【Article】

High Resolution Stream Network in Haji Dam Watershed

Ana PEREZ-KUROKI[1], Yoshiyuki ISOZAKI[2], Akira KIKUCHI[3], and Nobukazu NAKAGOSHI[4]
[1,2]Graduate Student, [3]Assistant Professor, [4]Professor
Graduate School for International Development and Cooperation,
Hiroshima University
1-5-1 Kagamiyama, Higashi-Hiroshima, 739-8529, Japan
E-mail: jagui5@yahoo.com

Abstract

The main objective of this research is to find landscape structure of watershed by using the method of hydrological simulations. A watershed is a basic physical entity of the landscape and most processes related to the movement and/or quality of the water occur in the catchment or sub-catchment areas of the watershed. The basic tool used to analyze the landscape of a watershed is Digital Elevation Model (DEM) in order to obtain the Drainage Direction Matrix (DDM) by which is possible to obtain stream network structure. One of the relevant applications of the DDM is to identify possible sources of water pollution by isolating and tracking back the pollutants inside a river network. The main contribution of this study is to present a high resolution stream network in Haji Dam watershed using 10m DEM. By calculating Horton ratios (R_b = 4.45, R_l = 1.93) and fractal dimensional parameters (d = 1, D = 1.97) it is been demonstrated the importance of a high resolution DDM for the precise comprehension of the watershed system and the correct interpretation of it relief, topography and complexity.

Keywords: Drainage Direction Matrix, Digital Elevation Model, Haji Dam, landscape structure, stream network.

1. Introduction

A watershed is defined as a topographically delineated area, hydrological unit, drained by a stream or river system, i.e. a watershed is an area of land that drains into a lake or river. As rainwater and melting snow run downhill, they carry sediment and other materials into the streams, lakes, wetland and groundwater. The watershed is often used as a physical-biological and socio-political unit for planning and managing the land resources. Watershed management is the process of guiding and organizing the use of the land and other resources on a watershed to provide desired goods and services without harming soil and water resources. The interrelationships among land use, soil and water, and the linkages between uplands and downstream areas have been investigated (Brooks et al., 1991).

Wetlands are a key link in watershed management. The role they play in watersheds is critical in protecting water quality and moderating water quantity. Wetland habitat serves as home for many plants and animals. Vegetated riparian wetlands in agricultural areas have proven to remove high percentages of phosphorus and nitrogen from runoff water (Kusler, 1996). The absence of wetlands or the force-environmental change caused by the construction of a dam, can and will affect the environment of the watershed, therefore without these wetlands, increased nutrient loading to rivers, streams and lakes could result in algal blooms and over-abundant aquatic plant growth (Hogan et al., 2000). When these algae and plants die, oxygen in the water is used during the decomposition process, this can result in oxygen deprivation which may lead to fish kills or ultimately to pollute the water for human consume.

Inside the watershed, following the movement of the water, sediment movement can be summarized in a one directional shift from high-level to downstream. By knowing stream network inside the watershed, it is possible to understand the physical relationship of the watershed and the water movement. Furthermore, to understand the stream network of an area, it is very effective to analyze the topographical structures in order to study the outflow processes of the water and the sediments.

One of the basic tasks in hydrological analysis is to delineate drainage basins and stream networks. Until now, in order to understand the stream network of an area, the general method was a manual operation of extracting the topographical information from the approved contour relief map that was printed in paper, and a great amount of time was necessary for those jobs. Nowadays, Digital Elevation Model (DEM) is being used worldwide, even when it was introduced in the late 1950s (Miller and Laflamme, 1958), their potential application was not fully considered until the late 1980s when DEMs became widely available. With the advent of Geographic Information Systems (GIS), DEMs have been used to delineate drainage networks and watershed boundaries, to calculate slope characteristics, to enhance distributed hydrologic models and to produce flow paths of surface runoff (Wiche et al., 1992; Garrote and Bras, 1995; McCormack and Hogg, 1997)

There are infinity numbers of advantages like speed up in work, and the number of analysis possible by computer programs which were not conceivable many years ago. In this research, it was examined the method of understanding the basic spatial structure of the watershed by extracting the channel network of Haji Dam area, processing 10m DEM data and compare them with 100m DEM, the comparison shows that 10m DEM represent an important contribution due to the high image resolution that allows to determine within a small error, the stream network system, and furthermore to construct the base map for the study of water pollution problems.

