, which also can significantly affect the mechanics of overland flow (e.g., [7–10]).

Overland flow with rainfall as a source of lateral inflow can be treated as an unsteady, shallow, open channel flow problem which occurs in natural watersheds and also in urban drainage areas. Several theoretical studies have been published about Hortonian overland flow [4] generated by rainfall on slopes of various shapes (e.g., [1,5,11,16–19,21,25,27]). Some of these studies use the non-linear kinematic wave approach. Although overland flow could ideally be represented by the Saint–Venant equations, the kinematic solutions have been shown to yield very reliable results for most hydrologically significant cases [20]. Thus the kinematic wave modelling is gaining wide acceptance as a fast and accurate way to handle not only overland flow but also a wide range of water modelling problems [20]. Also, kinematic modelling can account for detailed spatially distributed dynamic representations of rainfall.

The objective of this study was to study the influence of storm pattern, with respect to storm motion, on the shape of the runoff hydrograph, time to peak and peak discharge. The storms moved up and down the plane at a range of speeds, simulating one single dry–wet–dry cycle as shown in Fig. 1.

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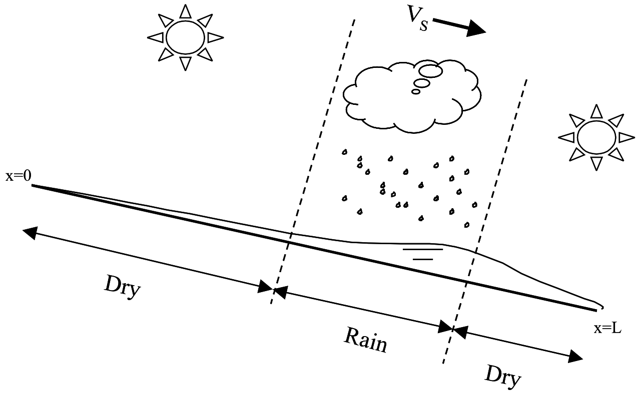

Fig. 1. Dry–wet–dry cycle on a plane due to a downstream moving rainstorm, where: V_S is the speed of the storm; x is the distance from top of field along the flow direction; and L is the total length measured along the slope.

2. Methodology

The kinematic wave theory was used to investigate the influence of storm movement on overland flow. The kinematic wave governing equation was solved numerically for moving storms on a one-dimensional runoff plane for the following situations: storm direction (downslope and upslope); storm speed (V_s from 0.5 to 5 m/s); storm length (smaller, equal and longer than slope length); and storm pattern (i.e., four hypothetical rainfall intensity patterns that were entitled uniform, intermediate, advanced and delayed, and are presented in Fig. 3).

2.1. Basic equations and numerical scheme

Any appropriate mathematical formulation of overland flow makes use of the fundamental mass and momentum equations. The equation of continuity (representing the conservation of mass) for shallow water flow (one dimension) may be written as:

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) \tag{1}$$

where h is the overland flow water depth (m), t is the time (s), x is the distance from the top of the field along the flow direction (m), Q is the discharge per unit width (m^2/s), and $q(x,t)$ is the lateral inflow or rainfall excess rate (m/s). Thus, $q(x,t)$ can, in this formulation, be varied in both space and time.

For simplicity, the following is assumed: the flow is one-dimensional; the plane is impervious; hydrostatic pressure distribution is valid across the flow depth; the surface tension forces are negligible; the variation of the momentum coefficient β along the x-direction is negligible; and the slope is small. By also assuming that the slope of the field S_o equals the friction slope S_f (kinematic wave assumption) and by using existing open-channel flow friction equations we can express the overland flow discharge at any point and time as a function of the water depth only as follows (Bakmeteff relation):

$$Q = \alpha h^n \tag{2}$$

where α is an empirical coefficient basically linked to the slope and the roughness, and n is an exponent which is also empirical.

Consequently, the overland flow discharge at the end of the plane is:

$$Q_L = \alpha h_L^n \tag{3}$$

where L is the total length measured along the slope (m).

For turbulent flow, if we use Manning's formula ($Q = k_M h^{5/3} S_f^{1/2}$), we then get:

$$\alpha = k_M S_f^{1/2} \tag{4}$$

$$n = 5/3 \tag{5}$$

where k_M is the Manning's roughness coefficient (m$^{1/3}$/s), and S_f the friction slope.

Substituting Eq. (2) in Eq. (1), the kinematic-wave equation can be written as:

$$\frac{\partial h}{\partial t} + n\alpha h^{n-1}\frac{\partial h}{\partial x} = q(x,t) \tag{6}$$

Eq. (6) is the governing kinematic wave equation which is solved using the Lax–Wendroff scheme. This is one of the most popular numerical methods for solution of the kinematic wave equations. The scheme involves a triangular approximation and is a second-order single-step numerical scheme. It can be expressed in finite-difference form as (a complete derivation of this equation is given in [20]):

$$\begin{aligned} h_j^{i+1} = {} & h_j^i + \Delta t\left(q_j^i - n\alpha \frac{{h_{j+1}^{i}}^{n-1} + {h_{j-1}^{i}}^{n-1}}{2}\,\frac{h_{j+1}^i - h_{j-1}^i}{2\Delta x}\right) \\ & + \frac{(\Delta t)^2}{2}\,\frac{q_j^{i+1} - q_j^i}{\Delta t} \\ & - \frac{(\Delta t)^2}{2}\alpha n\left[\frac{{h_{j+1}^{i}}^{n-1} + {h_{j}^{i}}^{n-1}}{2}\left(\frac{q_{j+1}^i + q_j^i}{2}\right.\right. \\ & \left. - n\alpha \frac{{h_{j+1}^{i}}^{n-1} + {h_{j}^{i}}^{n-1}}{2}\,\frac{h_{j+1}^i - h_j^i}{\Delta x}\right) \\ & - \frac{{h_{j}^{i}}^{n-1} + {h_{j-1}^{i}}^{n-1}}{2}\left(\frac{q_j^i + q_{j-1}^i}{2}\right. \\ & \left.\left. - n\alpha \frac{{h_{j}^{i}}^{n-1} + {h_{j-1}^{i}}^{n-1}}{2}\,\frac{h_j^i - h_{j-1}^i}{\Delta x}\right)\right]\Big/\Delta x \end{aligned} \tag{7}$$

where position x is denoted by j and time t is denoted by i.

For $x = L$ (the downstream boundary), a first-order scheme is employed [20]:

$$h_j^{i+1} = h_j^i + \Delta t\left(q_j^i - n\alpha\frac{h_j^{i\,n-1} + h_{j-1}^{i\,n-1}}{2}\,\frac{h_j^i - h_{j-1}^i}{\Delta x}\right) \tag{8}$$

The values of Δx and Δt were fixed during the simulation. Thus the grid system is uniform in space and time. Sufficient simulation time was allowed for the establishment of no-flow conditions after the storm.

