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# The Sensitivity of A Physically-Based Rainfall-Runoff Model to the Physiographic Factors of Real Basin

By

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***Summary***: Sensitivity of the physiographic factors of the basin such as the terrain, infiltration, river geometry and size of the mesh used in numerical analysis, which cause the drawback in modeling, is investigated employing a practical approach. This is shown using a new physically based model which estimates both the surface and the subsurface runoff. Both runoffs are coupled simultaneously through the infiltration rate in which land uses and ground elevation of the basin were obtained using numerical remote sensing and GIS data via data processing, respectively. Results of this approach are promising.

***Keywords***: Physiographic factors, Surface-subsurface runoff, Infiltration, Physically-based model.

## 1. Introduction.

Rainfall-runoff relationship is complicated by nature because of the involvement of the abundant physiographic and climatic factors which affects the process(Yen, 1986). In addition, the recent environmental degradation in the quantity and the quality of the watersheds due to urbanization, population and development growth, etc. demands a precise estimation of the runoff from river basins. In modeling, estimation of the total runoff is generally achieved in either conceptual or physical models. The former has its own setback because of the involved assumptions which ignore part of the actual physical process (Tahat and Noguchi, 1993). The accuracy of these models should depend to a certain degree on parameters estimation. On the other hand, the drawbacks in the latter, are the large number of the input data for the model, the interrelated factors of rainfall-runoff process and the computational time as well. Nevertheless, comparatively, the pressing demands to estimate the runoff based on the physical aspect of the process by far exceed the drawback (Noguchi *et al.*, 1994). Furthermore, it is seemingly the only solution to the problems of the watershed wherein the necessity of a sound environment and sustainable development in the watershed is increasingly recognized as the compromise between developments and conservation. Thus, the runoff must be estimated based on the actual physical process of the watershed, yet the drawbacks of the physical models should be overcome in order to achieve the desired total water environment and management of the watershed. Therefore, in this paper, a practical approach to handle these drawbacks is proposed and investigated through a new physically based model to estimate the total runoff from real basin. The surface runoff is estimated as a plane-overland flow in the two-dimensional (2-d) model, in which river flow has been evaluated in parallel by one-dimensional (1-d) approach to avoid degradation of the accuracy. While, the subsurface runoff is estimated and coupled simultaneously with the surface runoff in 3-d through the infiltration rate. Experimental field data for the infiltration rate of a nearby basin believed to have the same geological formation of the applied real basin have been

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used. In this methodology, the ground elevation of the grid points in the basin was obtained through data processing of the digital geographical information system (GIS) data. On the other hand, estimation of the infiltration rate was carried out in terms of the land use classification based on remote sensing data.

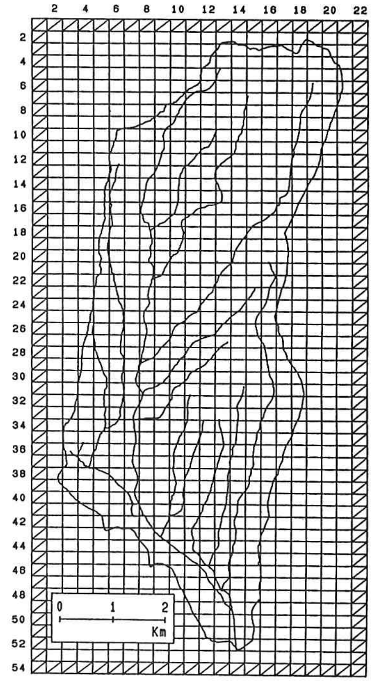

Figure 1. The watershed covered with the orthogonal grid.

