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AN APPROACH TO AUTOMATIC SURFACE RUNOFF ANALYSIS BY COMPUTER AIDED DESIGN SYSTEM

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ABSTRACT : In the planning of runoff control facilities for housing sites and golf courses, a set of automatic and innovative design techniques is preferable following recent advances in computer application. This paper is a response to such innovation. A three-dimensional topography is reconstructed after inputting a contour map into a developed Computer Aided Design system. The digital model of the catchment basin can be used in the realization of modelling with respect to runoff phenomena and the digital model reveals main characteristics of the runoff process. The knowledge from the CAD system provides us with much information in engineering design and this system has a very wide application in the field of hydroscience.

Keywords : computer aided design, runoff analysis, graphics

1. Introduction

In recent years, with an increase in demand for developing housing sites and golf cources as well as construction sites, the surface runoff from developed areas begins to have an marked influence on the surrounding environment. Under these circumstances, farther practical design and planning techniques is needed to minimize the impact on the natural environment, based on an accurate prediction of the runoff dynamics caused by a large-scale land development.

Several authors have pointed out that Computer Aided Design (CAD) systems are useful for runoff analysis. The first task in carrying out a runoff analysis is to make a model of the three-dimensional topography from a plane map. Chiba et al.(1987) (1), Yamada et al.(1988) (2), and Takasao et al.(1989) (3) made the three-dimensional topographical model as an ensemble of a large number of element cells on a digital elevation map. Cheng et al.(1988) (4) tried to obtain a more accurate topographical model with the aid of the spline curve. They also studied the realization of the ridges, valleys and slope gradient vectors in the topographical model. According to their investigations, it is hard to realize a knowledge of runoff aimed at practical use if the runoff analysis and visualization technique are not combined.

This study intends to create a new application of the Computer Aided Design system through topographical modelling and runoff analysis. An innovation of the optimal scheme for saving computation time and for realizing results is emphasized in view of the practical use. This investigation may help us to well understand to runoff phenomenon, and in the planning and design of control facilities.

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2. Basic System of Analysis and Computation

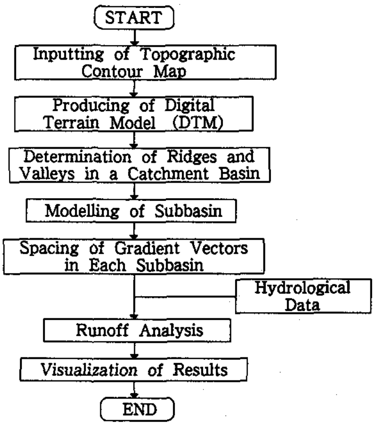

Fig.1 Procedure of Runoff Analysis by the CAD System

In its early stages, CAD system has been applied to machinery design and the spacing design of structures. The CAD system is usually composed of a computer, digitizer, display equipment, XY plotter and printer. In order to create the runoff analysis we have to make the Digital Terrain Model (DTM) after inputting a topographic map. In rebuilding a three – dimensional topography with accuracy, close attention must be paid to selecting the size and shape of discrete element cells and spline elements which cover the topography. Based on the topographical model, we are able to determine the geometry of the ridges and valleys. This allows us to realize a catchment basin and structure available for runoff analysis. The next task is to compute the slope gradient vectors in a whole basin, and a rule with respect to distribute runoff on an element cell in applying the kinematic wave method. Finally, all the results can be visualized by computer graphics, and from this we can understand the runoff process as well as characteristics. It is desired that the sequence of works is done with economy and with a specified accuracy. Fig.1 shows a flow chart of the procedure of runoff analysis by the CAD system.

3. Modelling Process of Catchment Basin

3 – 1 Schematization of Digital Terrain Model (DTM)

The catchment basin model is essential for carrying out the runoff analysis. In order to produce the digital terrain model from an elevation contour map, a reading rule by means of the digitaizer must be introduced after covering the original contour map with a large number of grid cells. For convenience of explanation let us prepare the elevation contour map as shown in Fig.2. The elevation cunfour map is covered with many grid cells. Fig.3 shows a localized map on an enlarged scale. To determine the elevation height H_i at the nodal point i the rule given by Eq.(1) is employed,

$$H_i = \sum \frac{H_{oi}}{d_i^2} / \sum \frac{1}{d_i^2} \qquad (1)$$

in which H_{oi} is the original elevation at a nodal point i and d_i is the radius of the circle at node i. Eq.(1) is called "gravity model", and this means that the original elevation height H_{oi} at the node i is modified by an inverse proportion to a square of the distance d_i within a circle. In this study the radius of circle d_i is taken twice or more times of the grid width.

Fig.4 presents a digital terrain model obtained by the rule of Eq.(1).

