The Effects of Space Averaging on Rainfall-Runoff Analysis

by

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The effects of space averaging on rainfall-runoff have been shown through a proposed physical based model in comparison with another model which suffers from a clear cut between the physical and conceptual models as well as a third method. The results of this study show that space averaging influences the generated runoff. The results of the proposed model show the spatial occurrence of a virtual storage depression throughout the basin. Data acquisition and the tediousness as well as the tremendous job required are one of the drawbacks in modeling the rainfall-runoff relationship. In this study unconventional approach has been used for the data acquisition using the GIS data utilizing data processing. This method proved to be very useful in getting the input data of the model, nevertheless, checking the accuracy of the obtained runoff using GIS becomes necessary.

1. Introduction

Modeling of rainfall-runoff of the watersheds in most of the cases can be classified into two major categories in the broad sense. The first one is the conceptual based, while the second is the physical based model. These models to ascertain degree involve different assumptions. These assumptions usually vary in accordance with the degree of the sophistication as well as the purpose of the model (Yen, 1993). Numerically, the first one has its own merit and was the building blocks for the second one earlier than 1970's. It is only when the first category could not cope with some of the questions by that time and onward in relation to the real happening of the physical process, as well as the reliability of the parameters involved in the models within the watershed, the second category started to grow in demand (Abbott et al, 1986a).

The physical based models grew also due to the increase in environmental problems which were started to be recognized in many countries within the watersheds which in turn affected the quantities and the qualities of the water. Thus, this recognition led to the realization that the spatial and the temporal variation within the watershed could only be represented through the physical models wherein the parameters of the model could be close to the actual process of the rainfall-runoff phenomena within the watershed (Dunne, 1983, Abbott, 1986a). Furthermore, Dunne (1983) pursued in pointing out that prediction of the changes in the quantity and the quality through modeling increased the needs in understanding other characteristics of runoff as well. However, one must remember that the input data of the physically based models for the watersheds are laborious and a lot of data are needed. Indeed, it is one of the disadvantage of the physical models in contrast to the conceptual one. On the contrary, the accuracy of the model is more reliable since it describes the natural process to a closer picture from physical point of view (Noguchi, *et al*, 1991). Moreover, depiction or representation of the exact shape of the subchatchments as it is in the natural state is very rarely met in modeling the

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rainfall-runoff relationship in conceptual models. That is even also true for some of the models which are classified as a physical model even though they do not meet this criteria. It is because of the numerous factors involved in the rainfall-runoff phenomena the above criteria is sometimes being neglected. Therefore, in this paper, the spatial average is investigated to show the effects on the produced runoff through a proposed two dimensional model for the overland flow using finite difference scheme applied to orthogonal grid over the whole basin. The results are compared with those obtained Kinematic Wave model and the Unit Hydrograph Method (UHM). The input data of the physical models are cumbersome as mentioned above. Thus, unconventional approach has been used here using Geographical Information System (GIS) data to get the input data (as it is explained in the methodology section) of the basin through data processing utilizing the Personal Computer (PC). The approaches together with the proposed 2-D model were applied to Honmyo River Basin in Isahaya City for application purpose.

2. Methodology

The tremendous input data needed for the physical models are one of the drawbacks in the simulation of rainfall-runoff. This is because of the nature of the spatial and the temporal variation within the watershed. The input data for any physical model could be obtained from different sources such as the topographical maps, published researches, field observation and experimental data etc. Obtaining these input data are a very laborious job. The amount of the input data will depend mainly on three factors as follows:

1) The degree of assumption involved in the mathematical part of the model

2) The sophistication of the model based on the different aspects of the heterogeneity of the basin and being involved in the model, and