## 2. Methodology.

The methodology employed here considers only the physically based model. It is known that in order to solve the Saint-Venant equations of the gradually varied unsteady flow, numerical analysis should be used. The river basin under study was covered with orthogonal grid (Figure 1) wherein the Saint-Venant equations were integrated over the control volume. In the development of the model, first the surface runoff was estimated in only two-dimension. However, an appearance of scattered virtual ponds was noticed though the stability condition was satisfied. This condition has drawn the attention to the fact that the grid size cannot be reduced to infinitesimal one for practical application and computational time, when the drawbacks of modeling should be overcome. Hence, the river flow in one-dimension using the actual river size was rather considered instead of reduction in grid size in addition to the two-dimensional flow. Another fact which should be noted here, even if the grid size is to be reduced an exact representation of geomorphology of the grid is not possible because a very fine grid size actually adds to huge computational time. Therefore, in the employed methodology, rather digital GIS data have been used to get the ground elevation for each grid of the covered basin via data processing (Photo 1) in addition to routing the river flow in one-dimensional. Tachikawa *et al.* (1992) introduced a Triangulated Irregular Networks (TINs) to account for the flow of the water, however, the fear here was the computational time since one of the objectives of this paper is to overcome the drawbacks in physically-based models. Moreover, land use classification for the basin has been accomplished using remote sensing data (Photo 2) through data processing. Thus, this method was found to be a solution to a major setback and problems encountered in modeling the runoff analysis such as the river size, which in reality does not coincide with the grid size, and the spatial variation in the watershed, like land use which affects infiltration, resistance factor and so on. In addition, it saves computational time as indicated by Iwasa *et al.*(1986) and Noguchi and Nakamura (1988) who have studied the effect of the boundary conditions on the simulated runoff from urban areas, by geometrically aligning the river over the grid to take the actual size. They have also shown that computation is remarkably affected in contrast to taking the whole grid as the river size. In the proposed model here, the surface runoff will be introduced first followed by the subsurface flow. Another major problem in rainfall-runoff analysis is the determination of the infiltration rate. Even in estimating this rate other factors are also included such as the hetero-

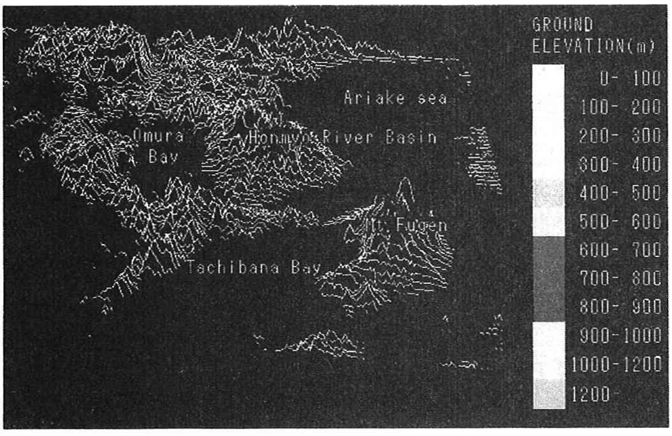

Photo 1. The three dimensional image of processed GIS data for ground elevation.

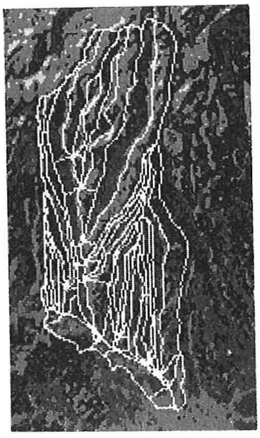
Photo 2. The watershed superimposed over the remote sensing scene for data processing of land uses classification.

geneity of the soil, the wetting and drying phases, etc. Nevertheless, these parameters can be estimated based on the well-known principles and experiments. In this paper, field experimental data mentioned above in several location have been obtained and used to express these relationships in the 3-d of the subsurface flow.

## 3. Outline of the Model.

The well-known Saint-Venant equations are solved in 2-d and 1-d to route the overland and the river flows for the surface runoff. Subsurface runoff is estimated in 3-d, solving the Richard's equation. The two runoffs are solved simultaneously and coupled through the infiltration rate. First, for the overland flow these equations were used, so the continuity equation and the equation of motion in two-dimension can be written as the following, respectively:

$$\frac{\partial h}{\partial t}+\frac{\partial Mv}{\partial xv}=r-i \quad ; \qquad (v=1,2) \qquad (1)$$

$$\frac{\partial M\mu}{\partial t}+\frac{\partial}{\partial xv}\left(\frac{M\mu Mv}{h}\right)=-gh\frac{\partial H}{\partial x\mu}-\frac{\tau\mu b}{\rho} \quad ; \qquad (\mu,v=1,2) \qquad (2)$$

Where $h$ is the water depth ; $M_\mu$, the $x_\mu$-component of the discharge flux per unit width; $r$, the effective rainfall intensity; $i$ , the infiltration rate; $H$, the water stage; $\tau_{\mu b}$ , the $x_\mu$-component of the frictional stress on the bottom; g, the acceleration of gravity; $\rho$, the density of water; $x_\mu$ and $t$ , the spatial and temporal variables, respectively.