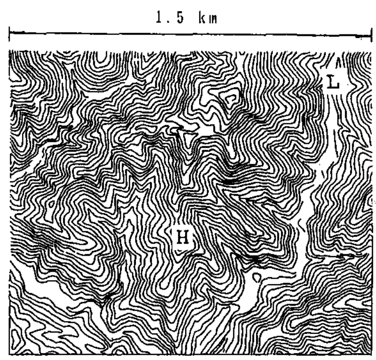

Fig. 2 Original Topographic Map

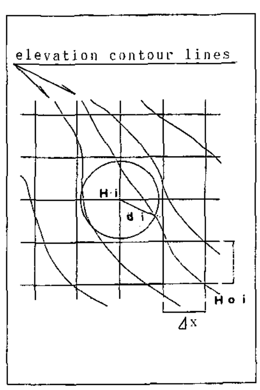

Fig. 3 Search Radius

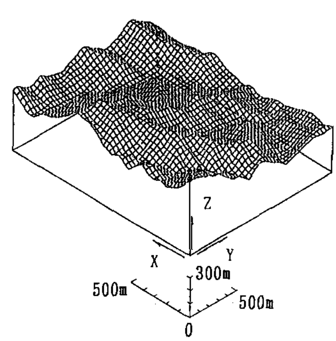

Fig. 4 Digital Terrain Model

3 − 2 Determination of Ridges, Valleys and Watershed

Upon an accomplishment of the runoff based on digital terrain model, the geometry of ridges, valleys and watershed in the catchment basin must be determined numerically. The task is performed by the following procedure.

$$H = f(x) \quad \text{or} \quad g(y) \qquad \cdots\cdots (2)$$

$$\frac{df(x)}{dx} = 0 \quad \text{or} \quad \frac{dg(y)}{dy} = 0 \qquad \cdots\cdots (3)$$

$$\frac{d^2 f(x)}{dx^2} < 0 \quad \text{or} \quad \frac{d^2 g(y)}{dy^2} < 0 \qquad \cdots\cdots (4)$$

$$\frac{d^2 f(x)}{dx^2} > 0 \quad \text{or} \quad \frac{d^2 g(y)}{dy^2} > 0. \qquad \cdots\cdots (5)$$

The spline carve $f(x)$ and $g(x)$ are determined from the elevation height H at each node. Both ridge and valley lines are computed by the fact that their first derivative is zero, and the second derivative is negative on ridge lines and positive on valley ones. Fig.5 demonstrates a configurated map with ridges, valleys and watershed.

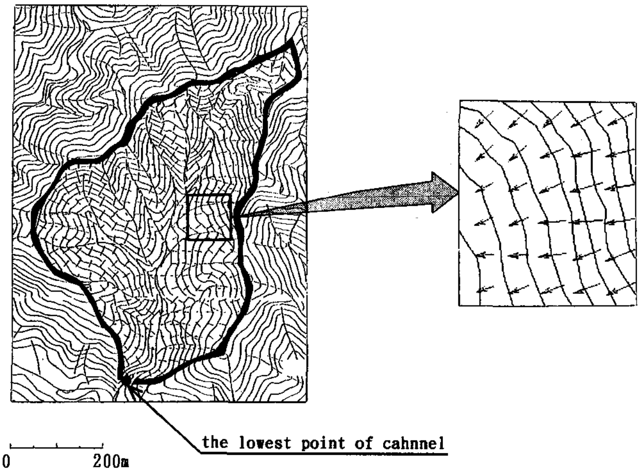

Fig.5 Catchment Basin and Gradient Vectors

3 − 3 Computation of Gradient Vectors

To compute the gradient vector on an element cell the authors proposed basically the following two ways. One is applied for the case of mild and monotonous slope, and another is for steep and variable slope.

(a) Case of mild and monotonous slope

A centroid point (x, y, z) of a triangular element cell which is composed of neighboring elevation points in the DTM map is specified by global coordinates (X, Y, Z) as shown in Fig.6 (a). The equation of a plane W through a point (x, y, z) is given by,

$$ax + by + cz = 0 \qquad \cdots\cdots (6)$$

in which a, b, and c are constants.
If we introduce a circle with a unit radius, an equation on a horizontal plane W′ is written by,

$$x^2 + y^2 = 1. \qquad \cdots\cdots (7)$$

Since the circle in the horizontal plane W' corresponds to an ellipse on the plane W, the direction of the maximun slope accords with that of the longest axis of the ellipse. An angle s of the slope along the horizontal plane can be determined by the following equation :

$$z = \frac{ax \pm b\sqrt{(1-x^2)}}{c} \quad \cdots\cdots \quad (8)$$

by putting $s = z/\ell$ (ℓ=1)

