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RESEARCH NOTES

Conceptual Watershed Modeling for Direct Runoff Computations

M. R. Najafi Shahri[1]* and S. M. R. Behbahani[1]

ABSTRACT

This paper describes a simple, physically-based conceptual model utilizing watershed drainage characteristics for rainfall-runoff simulation. This conceptual physiographic model is essentially based on the work of Najafi (2003), which has led to a model comprising the main tributary subwatersheds and a single main channel subwatershed. The Kinematic Wave (KW) theory is used to describe flow over the subwatershed plans. The dynamic wave theory is applied for channel flow computations to compute the watershed responses at the outlet. The proposed model was tested on a natural watershed where the results could be compared with the results obtained by Najafi (2003). The results show the proposed physiographic model has advantages over the former in terms of mathematical formulation and input data preparation as well as computation time requirements.

Keywords: Conceptual model, Dynamic wave, Kinematic wave, Runoff computation.

INTRODUCTION

Conceptual modeling of watershed physiography is conducted in various ways for runoff computations (Singh, 1989; Todini, 1996; Najafi, 2003). Some researchers adopt lumped conceptual models (Beven, 1996) and some others may adopt distributed ones (Abbott *et al*., 1986; Refsgaard and Storm, 1995).

Among the Dynamic Wave (DW) models such as those of Choi and Molinas (1993), Lamberti and Pilati (1996), Li and Fleming (2003) and Wang *et al*. (2003) and the proposed conceptual model by Najafi (2003), the present model is a more simplified form compared even to the latter. This model requires fewer mathematical formulations and less input data. It can incorporate the distributed effects of various physiographic parameters on the watershed response through unsteady flow equations.

Governing Equations

Channel Flow Equations

In the present study, channel flow is represented by the St. Venant one-dimensional equations (Liggett and Cunge, 1975; Huang and Song, 1985), simplified for wide rectangular channels as follows:

The continuity equation

$$\frac{\partial h}{\partial t}+u\frac{\partial h}{\partial x}+h\frac{\partial u}{\partial x}=q_0 \qquad (1$$

The momentum equation

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial h}{\partial x}=g\,(S_0-S_f)-\frac{q_0u}{h} \qquad (2$$

where x= Distance measured horizontally along the channel length; h= Water surface

[1] Department of Irrigation and Drainage Engineering, Faculty of Agricultural Engineering, College of Aboureihan, University of Tehran, Tehran, Islamic Republic of Iran
* Corresponding author, e-mail: mrnajafi@ut.ac.ir

elevation measured vertically from a horizontal datum; g= Gravitational acceleration; S_f= Friction slope; S_0= Bed slope; t= Time; q_0= The lateral inflow per unit length of channel; and u= The average velocity.

Numerical solution of Equations (1) and (2) is sought over a distance-time rectangular domain. The four-point implicit scheme (Preissmann, 1961) is employed for the solution of channel flow equations. Following Newton-Raphson's algorithm (Chow *et al.*, 1988), the solution is found to this system of equations is obtained.

The Overland Flow Equations

The kinematic wave approximation to the St. Venant equations is frequently used for overland flow routing because of the equation's simplicity and ease of solution. Therefore, seeking these two advantages, a unit width of the rectangular plane is considered and the kinematic wave equation is written as

$$\frac{\partial h_0}{\partial t} + a\, m h_0^{m-1} \frac{\partial h_0}{\partial x} = q_i \qquad (3$$

where $\alpha = \sqrt{S_o}/n_o$; m= 5/3 ; n_0= Overland Manning's roughness coefficient; q_i= Lateral inflows (rainfall excess intensity); and h_0= Overland flow depth.

The second-order Lax-Wendroff explicit scheme reported by Lax and Wendroff (1960) is used for solving Equation (3). The details can be found in the work by Najafi (2003).

Proposed Physiographic Model

An attempt has been made to modify the proposed conceptual physiographic model which was reported in the work of Najafi (2003) to reduce the amount of input data, as well as the routing length and routing span, without losing the accuracy. This model consists of tributary subwatersheds and a single main channel subwatershed.