2. Methodology

2.1 Stream Network Extraction from Digital Elevation Map (DEM)

In this research DEM was used to explore the land information in order to obtain the stream network of a large area. DEM patterns are presented as simple raster images, since there is a one-to-one correspondence between the catchment area grid and the final raster image. Pixels may be color-coded differently to indicate the elevation of the cell by using various thresholds of catchment area as criteria for assigning the colors.

Starting from the DEM image it is possible to obtain the stream network by using an algorithm that models the drainage system. The basic “Deterministic 8” also called D8 algorithm (O’Callaghan and Mark, 1984; Mark, 1984) is the most popular method for automated drainage recognition and catchment area determinations, which is based on the flow of water over the terrain along lines of steepest slope. Each cell is considered to drain to any of the eight neighbours that have the steepest downslope.

In order to extract the channel network, the difference in elevation between the grids of DEM is used. Water in a slope flows downhill toward a lower elevation area. In the raster style of DEM, the direction of the water in each cell is specify by the height of the surrounding 8 cells, the steepest inclination among the 8 neighboring cells will determine the water movement (flowing-down direction). In other words we obtain the direction where the slope becomes a maximum in the vertical downward look. By calculating flowing-down direction of all the cells in the study area, it is possible to draw up a Drainage Direction Matrix (DDM) as shown in Figure 1.

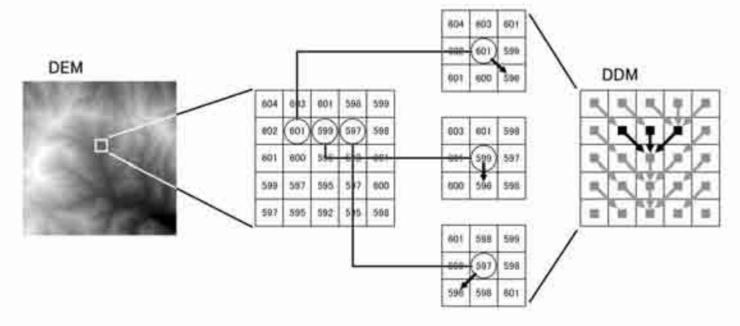

Figure 1: Construction method of the Drainage Direction Matrix (DDM)

However, D8 algorithm has a number of deficiencies (Martz and Garbrecht, 1998; Kiss 2004; Jones, 2002). The continuity of drainages does not extend across flat areas or anywhere that there is a ‘‘pit’’ in the DEM (a pit is a point that terminates a flow path in the downhill direction; water cannot flow pass a pit because none of the adjacent points around it have a lower elevation).

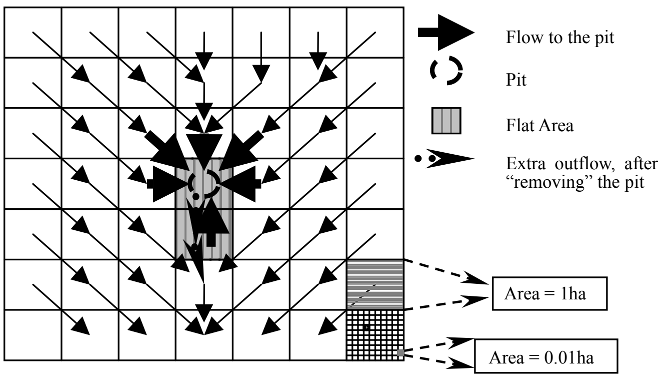

Figure 2: Schematic representation of the Flood-Routing Algorithm to remove a “pit”. The pit area is eliminated by modifying the height of the cell, in order to mach it with those who surround it and make the area “FLAT”**.**

To overcome the problem, this research used the method of searching an extra outflow, known as flood-routing algorithm in a topography concave condition (Nogami, 1995); where, by tracing back the DDM toward upstream until an optional output point, then the pit is normalize to the height of it neighbors, transforming it in a flat area, and then the process of finding the DDM continues. This is nothing else than the procedure to of “extracting” a hole from the drainage basin, as Figure 2 shows.