$$s = -\frac{\sqrt{a^2+b^2}}{c} \quad \cdots\cdots \quad (9)$$

(b) Case of steep and variable slope

In order to obtain the gradient vector for steep and variable slopes, the authors adopted the method proposed by Cheng et al.(4) and also a spline curve method. The former one is based on the following concept. Referring to Fig.6 (b), the gradient vector S at a nodal point P on the DTM map can be determined by,

$$S_x = S_o \cos\beta, \qquad S_y = S_o \sin\beta \quad \cdots\cdots \quad (10)$$

$$S_{xy} = S_o \cos(\pi/4-\beta), \qquad S_{yx} = S_o \sin(3\pi/4-\beta) \quad \cdots\cdots \quad (11)$$

$$S_o = \sqrt{S_x^2+S_y^2}, \qquad \tan\beta = S_x/S_y \quad \cdots\cdots \quad (12)$$

$$\widehat{S}_o = \sqrt{S_{xy}^2+S_{yx}^2}, \qquad \tan\beta = \frac{S_{xy}-S_{yx}}{S_{xy}+S_{yx}} \quad \cdots\cdots \quad (13)$$

Since the above mentioned discretization techniques are not suitable for computing gradient vectors near ridges and valleys, the fitting by a spline curve along several nodes is used.

4. Runoff Analysis

As is commonly known, the kinematic wave method has been used for the surface runoff analysis such as for urban river flooding. The task is to solve numerically the continuity equation and the equation of motion with an exponential type for all element cells and channels in the catchemnt basin. The computation is done by the discretization of Eq.(14). Basic equations are written by,

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = \gamma_e \quad \cdots\cdots \quad (14)$$

$$q = ah^m, \quad a = \sqrt{\sin\theta}/n_s \quad \cdots\cdots \quad (15)$$

in which q is the discharge, h the water depth, γ_e an effective rainfall intensity, n_s Manning's constant and θ an angle of slope (5). The total discharge into small branching channels from every cell maintains the main stream at the lower point of channel, and it establishes the formation of discharge hydrograph.

A reasonable technique (or rule) must be introduced in determining a share rate (giving and receiving rate) among cells and orientation of surface flow. In this computation the orientation is assumed to have four directions (j = 1,2,3,4), as shown in Fig.7, and the share rate in each direction is based on gradient vectors. The same rule is also adopted between channels and cells.

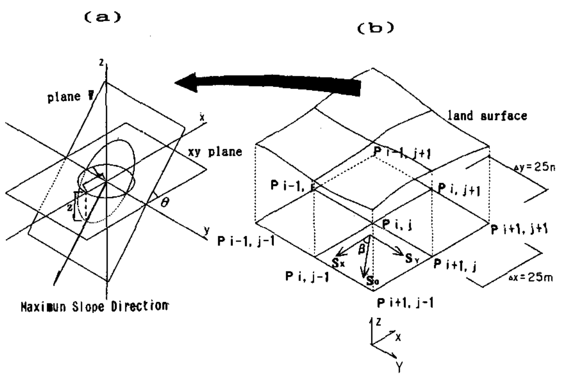

Fig.6 Determination of Gradient Vectors

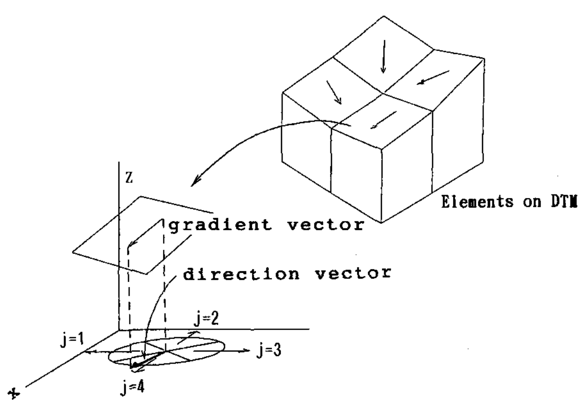

Fig.7 Flow Direction Vectors and Share Rate

In the present computation the Manning's constant is adopted as $n_s = 1.5\,(m^{-1/3}s)$ empirically (6) and $m = 5/3$ in Eq.(15). A constant intensity of rainfall is 10mm/hr. and the duration time is 15 minutes.

5. Visualization of Computed Results

It is obviously expected that the visualization of computed results will greatly promote the understanding of runoff process as well as the innovative design of various facilities. Some of typically visualized results obtained from the CAD techniques are demonstrated by the following ways.