To guarantee the stability of Eqs. (7) and (8) the ratio $\Delta t/\Delta x$ must satisfy the Courant condition for linear numerical stability [2,23]:

$$\frac{\Delta t}{\Delta x} \leqslant \frac{1}{n\alpha h^{n-1}} \tag{9}$$

2.2. Catchment geometry and physical characteristics

In this study we investigate the influence of a certain rainfall intensity pattern, fixed in time (for simplicity) and with a certain spatial extent, moving across a catchment. Ideally, this investigation of the effect of storm patterns should be undertaken for a range of physical properties of the catchment. However, we will concentrate on the rainfall intensity patterns and simplify the geometry and characteristics of the surface. Since different rainfall distribution patterns were assigned to move along the catchment, it was decided to use the simplest possible geometry for the idealized catchment consisting of an impervious plane surface (e.g., impermeable area in an urban environment; impervious hillslope plane). The plane (rectangular shape) was 100 m in length and 1 m in width (unit width) with a gradient of 10%. The plane was discretised in, at least, 20 segments. The roughness characteristics of the plane were assumed to be constant with a Manning's value of $k_M = 10\ \mathrm{m}^{1/3}/\mathrm{s}$, even during the recession of the hydrograph.

2.3. Rainfall patterns

The temporal pattern of a storm is determined by the arrangement of the rainfall intensity histogram. Storm patterns are important because they are one of the important factors determining the shape of the runoff hydrograph. Lateral inflow can be represented as a histogram in time, as presented in Fig. 2.

To evaluate the hydrologic response of storm movement, a fixed lateral inflow pattern with a certain spatial extent was considered moving in space, which induced a rainfall temporal pattern, in each Δx of the plane, depending on the speed of the storm. Arbitrary selected storm patterns of rainfall intensity used in this study are shown in Fig. 3.

For a given storm a constant spatial intensity pattern was maintained for the entire duration of the simulation (time required for the storm to cross the plane). Since one-dimensional flow was considered, the spatial rainfall intensity patterns did not vary in the direction perpendicular to the flow direction, as represented in Fig. 4, for an intermediate pattern.

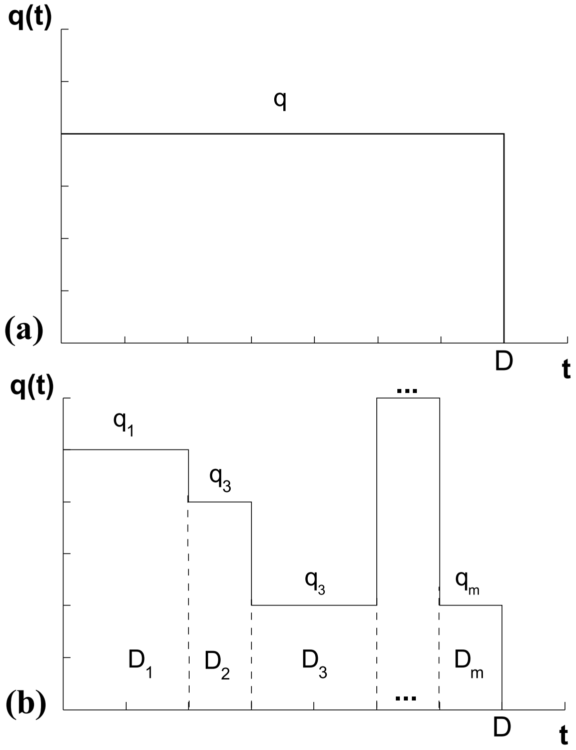

Fig. 2. (a) Histogram composed of one pulse, where D is the duration of the storm; and (b) Histogram composed of pulses. Each pulse has a different value of lateral inflow q and duration D_i ($q_i \neq q_{i+1}$, $D_i \neq D_{i+1}$, $i = 1, 2, 3, \ldots, m$) [20].

Let us consider the motion of a rectangular block storm (uniform pattern—Fig. 3) over an impervious plane surface, as represented in Fig. 5.

On the plane catchment surface (Fig. 5), the rainfall intensity or lateral inflow q, in time, is represented in Fig. 6.

The total time, the rainfall is felt on the surface (duration of the storm) from the instant the rainfall enters (at $x = 0$) until it leaves (at $x = L$) the surface, is:

$$D = \frac{(L + L_S)}{V_S} \tag{10}$$

where D is the duration of the storm (s), L is the length of plane (m), L_S is the length of storm (m), and V_S is the speed of the storm (m/s).

The total rainfall dropped on the surface by the storm moving across the plane is:

$$h = q\frac{L_S}{V_S} \tag{11}$$

where h is the total rainfall (m).

For a complex storm pattern, it is possible to decompose the storm in several rain blocks. The total rainfall is then given by:

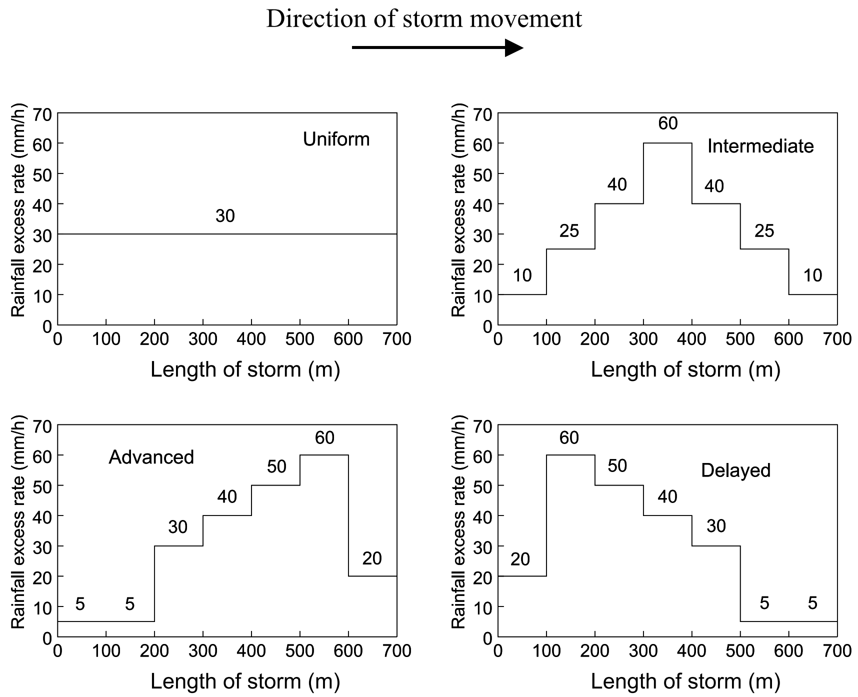

Fig. 3. Spatial rainfall intensity patterns used in this study. All the patterns produce the same amount of precipitation.