3) The size of the basin being studied

On one hand, involvement of some or all of these factors will either decrease or increase the amount of the input data. However, on the other hand, the tediousness of the job required in getting these input data has not been changed, and if there is any, it is just a slight one as far as a real basin is concerned. Hence, and in this research to overcome part of these difficulties in getting the input data, a different approach than those mentioned above in getting the input data has been introduced. The approach which was used here is to produce and handle the input data through the PC. The methodology employed utilizes the GIS data. The GIS data were obtained from Japan Map Center in the numerical-form on a magnetic tape. These data were transferred into floppy diskette, then data processing was followed using the Personal Computer. Here, it should be mentioned that the format of the stored data of the magnetic tape has been changed into a new one. That is because the current magnetic tape format needs a huge region to store the data. Through data processing the image of the total area where the basin is located was drawn on the PC screen or the CRT. From this image a delineation of the watershed was determined. Furthermore, via data processing the image of the area in three dimensional also can be drawn on the CRT as shown in Fig. 1. At this point, and based on the three dimensional image the ground elevation which was used in the input data for the whole basin could be obtained also using data processing. Table 1 shows the obtained ground elevation. For the computational methodology, the proposed 2-D model can handle the watershed data in two ways. The first computation in this research uses an orthogonal grid to represent the area of the watershed in simulating the runoff which uses the obtained ground elevation in Table 1. Delineation of the watershed in this first computation is being determined automatically in the model due to the fact that the water flows naturally through the meshes terrain. The outline of this model will be discussed on the succeeding section. The results of this model are then compared with a previous study and a third method using the UHM to show the effects of the space averaging on the produced results. The model which was used on the previous study is a modified model of the Kinematic Wave method (KW). The first two authors have already reported the

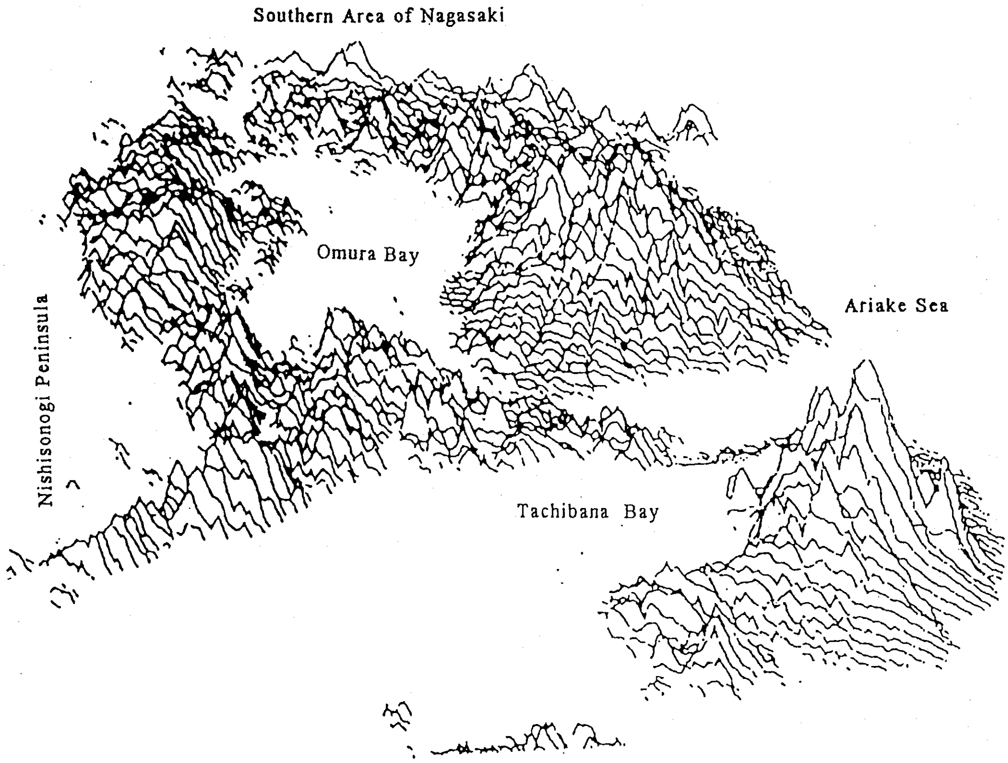

Fig. 1 The three dimensional Image using GIS data.

Modified Kinematic Wave Model (MKWM), which can estimate the subsurface runoff as well as the surface runoff (Tahat and Noguchi, 1993). Details of the study will not be repeated here. It is just for the purpose of this paper, wherein comparison is needed, it is important to point out the result obtained here by the KW is just for surface runoff. Another point is that most of the researchers consider the Kinematic Wave (KW) as a physically-based model even though that the subcatchments of the watershed are being averaged and usually of a cascading type (see Fig. 2). The real areas of the subcatchments are represented as a square or rectangular shape not depicting the original or the natural state of the real subcatchments.