When a constant intensity of rain continues within a limited duration of time, a discharge hydrograph with time t at an outlet of a subbasin i ($i = 1, 2, 3, \ldots n$) can be written as $Q_i\,(t)$. A characteristic time t'_{ci} for the i-th subbasin is defined as follows :

$$t_{ci} = \int (Q_i(t) \cdot t)dt \,/\, \int Q_i(t)dt \quad \cdots\cdots (16)$$

$$t'_{ci} = (t_{ci} - t_{cmin}) \,/\, (t_{cmax} - t_{cmin}) \quad \cdots\cdots (17)$$

in which t_{cimin}. and t_{cimax}. are the minimum value and a maximum one of t_{ci}, respectively. Fig.8 shows a map of contour lines with respect to the characteristic time in a computed basin. The figure shows that the discharge of runoff is collected from watershed boundary to the main channel, and that the runoff time is very short at steep mountains.

By defining the ratio of discharge $Q_i(t)$ at i-th subbasin to a peak discharge Q_{max}. at the lowest point of main channel as Q_{ri}, the confour map is given in Fig.9. This reveals an appearance of runoff process toward main channel.

Fig . 11 shows three hydrographs along main channel at different points. A full grown hydrograph at the lowest point can be recognized.

Some of three-dimensional pictures in runoff process are visualized by groups of pillars in Fig.10. The peak discharge corresponds to a highest pillar which is taken as a unit. It is clearly known that the runoff establishes with increasing time, and the discharge into the main

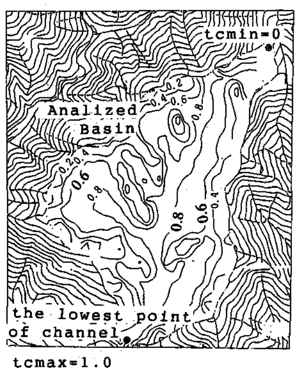

Fig.8 Contour Map of t'_{ci}

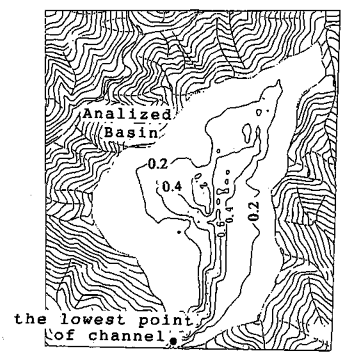

Fig.9 Contour Map of $Q_{ri} = Q_i(t) / Q_{max}$. (at time $3/4\overline{t_{ci}}$)

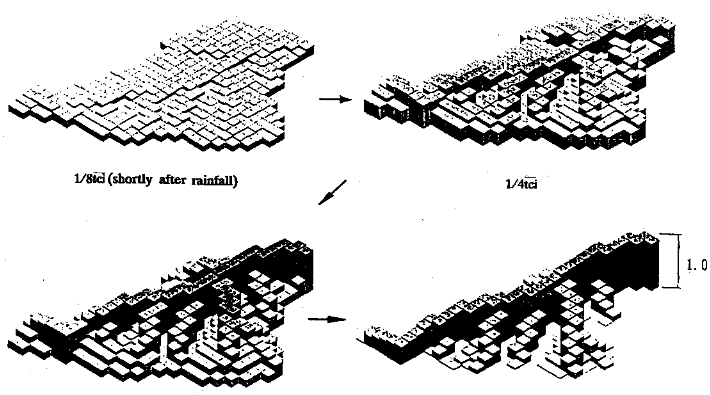

Fig.10 Transition of Discharge

channel is gradually collected from tributary channels.

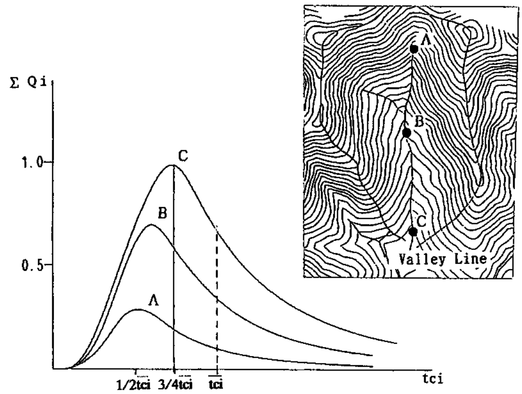

Fig.11 Hydrographs at Each Point

6. Conclusion

With increasing of demand for developing the runoff control facilities such as drainage channels, flood control ponds and pumping stations, the CAD system is a powerful tool for improving the design of them. This paper has dealt with a consistent applicatoin technique of the CAD system for realizing a more reasonable and economic design of runoff facilities.

The main conclusions from this study are summarized as follows :

(1) The realization of a more accurate topographical model can be done by adopting a group of elemental cells and spline curves in accordance with the complexity of slope gradient.

(2) The configuration of the catchment basin is automatically fulfilled by the aid of search rules with ridges and valleys.

(3) The application of the kinematic wave method for runoff analysis harmonizes with the optimal use of the CAD system.

(4) The visualization of runoff dynamics allows us to understand characteristics of phenomena and to realize the design of facilities.

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