For the conceptual representation of the physiographic model considering a watershed such as Figure 1(a) the subwatersheds are delineated. The main tributaries (T_j) are identified, with j standing for the number. The corresponding subwatersheds have the areas (A_j) and so the remaining portions marked ΔA_j (total watershed area minus tributary subwatershed areas) form the main channel subwatershed.

Modeling for each of the tributary subwatersheds is accomplished as an open book type model (Todini, 1996). These are folded onto the main channel. Thus, these subwatersheds are conceptually represented through rectangular planes parallel to the main channel. The rectangular configurations have the same areas as that of the corresponding subwatersheds and lengths equal to the length of the tributaries. The placement is set from the point of confluence to the upstream of the main channel as shown in Figure 1(b)

Besides this, the main channel subwatersheds are consolidated to form a single subwatershed. This subwatershed is modeled on the lines of an open book physiographic model, with the length of the channel equal to the length of river and subwatershed area represented by two rectangular planes of equal widths on the two sides of the main channel, as shown in Figure 1(b). Now, the overland flow model can be used for computing the overland flows of the main channel subwatershed q_M as well as from the tributary subwatersheds q_{Tj}. In the overlapping portions of the planes, the lateral flows from tributaries and main channel subwatersheds (q_M and q_{Tj}) are superimposed to form the reaches (R_j) as shown in Figure 1(b). Thus, each reach (R_j) has uniform lateral inflows (q_{0j}). The distributed lateral flows (q_{0j}) are routed through the main channel using the DW theory for each unit width of the channel sections.

Furthermore, there is one consolidated main channel subwatershed in this conceptual representation, which results in drastically reducing the number of main channel subwatersheds outlined by Najafi (2003).

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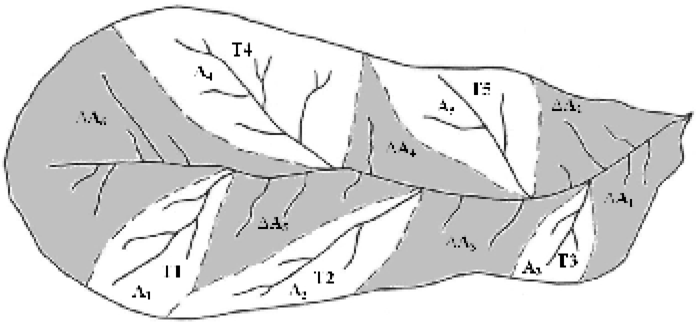
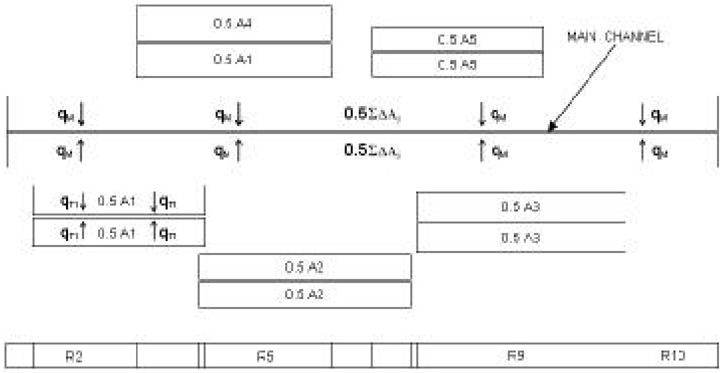


(a) Delineation of subwatersheds



(b) Conceptual representation

Figure 1. Watershed physiographic model.