2.2 Stream Order

The most successful system to characterize a drainage network was first proposed by Horton-Strahler (Horton, 1945; Strahler, 1952), which suggests that every hydrological area has a hierarchical distribution according to its stream category. The procedure to obtain the order of the stream is as follow:

-Channels that originate at a "source", which means that it doesn't have tributaries, are defined to be first-order streams;

- When two streams of order ω join, a stream of order $\omega+1$ is created;

- When two streams of different order join, the channel segment immediately downstream has the higher order of the two combining streams.

Mathematically these processes can be summarized as follow:

$$k = \max\ \{i, j, (1+[i+j]/2)\} \qquad (1)$$

where, k is the stream order of the downstream line, i and j are the order of the upstream branches (Gyasi-Agyei et al., 1995). By using this equation it is possible to assign an order for each stream in Haji Dam watershed.

Once calculated the order and number of streams, it is also possible to obtain the Hortonian ratios R_b, R_a and R_l, which represents the bifurcation, area and length ratios respectively (Horton, 1945; Strahler, 1952).

2.3 Drainage Basin for Specific Point

Because Drainage Direction Matrix (DDM) is the simulation of the stream network which really exists in a specific area, one must be able to trace the DDM without any discontinuity through the entire map. The delineation of catchments is an important aspect in hydrological modeling and is closely related to the definition of channel networks. A hydrological model must distinguish between overland runoff and water that flows into channels. On the other hand, a catchment's outlet must be on a river course. It appears clearly that the correct delineation of a catchment is related to the correct extraction of its stream network. For that DDM must meet the following conditions:

(a) The stream does not diverge midway,

(b) A loop does not exist in the stream, and

(c) The stream is not discontinue

After the DDM is done, the drainage basin becomes the fundamental unit that must be extracted. When DDM is used, it is possible to obtain the upstream section of all cells.

2.4 Fractal Analysis

Research has shown that individual streams and the networks which they comprise are fractals. Hydrologists are interested in calculating two fractal dimensions for streams (the fractal dimension of individual streams, d, and the fractal dimension of the stream network, D). The fractal dimension for an individual stream is a measure of its irregularity; it is a measure of the extent of a stream's meanderings. The fractal dimension for the network is a measure of the ability of a network to fill a plane, and it arises from the branching nature of the network and from the sinuosity of individual streams. If a stream network were truly space-filling, as is the case with a topologically random network, one would expect to compute a stream network fractal dimension of 2.0. Certain researchers, (Mandelbrot, 1983; Tarboton et al. 1988) believe that this may be the case, it is generally anticipated that the fractal dimension of a stream network is less than 2.0, and it is further acknowledged that the fractal dimensions vary from one location to another.

Some other researchers (La Barbera and Rosso 1989, 1990) countered that $D = 2$ is a limiting case, and that the fractal dimension of channel networks varies between two and unity, depending on the landscape, been the average between 1.6 and 1.7.

In other hand, the fractal dimension of individual stream d is reported to be between 1.0 to 1.3 with the bulk of the values between 1.1 and 1.2. But it is been reported values lower the 1.0 this suggest that the stream can have a lower dimension than a straight line. This contradiction can be explained in part, by recalling that defining fractal dimensions in terms of the length-area relationship assumes that streams are self-similar. If the streams are not self-similar, then the length- area relationship is not necessary an accurate estimate of the fractal dimension (Schuller et al., 2001).

The fact that R_b, R_a and R_l are common Horton's parameters in quantitative geomorphology allows an estimation of the fractal dimension of well-known drainage basins. In other words, Horton ratios can be employed to determine the fractal dimensions of individual streams and stream networks. Several researchers have followed this approach and proposed the following two equations for computing the individual stream and network fractal dimensions with the respective constrains for both parameters (Rosso et al., 1991).

$$d = \max [1, 2 * (\log R_l / \log R_a)] \quad (2)$$

$$D = \min [2, 2 * (\log R_b / \log R_a)] \quad (3)$$

This constrains request that d can not been less than 1.0, and D can not be higher that 2.0.