The second computation of the 2-d overland flow model handles the input data for the boundary grids areas considering the watershed only in which the delineation of the watershed is based on the drawn basin through the digitizer.

3. Outline of The Overland Flow Model

The proposed overland flow model is a two dimensional model which estimates the surface runoff using an orthogonal grid for the whole watershed. The model uses the continuity and the momentum equations, described as follows;

$$\frac{\partial h}{\partial t}+\frac{\partial M_\nu}{\partial x_\nu}=r \qquad (\nu=1,\ 2) \tag{1}$$

$$\frac{\partial M_\mu}{\partial t}+\frac{\partial}{\partial x_\nu}\left(\frac{M_\mu M_\nu}{h}\right)=-gh\frac{\partial H}{\partial x_\mu}-\frac{\tau_{\mu b}}{\rho} \qquad (\mu,\ \nu=1,\ 2) \tag{2}$$

Where, h is the water depth, M_μ is the x_μ-component of the discharge flux per unit width; r is the rainfall intensity, H is the water stage, $\tau_{\mu b}$ is the x_μ-component of the frictional stress on the bottom; g is the acceleration of gravity; ρ is the density, and x_μ and t are the spatial and temporal variables, respectively.

The frictional stress was evaluated as the following;

Table 1 Ground elevation of the orthogonal grid using GIS data via data processing