On the other hand, the subsurface runoff is evaluated in terms of water content of the soil as follows:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x_v}\left(D_v\frac{\partial\theta}{\partial x_v}\right)+\frac{\partial K_3}{\partial x_3} \qquad (3)$$

where, $D_v$ is expressed as

$$D_v=\frac{K_v}{\gamma}\frac{\partial P}{\partial\theta}=K_v(\theta)\frac{\partial\Psi}{\partial\theta} \quad ; \qquad v=(1,2,3)$$

wherein $\theta=nS$ is the volumetric water content in which $n$ is the porosity and $S$ is the degree of saturation of the soil; $K_v$ is the permeability coefficient in the $x_v$ direction; $g$, the acceleration of gravity; $P$, the hydraulic pressure; $\rho$, the water density; $\gamma=\rho\cdot g$, specific weight of the water; $\Psi=P/\gamma$, the moisture potential; $z$, the vertical axis; $D_v$, the diffusion coefficient, and $t$ , the time. Another consideration in relation to equation (3) for the saturated and the unsaturated zones can be found in Eagleson (1970) and Campbell (1974) and this relation has been used in the model and will not be repeated here due to space limitation.

The proposed model was numerically analyzed using the finite difference scheme. The spatial size of the grid is 292 m in longitude by 231 m in latitude and a time step of 5 sec. were used considering the utilization of GIS data and Courant-Friedrichs- Lewy stability condition for the computation.

## 4. Application of the Model.

The methodology using the physically based model was applied to the Honmyo River Basin in Isahaya City, Nagasaki Prefecture at the western part of Japan. This basin has been taken as the case study due to its importance and because it is often damaged with heavy rainfall.

## 5. Results and discussions

Even though the proposed model handles and estimates the surface and the subsurface runoff simultaneously, it is preferable to discuss and show the results separately before showing the final results of the model. In this way, the problems encountered in rainfall-runoff analysis during the computation and modeling are shown in a clearer picture. Therefore, results and discussions are pursued in three sets of computation. That is, the first is the surface runoff considered in only two-dimension. The second is based on two-dimension for the overland flow conjugated with one-dimension for the river flow. The third is for the whole model that is the second plus the three-dimensional flow of the subsurface flow.

## *For the first set of computation:*

First, the surface runoff was estimated in two-dimensions using the orthogonal grid which covers the watershed (Figure 1). As mentioned earlier, the topography of the watershed for each grid has been obtained using the GIS data which was verified against the topographical map. Manning roughness coefficients were evaluated based on the classified land use by remote sensing data. It was noticed that scattered virtual ponds have appeared within the watershed, though the stability condition and topography were satisfied as shown in Figure 2. The shaded grid-cells in Figure 2 are the virtual ponds which appeared during the computation. Furthermore, with the elapse of time, the spatial distribution of the velocity and the water depth were checked to verify the virtual ponds. These results are shown in Figures 3 and 4, at the specified time, respectively. Hence, the runoff at the outlet of the basin as can be deduced from these Figures wherein the virtual ponds that still exist even after six hours from the onset of rainfall was very minimal (shown in the hydrograph of Figure 5) in the broken line. Moreover, in modeling the runoff of urban areas only, depression storage may be as a matter of definition as mentioned by Yen (1986). However, for the whole river basin , the depression storage, even if it is temporary one, might be of significance as this result (Figure 2) indicates. For the velocity distribution, it can be seen that it follows closely the distribution of the rivers in the watershed. In addition, the response of the velocity distribution and magnitudes which are also shown in Figure 3 seems to be fast at the early stage of rainfall. Hence, it should also be remembered that the urban areas of Isahaya City are located at the lower part of the basin and should be protected from natural disasters of floods. Nevertheless, for practical computations for real basin it is not possible or even practical to reduce the size of the grid to a very small one. Therefore, for routing the rivers, a a second approach and computation have been used to incorporate a one-dimensional flow with the first set of computation.

## *For the second set of computation:*

Even if it is possible to consider a small grid size for the computation, it will be almost impossible to align exactly the sizes of the rivers and that of the grid. Therefore, here in the second set of computation, the river geometry was routed through one-dimensional river flow incorporated with that of the two-dimensional for the overland flow. This routing which follows the river's path using the real sizes of the channel as in one-dimension is

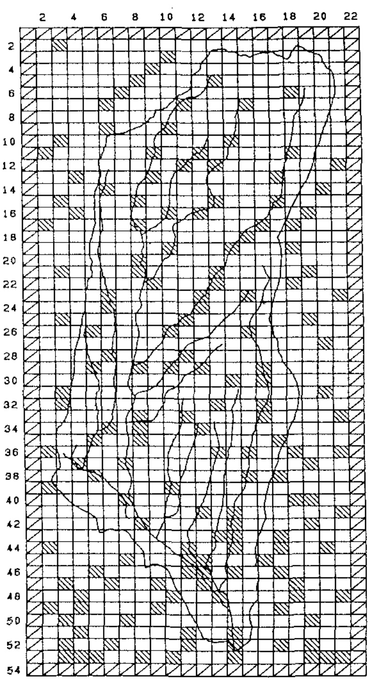

Figure 2. The result showing the virtual scattered ponds in the applied watershed.