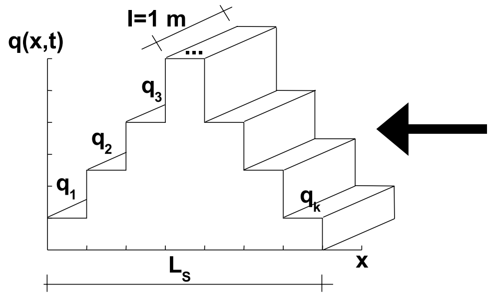

Fig. 4. Three-dimensional view of lateral inflow, per unit width, considered in the calculations (intermediate pattern—see Fig. 3).

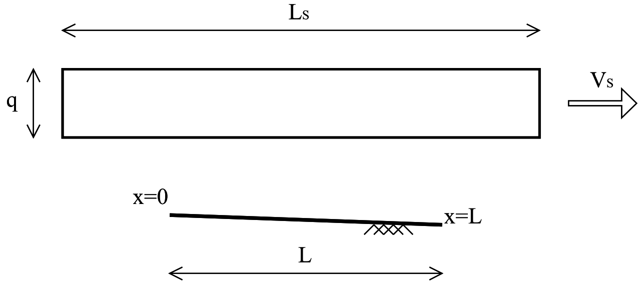

Fig. 5. Rectangular rainstorm moving across a plane (one-dimensional), at a speed of V_S.

$$h=\sum_{i=1}^{n} q_i \frac{L_{S_i}}{V_S}=\sum_{i=1}^{n} K_{q_i}\bar{q}\frac{K_{L_i}L}{V_S}=\frac{\bar{q}L}{V_S}\sum_{i=1}^{n} K_{q_i}K_{L_i} \tag{12}$$

with

$$q_i=K_{q_i}\bar{q} \tag{13}$$

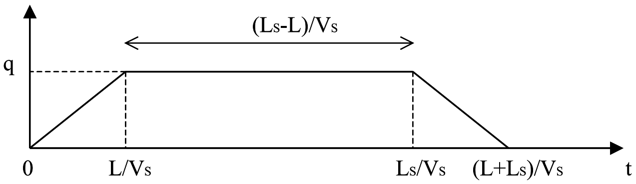

Fig. 6. Average rainfall intensity at the surface for a constant rainfall with length L_S, moving across a plane as represented in Fig. 5.

$$L_{S_i}=K_{L_i}L \tag{14}$$

where $\bar{q}$ is the average rainfall intensity (m/s), n is the number of rain blocks and K_{q_i} and K_{L_i} are coefficients.

Since the sensitivity of runoff to storm direction decreases at high storm speeds [26], which was confirmed in this study, storm speeds of 0.5–5 m/s were investigated. Storm movement was simulated by displacing a fixed rainfall pattern across the plane.

3. Results

3.1. Comparison of storms with the same average effective rainfall rate

For the 100 m long impervious plane surface, storms with different rainfall patterns were allowed to move across the plane. In order to establish the influence of spatially distributed rainfall induced by moving storms, simulations were performed with the four patterns presented in Fig. 3. Results are presented in Figs. 7–9, respectively for $V_S = 0.5$, 1 and 2 m/s, for both downstream and upstream storm movements. Summary of main results, including rainfall pattern, storm velocity, storm direction, peak discharge and time to peak, are shown in Table 1. All patterns have the same average effective rainfall intensity of 30 mm/h and, consequently, for the same storm speed they have the same amount of total precipitation and total runoff. Comparing hydrographs for the same storm speed, it is clear that slower storms generate larger differences in the hydrograph shapes, namely times to peak and peak discharges. The differences decrease for increasing storm speed. This is valid for both downstream and upstream storm directions.

When a storm is moving in the downstream direction (Figs. 7–9—top), which is also the direction of the flow, the beginning of runoff at the lower end of the plane is delayed and is dependent on both the storm speed and the surface flow velocity. When storm is moving in the upstream direction (Figs. 7–9—bottom), the time to rise is not so much dependent on the overland flow and storm speed and occurs shortly after the rainstorm enters the plane.

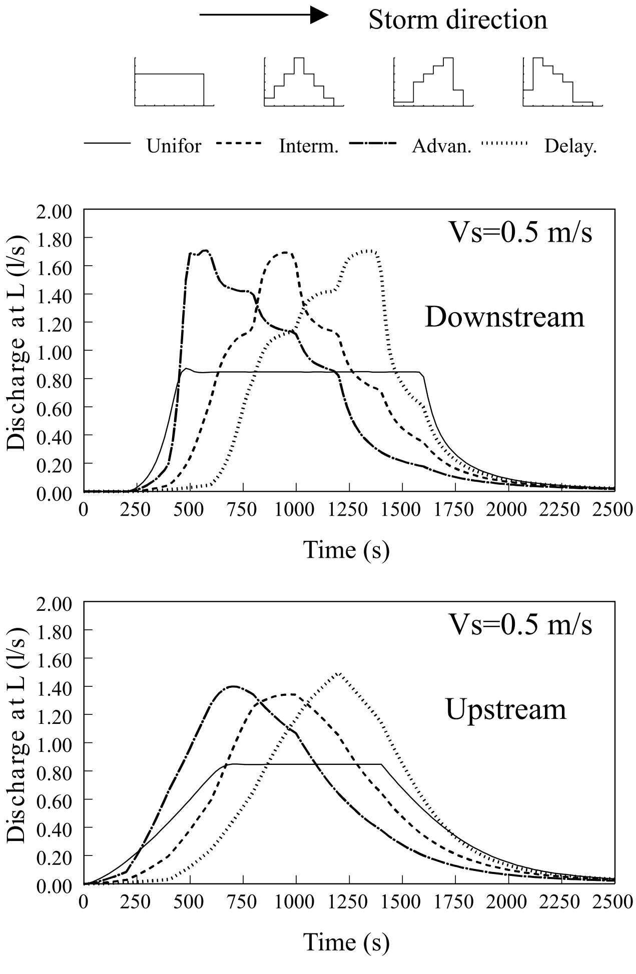

Fig. 7. Overland flow hydrographs for different storm patterns (see Fig. 3), for downstream and upstream moving rainstorms. The storm speed was 0.5 m/s.