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	230	114	190	260	370	490	540	510	390	460	570	680	690	700	740	780	820	790	760	700	770	870	1030	950
2	120	120	250	380	380	490	470	480	370	460	610	710	730	790	840	830	870	810	820	780	770	820	900	990
3	110	150	210	310	390	500	350	320	370	470	650	630	680	780	750	790	810	720	830	800	740	800	840	980
4	120	130	160	230	380	400	260	330	380	480	610	600	720	700	690	750	760	700	770	790	700	770	780	940
5	210	210	170	180	270	240	300	400	450	460	540	610	640	610	650	770	630	630	790	810	680	700	780	920
6	270	280	250	200	200	250	300	350	450	440	530	660	620	600	690	730	630	610	740	740	640	650	760	820
7	310	340	310	300	330	310	380	430	400	480	540	620	580	620	670	640	540	590	720	680	580	650	730	750
8	330	350	360	350	330	370	410	410	380	440	520	540	510	580	650	590	480	640	730	610	570	690	760	710
9	320	320	350	380	400	380	400	340	400	410	490	520	460	560	610	520	450	540	630	550	580	680	700	660
10	280	320	340	350	390	370	370	300	370	400	390	530	470	560	560	480	430	550	520	500	540	620	640	560
11	300	310	340	350	350	360	370	330	350	330	470	440	490	530	510	440	450	520	490	460	590	590	610	530
12	280	310	310	340	330	330	300	290	320	370	470	470	480	490	510	360	430	510	400	510	560	550	580	580
13	300	310	320	330	310	320	220	320	260	360	410	360	430	460	450	360	410	430	390	480	530	500	560	510
14	290	290	310	320	310	260	200	320	240	320	310	280	420	410	360	290	400	360	400	490	490	490	490	470
15	290	300	290	300	310	250	220	280	200	240	240	320	360	320	300	310	390	320	400	480	470	470	460	470
16	270	300	300	305	300	260	180	210	210	230	320	410	340	240	240	390	250	370	420	470	440	460	420	450
17	270	280	290	300	290	280	280	210	200	230	300	320	260	230	330	380	330	360	410	410	410	430	360	430
18	260	260	280	290	290	270	190	210	180	220	280	280	180	280	350	360	300	330	390	380	410	410	320	380
19	250	240	260	280	260	250	150	210	260	230	260	230	190	320	330	360	330	280	370	360	410	380	290	310
20	230	210	240	270	240	250	150	150	180	250	260	160	220	300	310	340	320	250	350	340	380	370	260	250
21	200	210	240	250	210	230	150	140	240	220	200	160	240	300	310	320	250	250	320	330	370	330	300	200
22	210	180	200	230	190	230	120	170	250	220	140	190	280	279	280	310	250	230	290	300	360	260	240	190
23	210	150	190	220	190	220	109	180	200	180	140	220	270	280	290	310	270	210	250	270	340	300	250	220
24	180	130	170	210	210	190	102	200	160	128	170	260	270	240	290	300	270	170	220	260	330	290	220	240
25	180	160	190	190	200	180	96	190	108	160	220	230	250	220	280	300	290	200	220	240	320	270	250	170
26	165	130	190	196	170	180	89	110	130	200	220	240	250	230	230	290	280	230	150	230	310	290	210	220
27	160	100	180	170	150	150	86	90	190	190	220	250	250	240	190	270	250	230	150	210	250	260	240	190
28	160	80	170	150	170	150	85	150	140	200	200	220	240	240	160	250	240	220	130	230	230	230	210	190
29	140	70	160	160	165	130	85	150	170	180	220	220	210	220	160	210	240	220	120	210	220	210	190	170
30	140	60	130	150	160	130	78	110	140	190	200	220	220	200	160	180	210	200	110	190	200	190	190	160
31	130	60	120	140	140	120	72	160	160	180	180	180	180	190	140	190	230	180	140	150	190	180	170	170
32	70	70	120	130	120	90	70	100	180	170	170	170	160	150	140	200	200	180	160	110	160	170	170	160
33	40	110	100	110	80	90	70	140	170	170	160	160	150	140	150	180	180	170	140	110	130	170	160	130
34	50	100	90	70	115	80	70	140	140	150	160	160	150	100	150	150	150	190	150	80	120	160	150	130
35	50	90	80	80	110	60	80	140	110	150	160	140	150	80	130	170	120	170	150	70	110	150	130	130
36	60	110	70	80	100	50	90	140	100	120	140	150	150	80	140	150	140	150	130	70	90	130	110	120
37	130	110	100	60	60	55	80	120	90	120	140	140	140	70	120	120	130	140	110	60	100	130	100	100
38	110	170	130	100	60	48	90	90	70	120	120	130	110	80	150	140	120	120	130	50	110	110	60	80
39	170	180	180	160	120	42	80	80	70	100	80	110	70	130	140	110	110	110	110	48	100	50	80	50
40	210	190	220	190	120	50	60	50	60	90	70	80	40	120	120	80	120	110	120	40	90	70	80	30
41	170	230	190	170	120	50	38	40	50	60	90	50	40	90	120	60	110	100	110	60	50	70	70	50
42	150	190	150	140	130	80	50	33	30	30	100	40	40	90	100	50	110	100	100	80	20	70	50	55
43	60	130	170	110	80	60	70	40	27	20	60	60	40	80	100	50	90	90	80	90	30	50	40	42
44	90	80	140	100	50	40	64	60	50	20	20	70	50	80	60	70	70	70	86	80	40	10	10	20
45	30	40	80	50	50	50	58	60	68	20	20	40	30	70	80	30	60	50	70	70	60	18	20	10
46	20	20	50	50	20	60	60	60	68	60	20	20	50	60	60	40	30	40	60	50	50	20	5	5
47	10	20	10	30	30	40	50	60	47	50	20	10	30	60	50	30	30	30	50	30	40	30	4	2
48	9	10	10	40	40	30	50	40	50	50	20	15	15	50	40	19	40	19	40	40	30	20	8	5
49	30	10	10	60	20	10	40	50	40	30	20	12	11	50	40	20	18	10	20	30	20	10	5	3
50	50	20	3	50	10	30	30	45	39	20	20	13	8	50	30	10	20	10	30	20	4	10	3	3
51	60	4	5	11	5	30	28	41	34	20	20	15	8	30	40	8	10	4	7	7	5	3	3	1
52	5	4	4	4	30	30	20	30	20	40	40	10	8	40	30	20	9	4	4	4	4	4	4	3
53	0	4	4	4	4	20	30	30	20	40	20	10	8	10	30	20	4	4	4	4	4	4	3	2
54	0	1	5	10	10	20	30	20	20	80	30	20	15	8	10	8	8	4	4	4	4	3	3	2