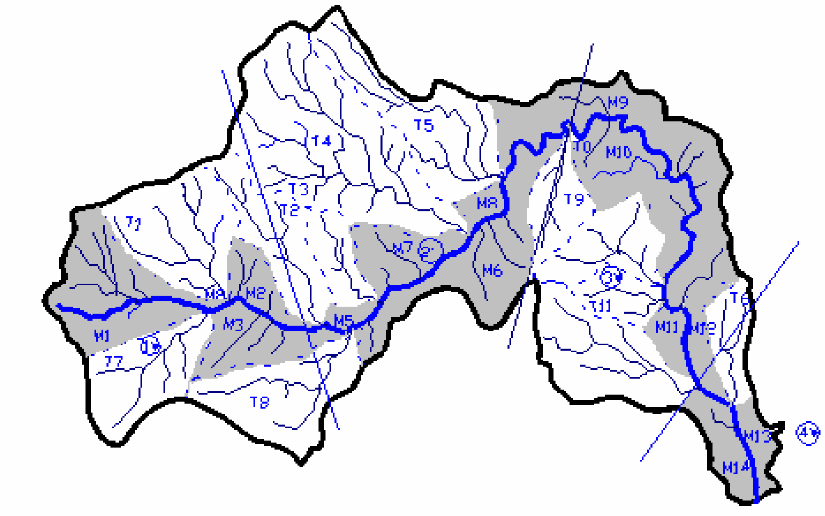
Model Application

The application of the proposed physiographic model was used to test the validity of the concepts used in model development. For this purpose, the Kolar River Watershed is adopted to utilize the results of the previous study for assessing the capability of the model, and for comparison of the results.

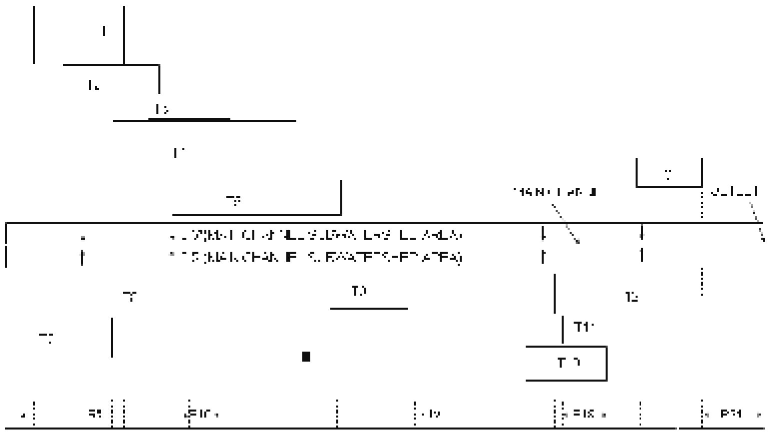
The Kolar River, 92.5 km in length, drains an area of 870.8 km^2 before joining the Narmada River at Satrana, India. The watershed is equipped with four recording raingage stations indicated as 1-4 on Figure 2(a). For the conceptual representation of the physiographic model the subwatersheds are delineated and their main tributaries are identified. The remaining portions (total watershed area minus the tributary subwatershed areas) form the main channel subwatershed. This is shown as shadowed in Figure 2(a). The physiographic parameters of these subwatersheds were adopted as reported by Najafi (2003).

The tributary subwatersheds are conceptually represented through two rectangular planes. Thus, each plane represents half of the area of the subwatershed and the length equal to the length of the drainage channel is involved. The main channel subwatershed (shadowed area in Figure 2(a)) is modeled through two equal rectangular planes of equal widths (1.875 km) at the two sides of the main channel whose lengths are equal to the length of the river (92.5 km) and the subwatershed area 346.89 km^2 as shown in Figure 2(b). The final conceptual configuration is arrived by folding the tributary subwatersheds onto the main channel. This is presented in Figure 2(b).

The rainfall excess function has been computed individually for four raingage stations located in the watershed. The areas of influence of these stations have been considered



(a)Delineation of subwatersheds



(b)Conceptual representation

Figure 2. Physiographic model of Kolar River Watershed.

to be their respective polygons. The time distribution of rainfall excess for each storm event is obtained raingage-wise by using the runoff factor for the storm and a constant rate of abstractions (Chow *et al.*, 1988) ϕ-index.