2.5 Application to a real Region

The study area for this research is Haji Dam (Figure 3), located in Hiroshima Prefecture (34° 39' N, 132 ° 38' E), and is part of the Gono River system (Yachiyo-cho, Akitakata City). The Dam was completed in 1974, as multipurpose dam, which provides flood control, maintenance of river flow, urban water supply, and electric power generation. It discharges water through an approximately 19 km tunnel into Nenotani River after using it to generate electric power.

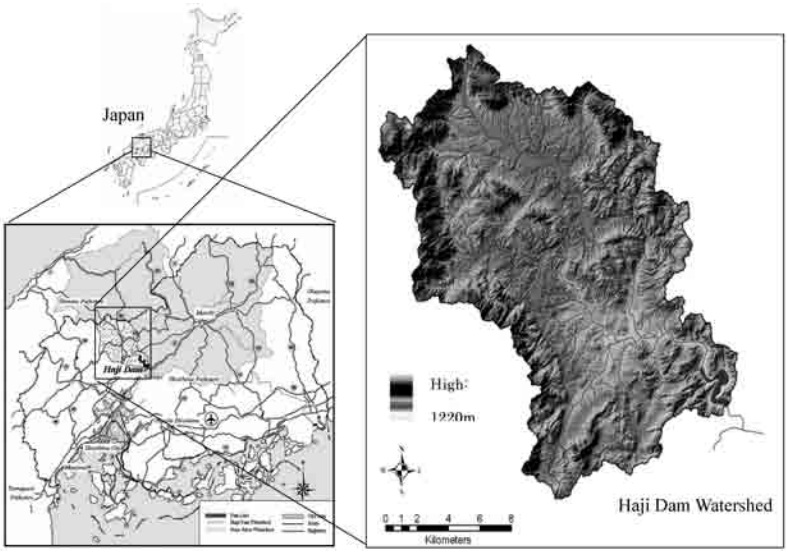

Figure 3: Left: Haji Dam Watershed in Hiroshima Prefecture (34° 39' N, 132 ° 38' E), that is a sub-watershed that belong to Gono river watershed. Contribute with 16% of the total amount of water consumed by Hiroshima City. Right: topography map of the watershed.

Table 1 shows the attributes (characteristics) related to Haji Dam; it is relatively a small dam, but represents an important source of water for Hiroshima Prefecture, and supplies more than 15% of the total amount of water used by Hiroshima City.

Table 1: Characteristics of Haji Dam

Dam statistics	
Dam Wall height	50.0 m
Dam Wall top length	300.0 m
Dam mass	210,000 m^3
Entire reservoir capacity	47,300,000 m^3
Effective storage	41,100,000 m^3
Watershed Area	307.5 km^2
Yachiyo Lake area	2.80 km^2
Purpose of the Dam	Flood control, water utilization and generation of electricity.
Electric enterprise	The Chugoku Electric Power Co. Ltd.
Power plant name (Approval output)	Kabe Electrical Power Plant (38,000kW)
Starting/completion construction year	1966 /1974 year

To study the population, agriculture or industrial impact in Haji Dam watershed, is necessary to use the available tools, such a DEM and DDM. In order to draw up the DDM and the drainage basin, it was used 10m DEM, issued by Hokkaido Map Co., Ltd. This DEM is suitable for the level 2 of the standard grid. In order to cover the whole area of Haji Dam Watershed, it was needed to join 8 DEM maps of 7.5 minute quad (using Real Basic 5.5v program).

3. Results

Figure 3 shows the location of Haji Dam watershed, which covers an area of 307.5 Km^2 (30750 ha) and the mountain elevation varies from 240mt to 1220mt high. The right map corresponds to the topography map drawn by using ArcGIS 8.2v.

Following the process of constructing a DDM described in Figure 1, we were able to obtain the "flowing–down lines" of the stream network for Haji Dam watershed. Figure 4 shows the DDM for the study site and the difference in accuracy for 100m DEM and 10m DEM. Figure 5a and Figure 5b, show the 3D topography map designed from 10m DEM and 100m DEM respectively.