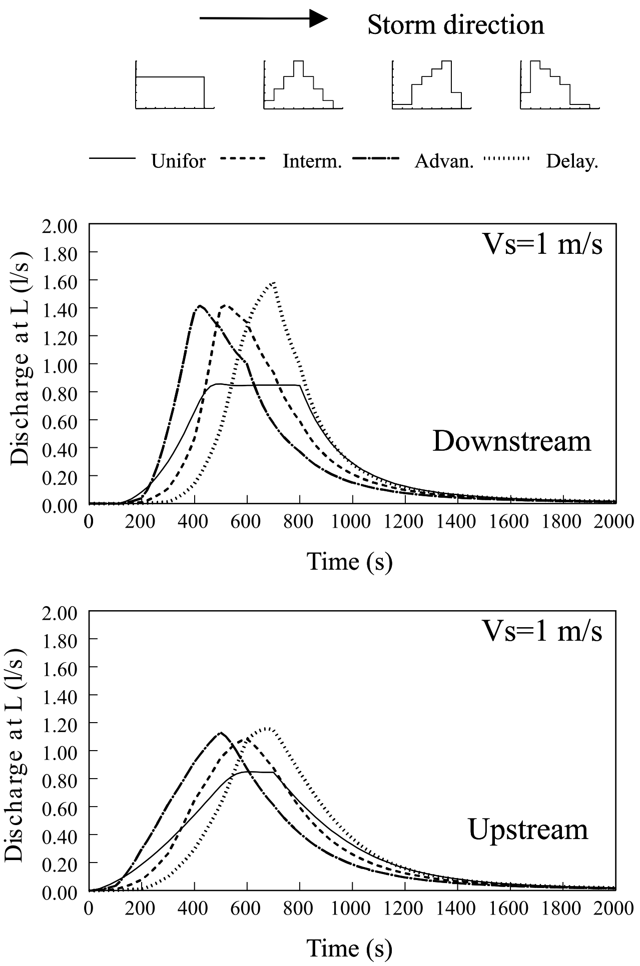

Fig. 8. Overland flow hydrographs for different storm patterns (see Fig. 3), for downstream and upstream moving rainstorms. The storm speed was 1 m/s.

Since the simulated rainfall patterns, presented in Fig. 3, were invariant, irrespective of the speed of the storm, slow-moving storms produced larger amounts of rainfall and, consequently, larger amounts of runoff volume, higher peak discharges and longer base times (Figs. 7–9).

In Fig. 10, peak discharge rates, of the hydrographs presented in Figs. 7–9, are plotted against storm speed for the four rainfall patterns.

For the uniform pattern, if rain persists at a constant rate in time and space, a steady state condition will be reached for the slower moving storms, as presented in Figs. 10 and 11. If the storm is varying in its intensity over time, which is the case of the intermediate, advanced and delayed patterns, steady state will not be reached, as shown in Fig. 12, for the intermediate rainfall intensity pattern.

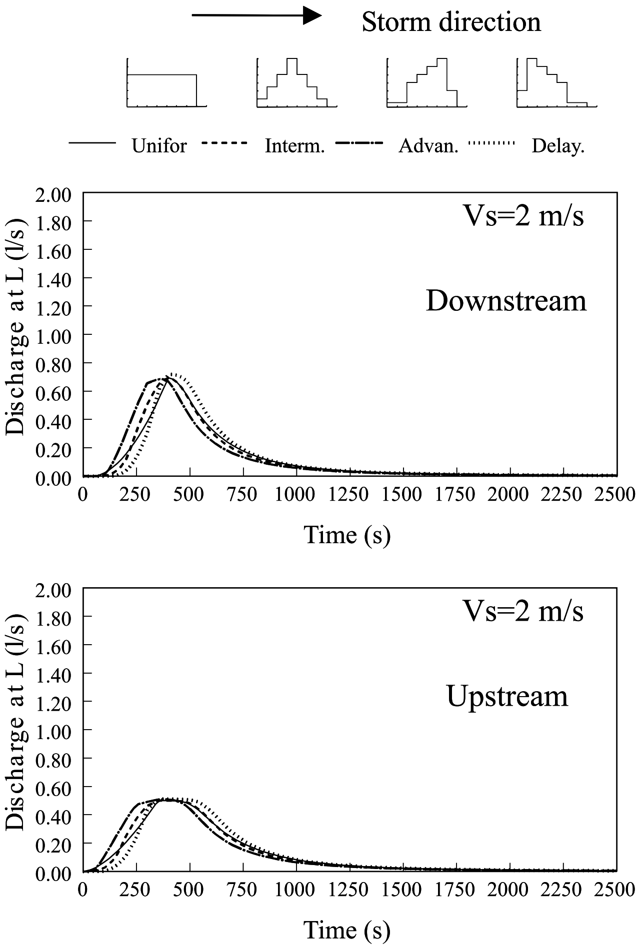

Fig. 9. Overland flow hydrographs for different storm patterns (see Fig. 3), for downstream and upstream moving rainstorms. The storm speed was 2 m/s.

Table 1
Summary of results for three storm velocities, as presented in Figs. 7–9

Storm velocity (m/s)	Direction	Hydrograph characteristics	Rainfall patterns			
			Uniform	Intermediate	Advanced	Delayed
0.5	Downstream	Q_L^{Peak} (l/s)	0.87	1.69	1.71	1.70
		t_{Peak} (s)	460	920	500	1320
	Upstream	Q_L^{Peak} (l/s)	0.85 (98%)[a]	1.341 (79%)	1.40 (82%)	1.50 (88%)
		t_{Peak} (s)	700	960	700	1200
1.0	Downstream	Q_L^{Peak} (l/s)	0.86	1.42	1.42	1.59
		t_{Peak} (s)	480	520	420	700
	Upstream	Q_L^{Peak} (l/s)	0.85 (99%)	1.08 (76%)	1.13 (80%)	1.16 (73%)
		t_{Peak} (s)	580	600	500	680
2.0	Downstream	Q_L^{Peak} (l/s)	0.69	0.70	0.69	0.72
		t_{Peak} (s)	400	400	360	400
	Upstream	Q_L^{Peak} (l/s)	0.50 (72%)	0.5 (71%)	0.51 (74%)	0.51 (71%)
		t_{Peak} (s)	360	360	340	360

[a] The percentage between brackets represents the ratio between peak discharges of upstream and downstream moving storms for a certain rainfall pattern and storm speed.

3.2. Comparison of storms with the same amount of total precipitation

Equivalent moving storms were defined by Yen and Chow [28] as storms moving at different speeds with the same duration of rainfall at each point on the watershed and identical total rainfall volume on the catchment. To maintain constant rainfall volume between equivalent storms, Yen and Chow [28] held the precipitation intensity constant and varied the size of the storms. By this definition, equivalent storms, moving at different speeds in a certain direction, must have lengths which vary in proportion to the ratio of the storm speeds:

$$L_{S_2} = L_{S_1} \frac{V_{S_2}}{V_{S_1}} \tag{15}$$

Ogden et al. [15] used an alternative definition where the size of the storm and the total rainfall volume are equal for equivalent moving storms but have rainfall intensities which vary in proportion to the ratio of the storm speeds in order to maintain constant the rainfall volume:

$$q_2 = q_1 \frac{V_{S_2}}{V_{S_1}} \tag{16}$$

In the simulations presented in this section, the total precipitation was always $h = 5$ mm. However, the same spatial rainstorm patterns presented in Fig. 3 were used (with different rainfall intensities to guarantee the same total rainfall amount). The physical characteristics and catchment geometry (rectangular plane) are the same as used in the previous simulations.