Here, the main channel subwatershed is divided among the four polygons. Therefore, the weighted average rainfall excess is computed as when a tributary is divided between two polygons. The computed rainfall excess functions are considered as lateral flows (q_i) to the overland flow kinematic wave model. Further, the overland surface runoff from different tributary subwatersheds as well as from the main channel subwatershed has also been computed. For all planes, the time step is taken as 300 s throughout the overland flow computations. The space step Δx, adopted for the main channel subwatershed is taken as 208.33 m. In regions where the overland planes of different subwatersheds

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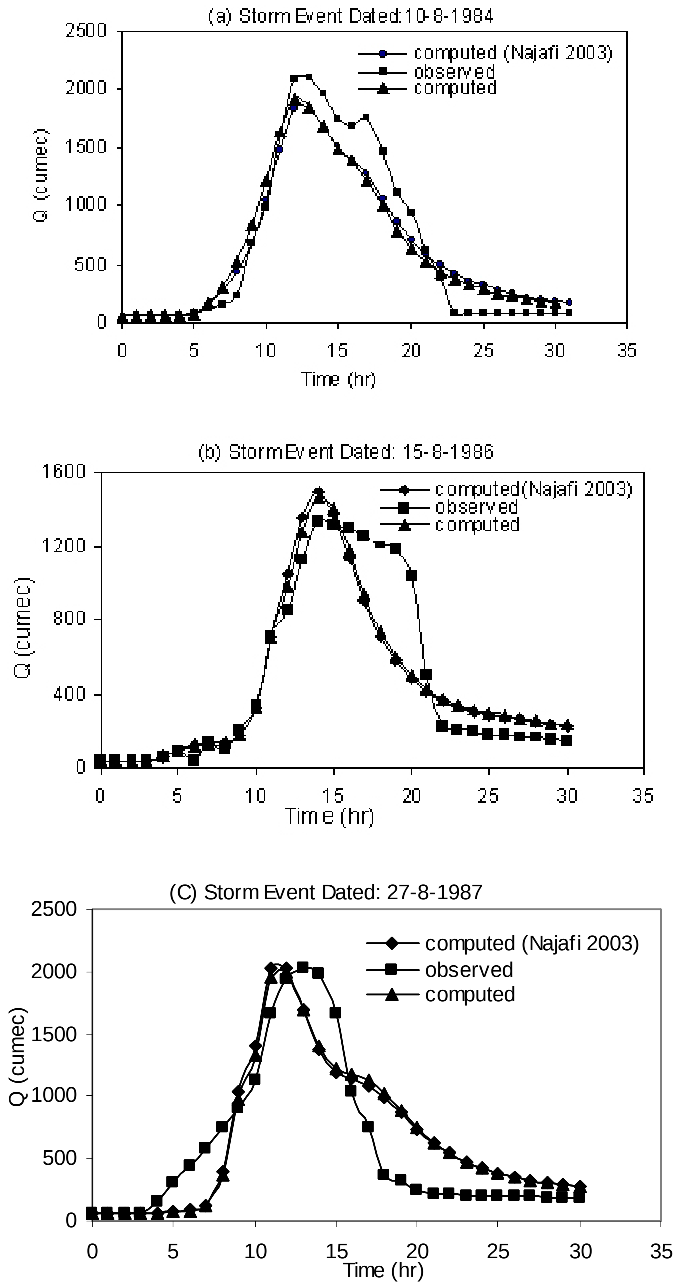

Figure 3. Comparison of the computed and the observed hydrographs.

have overlapped, the outflows are superimposed. At a time, in different stretches of the main channel different lateral flows q_{0j} are received. These stretches of the main channel, having the same lateral flows $q_{0j,}$ are identified as its reaches (R_j). Twenty-four such reaches were formed, varying from 0.5 to 9.5 km. Therefore, twenty-four q_{0j} were established as distributed inputs to the channel reaches, through which the flows are routed, by using the concepts of the dynamic wave theory.

The DW model was applied to route the flows through the main river. The model

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parameters (channel slope, channel roughness, time weighting coefficient, time step Δt, and the initial condition were taken to be the same as computed or estimated by Najafi (2003). The values of Δx were adopted according to the physiographic model developed. These values range from 500 m to 3,000 m. The channel flow computations were performed for five storm events. The comparison of the computed hydrographs and the observed hydrographs at the outlet are shown in Figures 3(a)-(c) for three storm events. Table 1 gives the values of the significant parameters (time to peak T_p, peak discharge of Direct Runoff Hydrograph (DRH) and DRH peak) of the computed and observed hydrographs as well as the values of the same parameters computed in the previous work (Najafi, 2003).