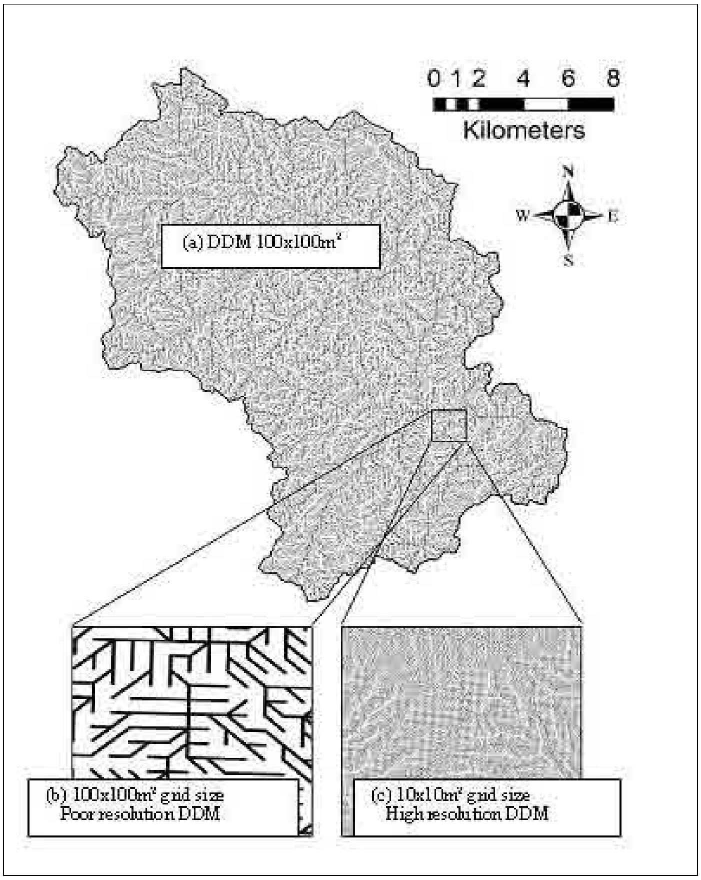

Figure 4: (a) Drainage Direction Matrix (DDM) from 100m DEM, (b) an enlargement for 100m DEM and (c) the enlargement for 10m DEM resolution.

The calculation of streams orders were done with Horton-Strahler system and the drainage basin division figure was drawn up individually for every order. Once the stream order have been calculated, it is easy to estimate the amount of a determinate stream order; also the average for all the orders, this could be used to classify the watershed, as a *k*-order watershed. The result of the calculation of the stream order (Eq. (1)) is presented in Figure 6. Although all the orders of streams were calculated in DDM algorithm, we will only present from the order 5^{th} and higher, otherwise it will be difficult to appreciate the streams (all the blank parts correspond to the orders lower than 5, from 1^{st} to 4^{th} order). Moreover, the high-level limits were extracted among the respective streams, and the drainage basin division figure was drawn up from the 4^{th} order until the 9^{th} in Figure 7 showing the area covered by each order.