3.2.1. Equivalent moving storms of equal rainfall volume and size

Using the definition of Yen and Chow (1969), to maintain constant rainfall volume between equivalent storms moving at different speeds, precipitation intensity was held constant and the storm size was varied. In Figs. 13 and 14 the hydrographs of equivalent storms with different rainfall patterns (total precipitation of 5 mm) are compared for three storm speeds ($V_S = 0.5$, 1 and 2 m/s). Summary of main results, including rainfall pattern, storm velocity, storm direction, peak discharge, time to peak and hydrograph base time, for downstream moving storms as well as for upstream moving storms, are shown in Table 2.

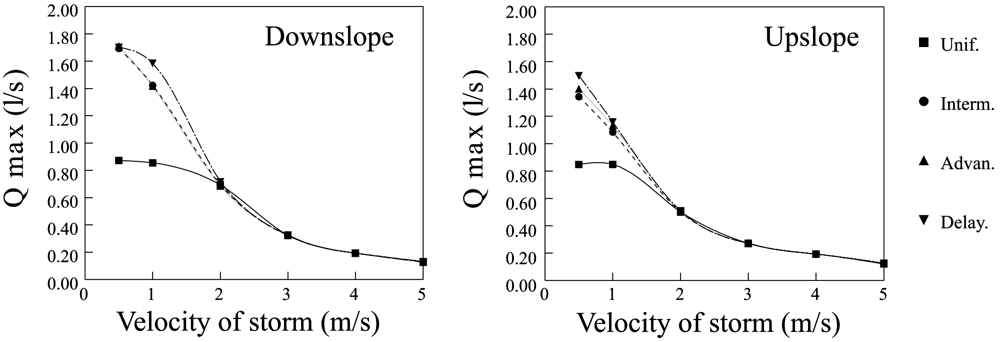

Fig. 10. Peak discharges from storms moving downstream and upstream for different storm patterns (see Fig. 3).

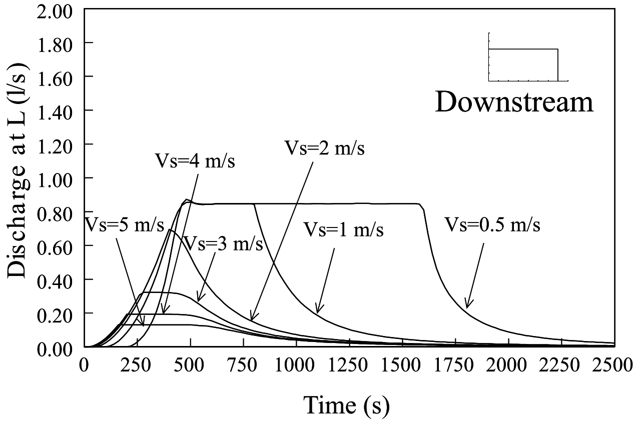

Fig. 11. Overland flow hydrographs for different storm speeds (uniform pattern, $\bar{q} = 30$ mm/h).

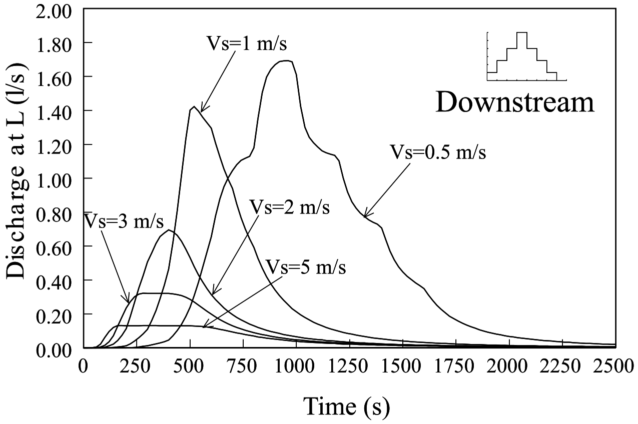

Fig. 12. Overland flow hydrographs for different storm speeds (intermediate pattern, $\bar{q} = 30$ mm/h).

A peak discharge from a storm moving downstream normally exceeds that from an equivalent storm moving upstream. Only in the case of the uniform pattern the peak discharge is equal for storms moving up and down the slope. In this case the length of the storm is sufficiently larger than the length of the plane and the steady state is reached, as illustrated in Figs. 13 and 14 (top).

For the situations studied, the downstream slow-moving storms have normally higher peak discharges, although fast-moving storms have an earlier rise (Fig. 13). The exception is the situation where the steady state is reached. The opposite situation happens for upstream moving storms (Fig. 14). It should be noted that storms of different speeds have different sizes.

The relative differences of peak discharges for equivalent storms moving in the downstream and in the upstream directions are shown in Fig. 15, for the speed of 1 m/s. A peak discharge from a storm moving downstream exceeds or equals that from a storm moving upstream.

3.2.2. *Equivalent moving storms of equal rainfall volume and precipitation intensity*

Using the definition of Ogden et al. [15], to a maintain constant rainfall volume ($h = 5$ mm) between equivalent storms moving at different speeds, the size of the storm was held a constant and the precipitation intensity was varied (i.e., rainfall intensities were chosen to ensure constant total rainfall regardless of the storm speed). In Fig. 16 (downstream movement) and Fig. 17 (upstream movement) the hydrographs of equivalent storms are compared, for $V_S = 0.5$, 1 and 2 m/s. Summary of main results, including rainfall pattern, storm velocity, storm direction, peak discharge, time to peak and hydrograph base time, for downstream moving storms as well as for upstream moving storms, are shown in Table 3.

The peak runoff discharge, time to peak as well as the shape of the overland flow hydrograph are significantly different for equivalent storms moving at different speeds. Whatever the rainfall intensity pattern, the faster is the moving storm then: (1) the higher is the rainfall intensity (to guarantee that the total amount of rainfall is constant; (2) the earlier and higher is the peak discharge; and (3) the shorter is the base time. This is valid for both downstream and upstream moving storms, as observed in Figs. 16 and 17.