CONCLUSIONS

This research was carried out in order to develop a physiographic distributed conceptual model that is simpler in application than the model proposed by Najafi (2003). To study the effects of approximations imposed on the main channel subwatersheds, the Kolar Watershed and the same equations and mathematical formulations were typically chosen for the model's development. While applying the model to the Kolar Watershed a single main channel was formed by coalescing the fragmented areas adjacent to the main channel. Thus, fourteen main channel subwatersheds were reduced to one. Consequently, this single main channel subwatershed was divided into four subareas influenced by the four existing raingage stations. The integration of these subwatersheds converted the variable subwatershed widths into one and, subsequently, the overland routing practice was to be performed only for one length instead of fourteen main channel subwatersheds. This model reduced the number of planes receiving the same rainfall excess functions from 26 to 16-twelve tributary subwatersheds and the main channel subwatershed which is influenced by four raingages, receiving four different rainfall excess rates at the same time.

The reduction in the number of overland planes resulted in the reduction in the number of reaches receiving uniform lateral flows. However, at places in the main channel subwatershed where it is necessary to study the distributed aspects at micro level, the elemental area can be identified on the basis of drain-

Table 1. Comparison of parameters of the computed hydrographs to the observed hydrographs of the Kolar River.

Sl. No.	Storm dated	Parameters of observed hydrograph			Parameters of computed hydrograph (Najafi 2003)		
		DRH volume MCM	DRH peak cumec	Tp hr	DRH volume MCM	DRH peak cumec	Tp hr
		1	2	3	4	5	6
1	10.8.84	66.864	2027	12	65.849	1776	12
2	15.8.86	40.866	1242	14	39.567	1396	14
3	27.8.87	50.725	1898	13	53.68	1915	11

Error in prediction		Parameters of computed hydrograph			Error in prediction	
Absolute	Relative %	DRH volume MCM	DRH peak cumec	Tp hr	Absolute	Relative %
7	8	9	10	11	12	13
1.015	1.5	66.32	1859	12	0.544	0.81
1.299	3.2	39.59	1375	14	1.276	3.12
2.955	5.8	52.81	1876	12	2.09	4.11

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age characteristics and modeled accordingly.

Comparison of the significant parameters of the computed hydrographs, and the results of the same parameters in the previous work (Najafi, 2003) shows that total relative error in DRH volume in the previous model was 10.18 percent whereas in the present model it is 8.04 percent and the maximum relative error in prediction of DRH volume is 4.11 % where the same error in the previous conceptual model (Najafi, 2003) was 5.8% for the same storm event.

However, if the model is linked with the Geographical Information System, the time required for data preparation will obviously be reduced but it will still enjoy simplicity in its understanding and application.

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مدل مفهومی حوضه برای تبدیل باران اضافی به رواناب

س.م. ر. بهبهانی و م. ر. نجفی شهری

چکیده

در این مقاله یک مدل مفهومی ساده و مبتنی بر خصوصیات فیزیکی حوضه آبریز برای شبیه سازی باران-رواناب پیشنهاد شده است. این مدل فیزیوگرافی ساده به طور اساسی در ادامه کار قبلی (Najafi, 2003) بوده و مدل جدیدی متشکل از یک زیرحوضه برای رودخانه اصلی و زیرحوضه‌های سرشاخه‌های رودخانه می‌باشد. تئوری موج دینامیک برای محاسبه جریان رودخانه و محاسبه پاسخ حوضه در خروجی استفاده شده است. مدل پیشنهادی روی حوضه‌ای طبیعی آزمایش شد که بتوان نتایج را با نتایج منتشر شده (Najafi 2003) مقایسه کرد. نتایج نشان می‌دهند که مدل ارائه شده در مقایسه با مدل معرفی شده قبلی از نظر مدلسازی ریاضی، آماده‌سازی داده‌های ورودی و زمان لازم برای انجام محاسبات برتری دارد.

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