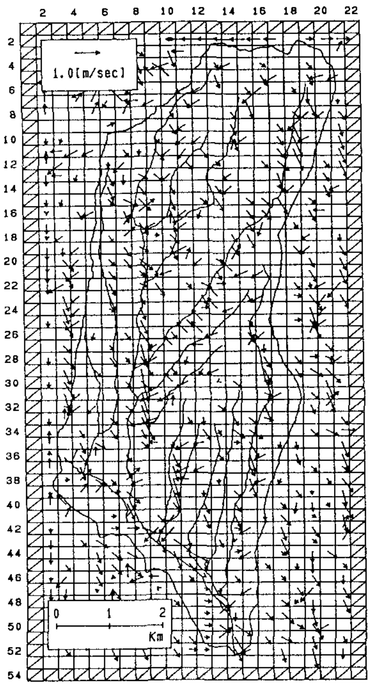


Figure 3. The velocity distribution after 0.5 hr. from the onset of the computation.

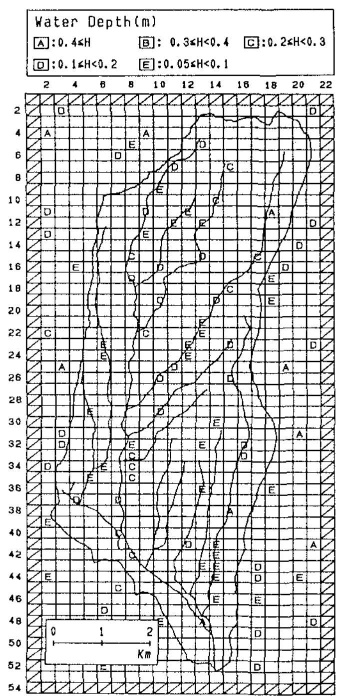


Figure 4. The water depth after 6.0 hrs. from the start of the computation.

shown in Figure 6. To verify this computation the water depth has been checked after six hours from the start of the rainfall. Indeed, only one pond within the watershed was left. This indicates that depression storage is not just a mere subtraction loss from rainfall but rather it may exist even after quite some times from rainfall. On the other hand, it explains in part the difference in amount between the input, the rainfall and the output, the runoff. To show clearly the differences between the above two sets of computation, their calculated hydrographs are plotted together as shown in Figure 5 in comparison with another two methods that is the Modified Kinematic Wave Model used for the same watershed in a previous study (Tahat and Noguchi, 1992, 1993) and the unit hydrograph method for 100%

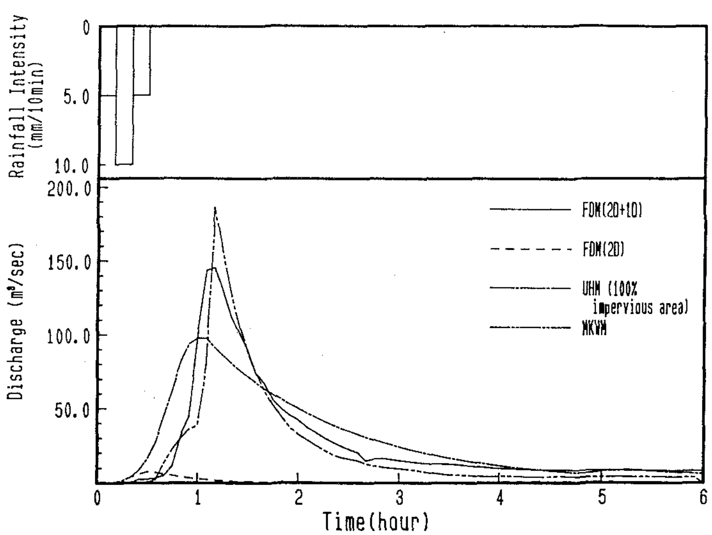


Figure 5. The resulted hydrographs of only the surface runoff of the first two sets of computation with the other two methods.