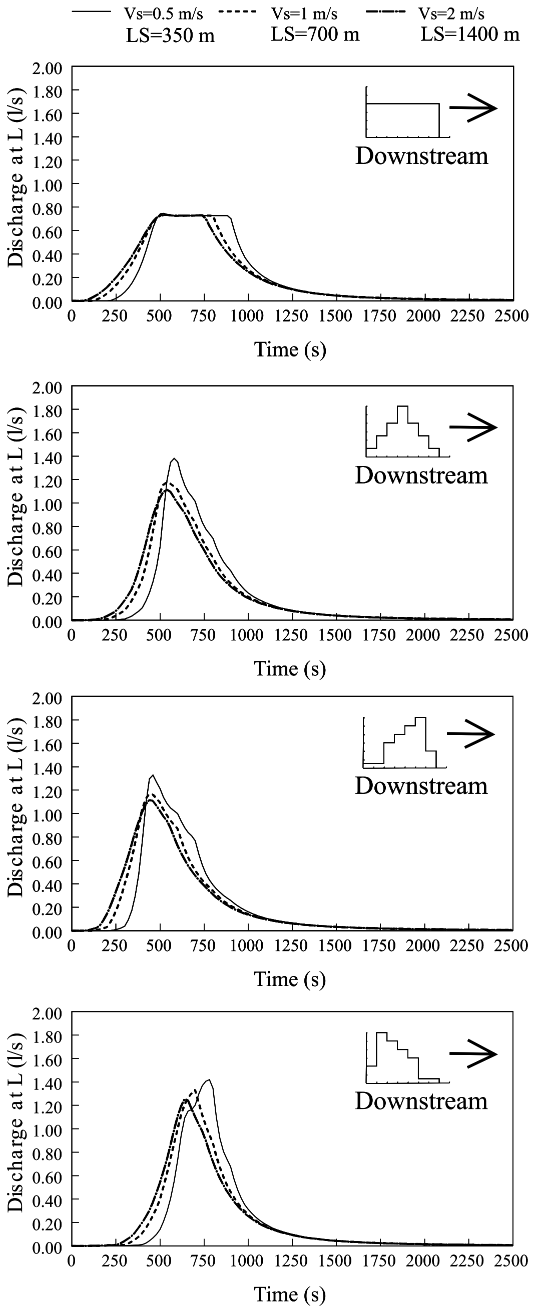

Fig. 13. Overland flow hydrographs of equivalent storms (equal rainfall volume and precipitation intensity and varying size, moving downstream at different speeds), for the uniform, intermediate, advanced and delayed patterns.

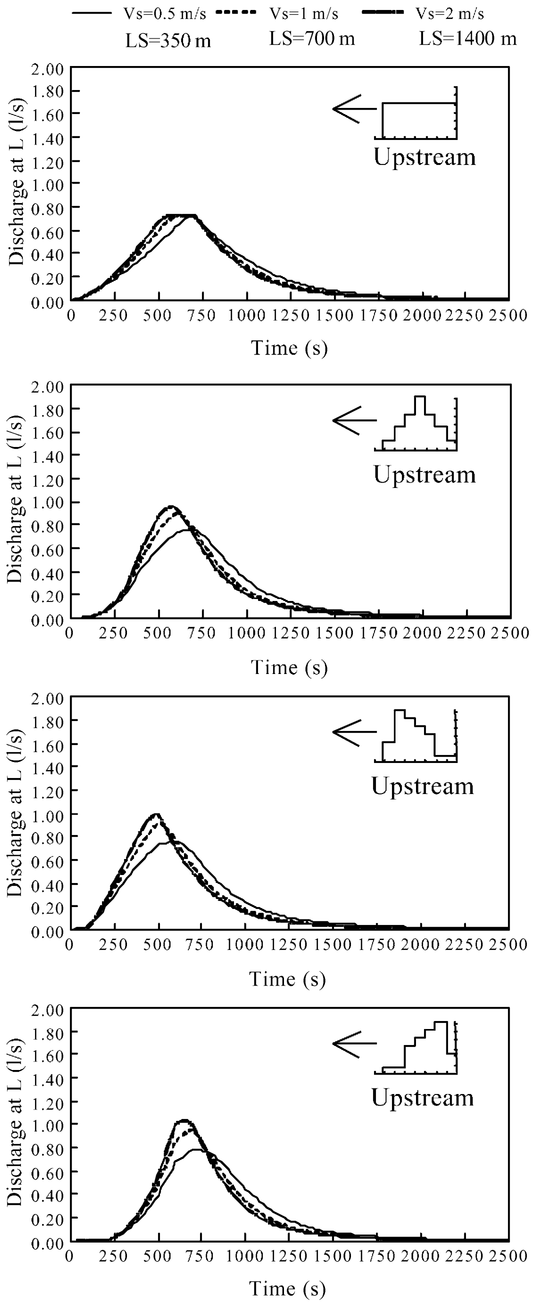

Fig. 14. Overland flow hydrographs of equivalent storms (equal rainfall volume and precipitation intensity and varying size, moving upstream at different speeds), for the uniform, intermediate, advanced and delayed patterns.

Fig. 18 (uniform pattern) and Fig. 19 (intermediate pattern) illustrate the effect of the storm direction (upstream or downstream), for equivalent storms moving at different speeds. A rainstorm moving downstream a plane produce higher peak discharges than the same storm moving upstream (or equal in the case that steady state is reached), which is strongly dependent on the storm speed.

4. Summary and conclusions

This study deals with the description of runoff from areal and temporal distributed rainstorms, with importance for urban environments or overland flow dominated catchments, because of their rapid response, which is most sensitive to variations in rainfall. The variations in runoff are investigated numerically by moving hypo-

Table 2
Summary of results for equivalent moving storms of equal rainfall volume and size, as presented in Figs. 13 and 14

Direction	Storm velocity (m/s)	Hydrograph characteristics	Pattern			
			Uniform	Intermediate	Advanced	Delayed
Downstream	0.5	Q_L^{Peak} (l/s)	0.74	1.38	1.33	1.42
		t_{Peak} (s)	520	580	460	780
		t_{base} (s)	2069	1960	1931	1887
	1.0	Q_L^{Peak} (l/s)	0.74	1.18	1.17	1.33
		t_{Peak} (s)	520	540	440	700
		t_{base} (s)	2167	2040	2030	1980
	2.0	Q_L^{Peak} (l/s)	0.73	1.12	1.12	1.26
		t_{Peak} (s)	520	540	440	640
		t_{base} (s)	2216	2092	2077	2033
Upstream	0.5	Q_L^{Peak} (l/s)	0.72 (97%)[a]	0.76 (55%)	0.75 (56%)	0.78 (55%)
		t_{Peak} (s)	700	700	600	700
		t_{base} (s)	2442	2334	2324	2275
	1.0	Q_L^{Peak} (l/s)	0.73 (99%)	0.90 (76%)	0.92 (79%)	0.96 (72%)
		t_{Peak} (s)	620	600	500	700
		t_{base} (s)	2343	2235	2224	2176
	2.0	Q_L^{Peak} (l/s)	0.73 (99%)	0.96 (86%)	1.00 (89%)	1.04 (83%)
		t_{Peak} (s)	580	580	500	640
		t_{base} (s)	2305	2197	2187	2118

[a] The percentage between brackets represents the ratio between peak discharges of upstream and downstream moving storms for a certain rainfall pattern and storm speed.

thetical storms, up and down an idealized catchment (impervious plane surface) at a range of speeds. To evaluate the hydrologic response of storm movement, four arbitrary selected fixed lateral inflow patterns (uniform, intermediate, advanced and delayed), with a certain spatial extent, were considered moving in space. The numerical simulations, using the kinematic wave equation, did not account for time varying losses such as abstraction and infiltration.