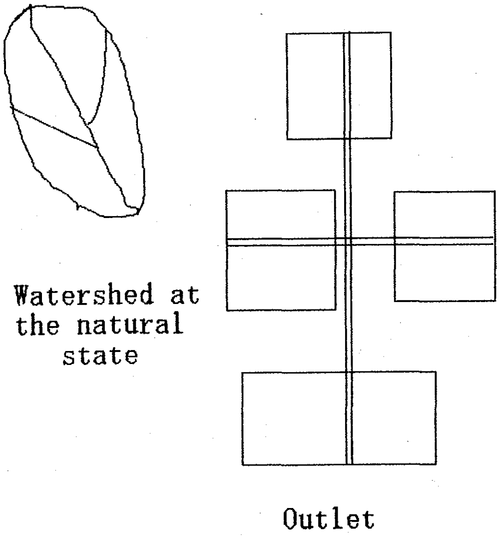

Fig. 2 The usual cascading type of the KW.

$$\frac{\tau_{xb}}{\rho}=gn^2\frac{\sqrt{U^2+V^2}}{R^{1/3}}*U\cong gn^2\frac{\sqrt{U^2+V^2}}{h^{1/3}}*U \quad (3)$$

$$\frac{\tau_{yb}}{\rho}=gn^2\frac{\sqrt{U^2+V^2}}{R^{1/3}}*V\cong gn^2\frac{\sqrt{U^2+V^2}}{h^{1/3}}*V \quad (4)$$

Here, R is the hydraulic radius; n is the Manning roughness coefficient; U and V are the x_1 − and x_2 − components of the velocity, respectively.

Equations 1 and 2 were numerically analyzed in an explicit finite difference scheme. In the above computation 5 seconds interval was used together with a spatial grid of 292 m in longitude by 231 m in latitude, satisfying the Courant-Friedrichs-Lewy stability condition.

4. Application of The Model

For application of the model as well as the methodology employed, Honmyo River Basin in Isahaya City, Nagasaki Prefecture, was taken as a case study. The western part of Japan where this basin is located is frequented with heavy rainfall causing floods and severe damages to the area (Iwasa *et al*, 1986). Furthermore, this study is still going on for further precession of the model and improvement in the methodology. Thus, a hypothetical short rainfall event is used for the purpose of the reduction in the computational computer time. Nevertheless, simulation using the proposed 2-d model of the overland flow and the above mentioned methodology was carried out for Honmyo River Basin in which the whole basin was covered with an orthogonal grid of the above mentioned size as shown in Fig. 3. Results of the computation are shown and discussed in the following section.

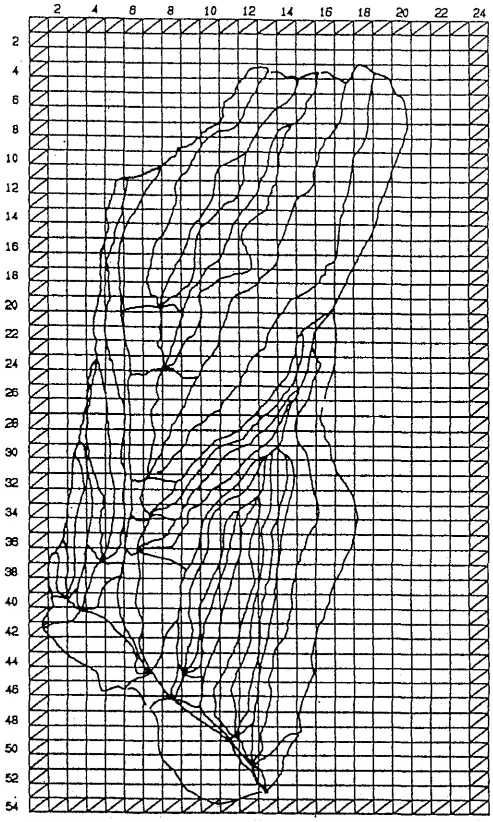

Fig. 3 The watershed understudy covered with the orthogonal grid.