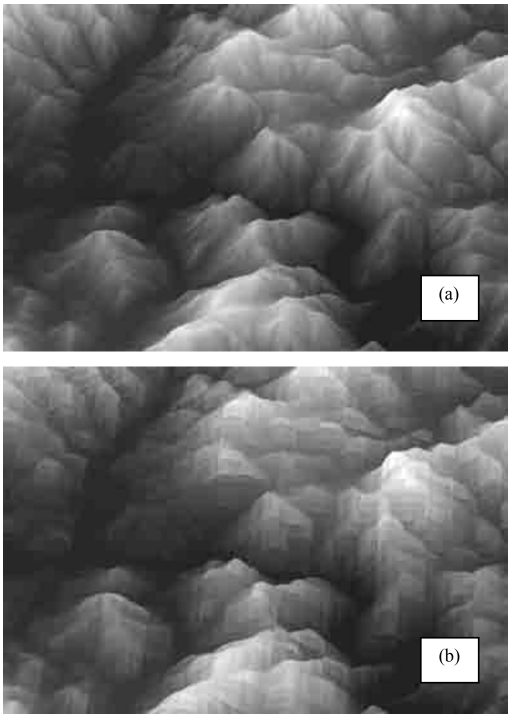

Figure 5: 3D image for (a) 10m DEM and (b) 100m DEM

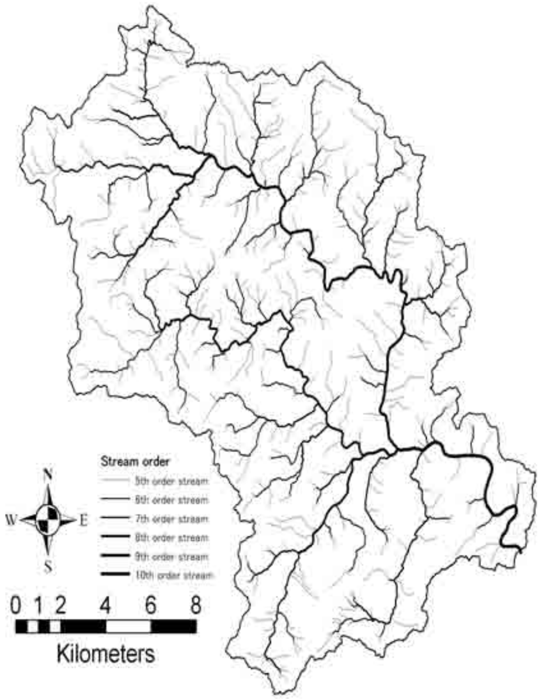

Figure 6: Stream order representation from the 5th until the 10th order.

The analysis of the stream order and drainage basin structure was done with an overlay process using GIS software, ArcGIS 8.2v. The objective was to find the relationship involving the stream order, the number of stream order, the area that correspond to each order and its length (the entire area of the each stream order and it total length). In addition, the respective bifurcation, area and length ratio were found from streams data and the average was plotted.

Concerning the number of streams, they decrease geometrically upon the increase of the stream order as shows Figure 8a and Figure 8b. They represent the values for 100m DEM and 10m DEM, and the average of the bifurcation ratio which is obtained from the fitted regression of the number of streams vs. the stream order. In the same way that we obtained R_b, the area of each order can be analyzed and calculate from the stream area plot that the area ratio (R_a) can be obtained as is shown in Figure 9a and Figure 9b, which typically increases geometrically upon the increase of the stream order, revealing the characteristic size of the components of a drainage network. In Figure 10a and Figure 10b, we observe the behavior of the stream length vs. the order of stream, and obtained the length ratio (R_l). In Table 2, we summarized all the values. It is really interesting that a low resolution DEM, such as 100m DEM gives a smaller *k*-order (maximum of stream order was 8th), which is a remarkable difference compare with the fine resolution grid of 10m DEM, in which we obtain a maximum order of 10th, this is of course explain by the inaccuracy 100m DEM introduces.