The main finding of this study is that peak discharges and hydrograph shapes depend strongly on the storm pattern. However, these differences also depend strongly on catchment characteristics and on the direction and speed of storms. The main conclusions are:

- As also concluded elsewhere (e.g., [6,12,22]), two distinct hydrologic responses are observed for storms moving upstream and downstream. Storms moving upstream are normally characterised by hydrographs with: (1) early rise, (2) low peak discharge, (3) not so steep rising limb, and (4) long base time.

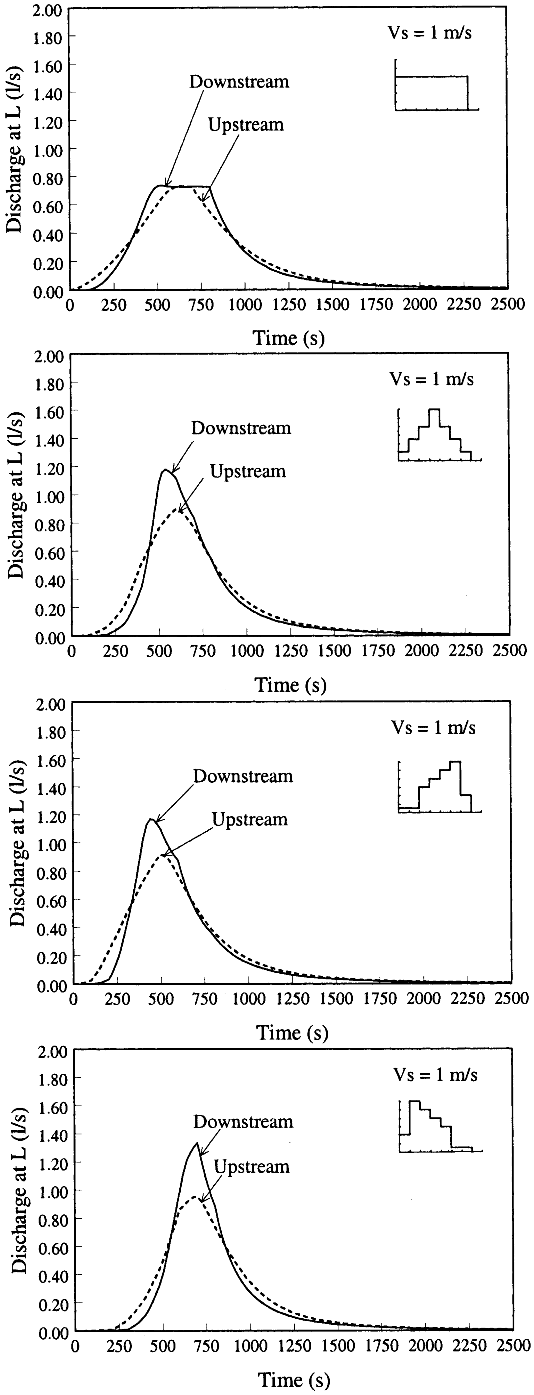

Fig. 15. Effect of storm-movement direction (upstream and downstream) on hydrographs for equivalent storms (equal rainfall volume and precipitation intensity), for storm moving at a speed of 1 m/s, for the uniform, intermediate, advanced and delayed storm patterns.

- The sensitivity of runoff to storm patterns decreases at high storm speeds. Rainfall intensity patterns are important in the hydrological response (e.g., prediction of peak runoff discharge, time to peak as well as the shape of the overland flow hydrograph) for slow moving storms.

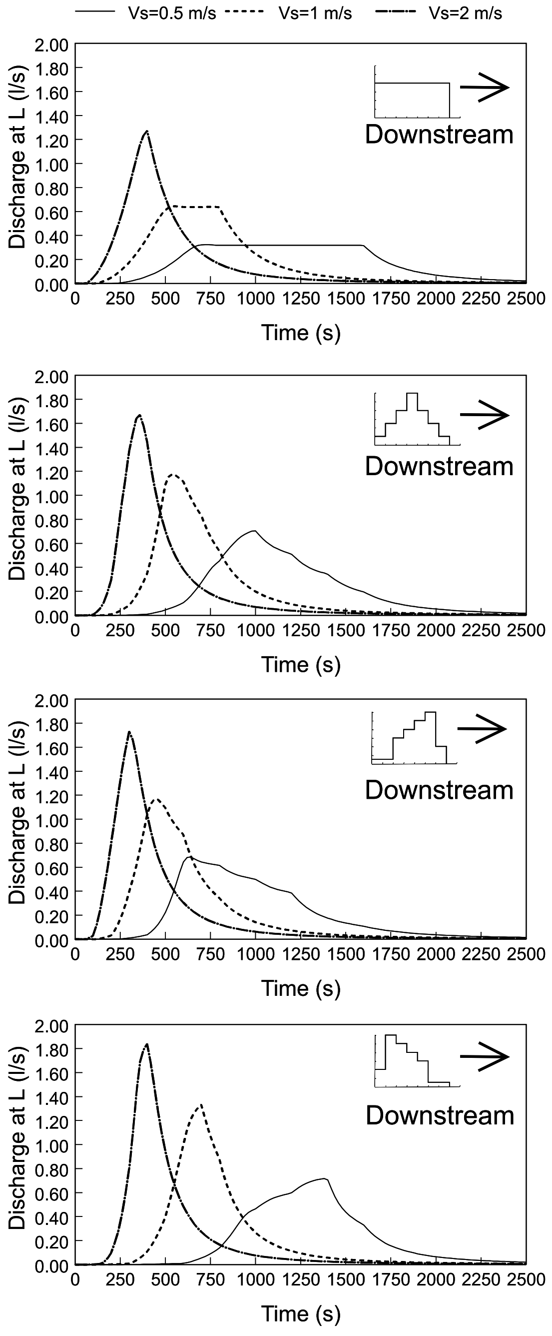

Fig. 16. Overland flow hydrographs of equivalent storms (equal rainfall volume and size and varying precipitation intensity, moving downstream at different speeds), for the uniform, intermediate, advanced and delayed patterns.