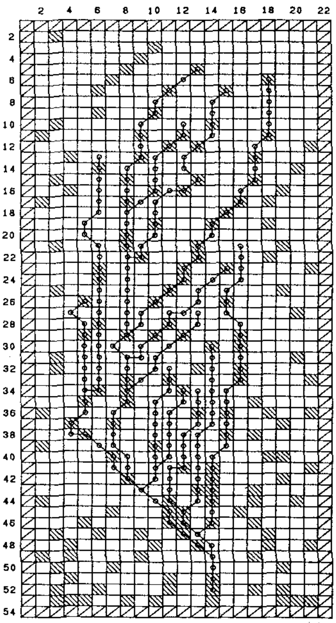

Figure 6. The routing of the river flow with the location of the ponds.

impervious area which means only surface runoff. Comparison of the resulted hydrographs in Figure 5 with respect to peak discharge and lag time is very clear without explanation. However, what is to be explained here, is more on the total runoff and the differences between the two sets of computation. Firstly, it can be seen that the hydrograph of the surface runoff from the 2-D only is very minimal and accounts for only about 9 % of the total rainfall. This is because of the appearance of the virtual ponds within the watershed. On the other hand, when the 2-D was combined with 1-D for river flow, the resulting hydrograph in solid line accounted for 75 % of the total rainfall. However, even after combining the 1-D one pond remains as mentioned above, which could be explained as a storage depression. It could be said that this result is very good in comparison with the other two methods. Therefore, this method of combining the two-dimensional overland flow with routing the river flow in one-dimension for surface flow seems to solve a problem in modeling, particularly contributing to the reduction in number of the grid points and computational time.

### *For the third set of computation*:

The third set of computation is the whole physically-based model that is the second set of the two- and one-dimension for the surface runoff and coupled with three-dimension for the subsurface runoff as explained above. The results of this set are shown through the hydrograph at the basin outlet as in Figure 7 for clarity purposes. The differences between the hydrographs in this Figure 7 are quite obvious. Of course, what should be noted is the resulted hydrograph of the proposed model in the solid line (1-D+2-D+3-D) which differes from the second set of computation because of the infiltration rate. The result of the whole model is as expected in terms of the lag time that is a little delayed, while in terms of volume, it is less than that of the only surface runoff (1-D+2-D). This is due to the infiltration from the ground surface. This realistic estimation of the runoff by the proposed model also shows the importance of the infiltration for the ground water recharge. Furthermore, in this result, it is not necessary to show the effects of the land uses, particularly, the urbanization on the runoff. This is because of the fact that it can be imagined that the hydrograph of the second set (1-D+2-D) to act as the behavior of the impervious area which is the byproducts of urbanization. On the other hand, the result of the whole physically-based model as the natural watershed in its condition at the present time. Moreover, comparison of the resulting hydrographs of the proposed model with that of the UHM 50% impervious assumption (one dotted chain line) and that of the MKWM (two dotted chain line ) shows the differences again in lag time and the volume of water quantity. It should be noted that further enhancement on the methodology using GIS and remote sensing data is still being considered. Thus, in the near future a real set of rainfall-runoff data should be used for parameter identification of the proposed model. However, we believe as of date that the hydrographs of the proposed model behaved as expected and the employed methodology seems to be appropriate.

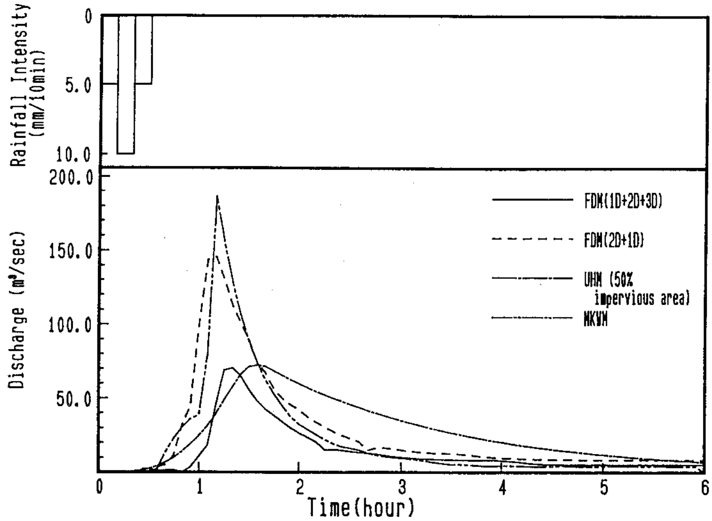


Figure 7. The resulted hydrographs of the proposed physically-based model (2-D+1-D+3-D) with the other two methods.

## 6. Conclusions

It is concluded that the introduced methodology seems very suitable for overcoming the drawbacks in the physically-based models. The proposed physically-based model can estimate the surface and the subsurface runoff simultaneously. Furthermore, when the model combined with the GIS and remote sensing via data processing, integrating the watershed and the rivers, including the urban areas within the basin is accomplished. Therefore, it is further concluded that managments of the water resources for the various uses and environmentally sound and sustainable development can be achieved. It is also concluded that the physiographic factors of the watershed should be treated very closely as found in nature since it affects the results remarkably as shown in the above hydrographs.

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