5. Results and Discussion

The proposed 2-d overland model estimates the surface runoff in accordance with Freeze definition (1972). As it was mentioned in the methodology section two ways of computation were pursued in the model. The first is that the delineation of the watershed is determined automatically through the orthogonal grid of 24 by 54 meshes. The result of this computation is shown in Fig. 4. This Fig. shows the spatial velocity distribution of the surface runoff. While the second computation is that, the grids of the watershed only is considered, the boundary grids can be handled by the model through the input data. The results of the spatial distribution of the velocity of the second computation are shown in Fig. 5. A closer look at these results in the two Figs. 4 and 5 shows that the surface runoff path seems in a very good agreement with the rivers path and following the terrain of the topography. In spite of this good agreement, Fig. 6 shows the results of the hydrographs obtained by the proposed overland model, the KWM and the UHM using the same hyetograph of rainfall event at one main outlet of the basin. From this Fig. 6 it is obvious that the peak discharges and the lag times are not in a good agreements even though the KW is considered as a physical based and the overland flow model is also a physical based one. This result is interesting one and needs to be scrutinized. For this reason the spatial water depth over the basin was drawn. Fig. 7 shows the water depth spatially over the basin using the orthogonal grid. Inspection of this result shows that the water depth is varying based on the topography of the basin. In another words, virtual depression storage is occurring spatially over the basin. Again, inspection of the results of the hydrographs in Fig. 6 shows also that the peak discharge and the lag time by KW is the highest and the least respectively. The peak and the lag time by the UHM is also higher and a little delayed than those obtained by the 2-d model. These differences can be attributed to the fact that rainfall which falls over the subcatchments of the basin are completely routed to the outlet in a shorter time without consideration to the spatial variation such as those obtained by the 2-d model and reflected in Fig. 7. We can also explain the difference in the hydrographs in Fig. 6 which could be due to the spatial irregularities of the ground-surface, where

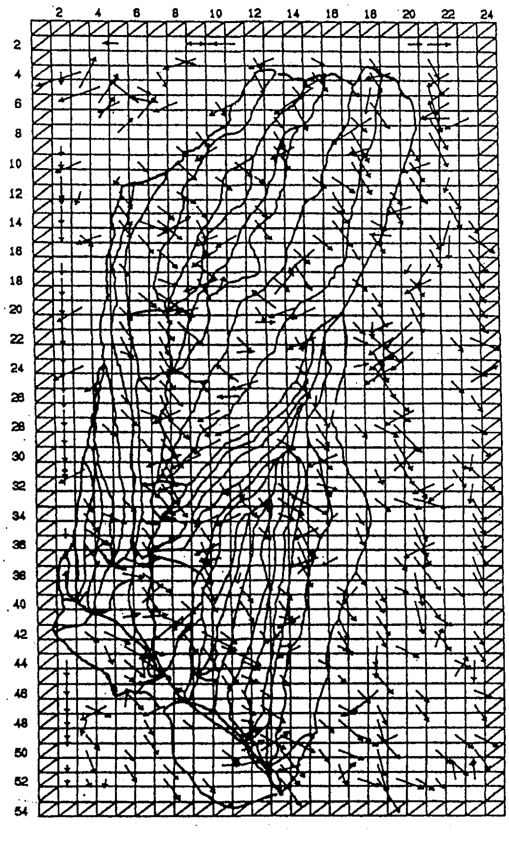

Fig. 4 The spatial distribution of the velocity for the basin using the whole orthogonal grid.

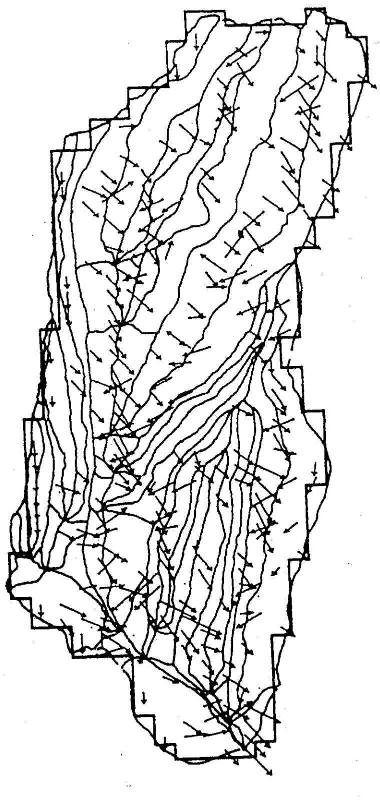

Fig. 5 The spatial distribution of the velocity for the basin only.