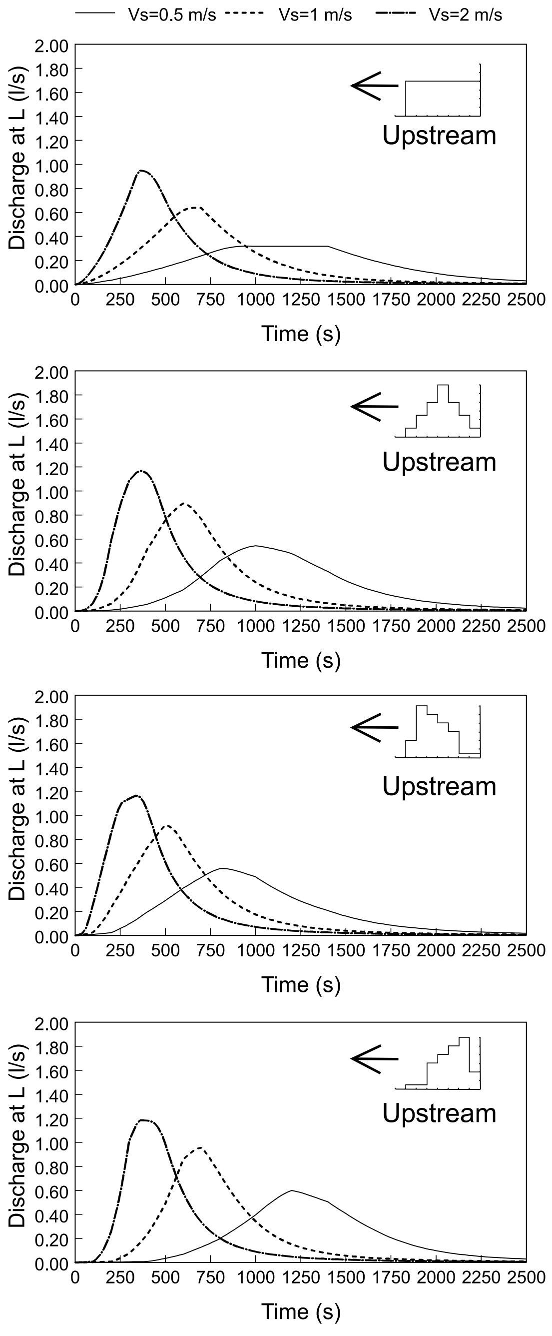

Fig. 17. Overland flow hydrographs of equivalent storms (equal rainfall volume and size and varying precipitation intensity, moving upstream at different speeds), for the uniform, intermediate, advanced and delayed patterns.

- When comparing equivalent storms, downstream storm movement presents bigger differences in the hydrograph shapes for different rainfall patterns than do the upstream movement.
- Hydrographs, times to peak and peak discharges of equivalent storms determined according to the definition of Ogden et al. [15] present significantly larger differences than those determined according to the definition of Yen and Chow (1969).

The numerical results should not be extrapolated to other situations without caution, due mainly to the assumption of the rainfall pattern (e.g., fixed pattern, independent of storm speed and direction), a very sim-

Table 3
Summary of results for equivalent moving storms of equal rainfall volume and precipitation intensity, as presented in Figs. 16 and 17

Direction	Storm velocity (m/s)	Hydrograph characteristics	Pattern			
			Uniform	Intermediate	Advanced	Delayed
Downstream	0.5	Q_L^{Peak} (l/s)	0.32	0.70	0.69	0.71
		t_{Peak} (s)	700	980	640	1360
		t_{base} (s)	2685	2500	2500	2350
	1.0	Q_L^{Peak} (l/s)	0.64	1.18	1.17	1.33
		t_{Peak} (s)	520	540	440	700
		t_{base} (s)	2140	2040	2030	1980
	2.0	Q_L^{Peak} (l/s)	1.27	1.67	1.73	1.84
		t_{Peak} (s)	400	360	300	400
		t_{base} (s)	1892	1840	1825	1817
Upstream	0.5	Q_L^{Peak} (l/s)	0.32 (100%)[a]	0.54 (77%)	0.56 (81%)	0.60 (85%)
		t_{Peak} (s)	920	1000	820	1200
		t_{base} (s)	3053	2847	2827	2710
	1.0	Q_L^{Peak} (l/s)	0.64 (100%)	0.90 (76%)	0.92 (79%)	0.96 (72%)
		t_{Peak} (s)	660	600	500	700
		t_{base} (s)	2333	2235	2224	2176
	2.0	Q_L^{Peak} (l/s)	0.95 (75%)	1.17 (70%)	1.17 (68%)	1.18 (64%)
		t_{Peak} (s)	360	360	340	360
		t_{base} (s)	1980	1933	1934	1900

[a] The percentage between brackets represents the ratio between peak discharges of upstream and downstream moving storms for a certain rainfall pattern and storm speed.

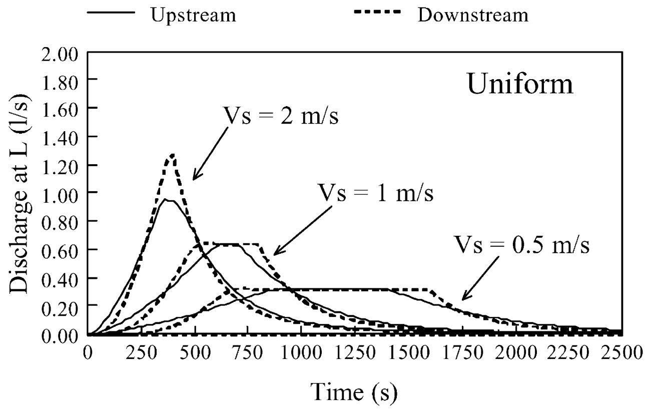

Fig. 18. Effect of direction of storm movement (upstream and downstream) on hydrographs for equivalent storms (equal rainfall volume and storm size), for storm moving at various speeds, for the uniform storm pattern.

ple catchment (e.g., plane surface) and of the numerical scheme (e.g., one-dimensional kinematic wave model).

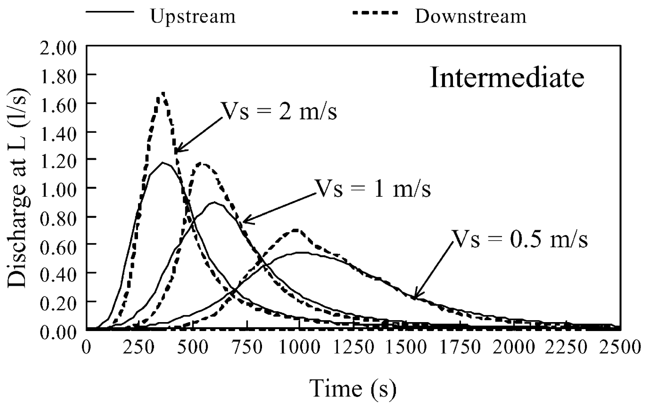

Fig. 19. Effect of direction of storm movement (upstream and downstream) on hydrographs for equivalent storms (equal rainfall volume and storm size), for storm moving at various speeds, for the intermediate storm pattern.

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