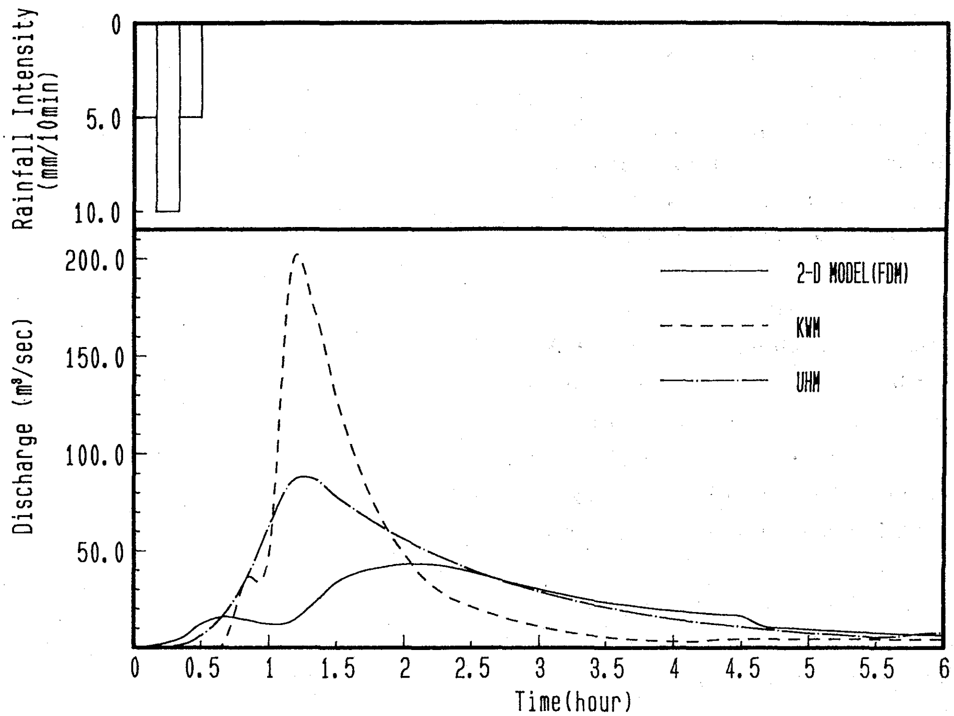

Fig. 6 Obtained hydrographs by the three models.

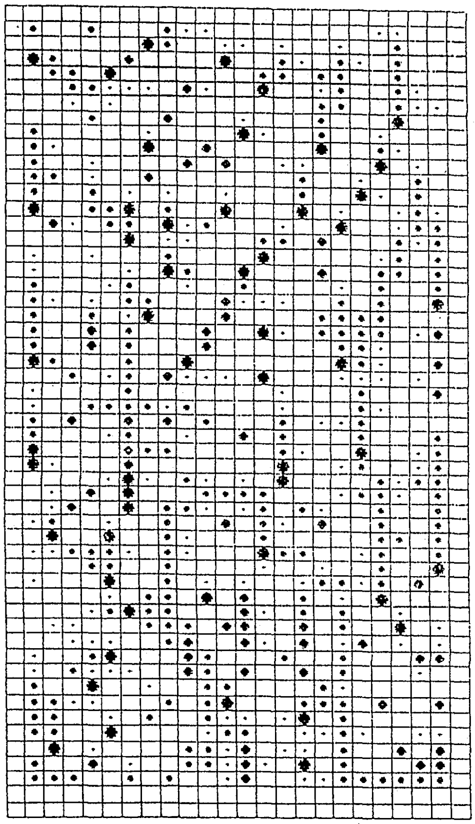

Fig. 7 The spatial distribution of the water depth.

virtual depression storage takes place in which this rainfall did not reach the outlet of the basin. In contrast to the MKWM which assumes all the rainfall to reach the outlet irrespective of the terrain within the subcatchments.

6. Conclusions

It can be concluded that the above approach in the methodology section using the GIS data proves to be a very good potential in data acquisition for the modeling of rainfall-runoff of real basins wherein the input data are one of the drawbacks. In fact, this drawbacks lead many researches to be conducted on hypothetical basins. Abbott et al, 1986 pointed out the predicted output of rainfall -runoff relationship which suffers from lack of input data may have significant uncertainties. It can also be concluded as it is shown in the above results that the effects of the space averaging have an influence on the peak discharged and lag time (see Fig. 6). The exact prediction of the runoff has many application in hydraulic Engineering problems and in this paper the effect of the space averaging has been shown to influence the peak discharged and the lag time. This research is still going on, hoping to show the exact runoff in the near future incorporating the subsurface flow and other factors. Finally, the mechanisms of rainfall -runoff relationship are better revealed in using real basin as it is in the natural terrain state.

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