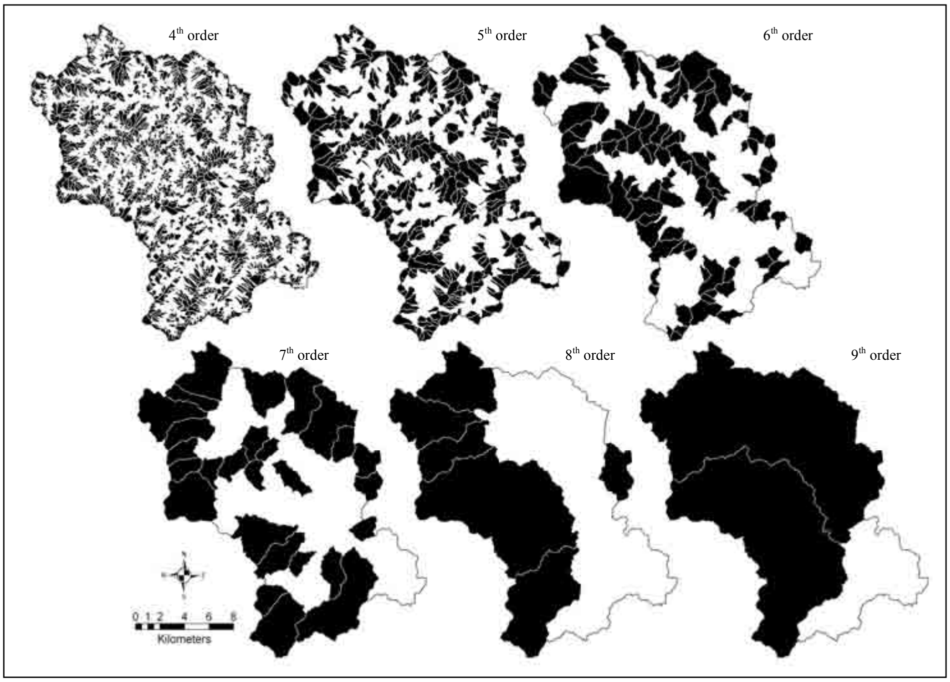

Figure 7: Haji Dam landscape structure, from the stream order 4th until the 9th.

In Table 2, we summarized all the values. It is really interesting that a low resolution DEM, such as 100m DEM gives a smaller *k*-order (maximum of stream order was 8th), which is a remarkable difference compare with the fine resolution grid of 10m DEM, in which we obtain a maximum order of 10th, this is of course explain by the inaccuracy 100m DEM introduces.

Table 2: Horton's Parameter for 100m DEM and 10m DEM

	Max stream order	Bifurcation Ratio	Area Ratio	Length Ratio
100m DEM	8	3.90	4.19	2.03
10m DEM	10	4.5	4.56	2.19

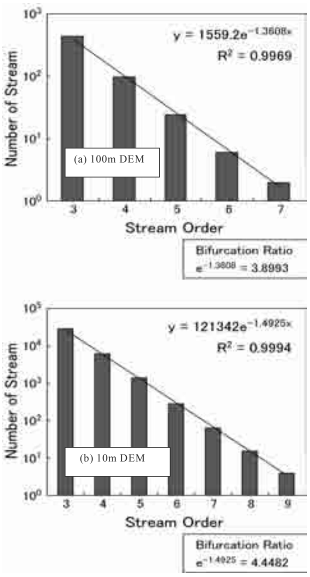

Figure 8: Horton's Law of number of stream order (a) for 100m DEM and (b) for 10m DEM.

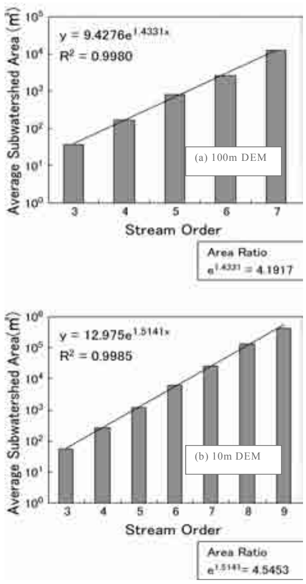

Figure 9: Horton's Law of area and the stream order (a) for 100m DEM and (b) for 10m DEM.

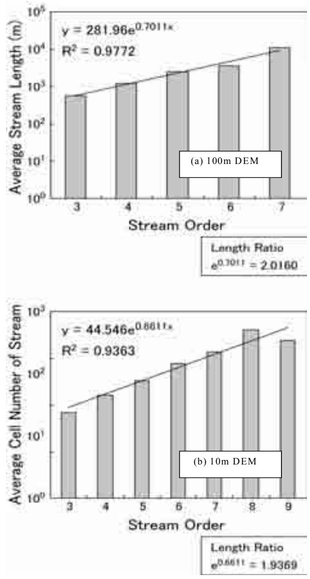

Figure 10: Horton's Law of stream length and stream order (a) for 100m DEM and (b) for 10m DEM.

Now, the main objective of this study is to design the data platform for water quality assessment in Haji dam watershed, in order to do that, we have to be able to follow the streams from a certain point to the source. Figure 11 shows a map with some examples of catchment areas, where the marked areas correspond to a sub-drainage basin for a certain node (the node is represented by a point placed in a "downstream position" of the sub-drainage). A GIS program was used to superimpose ''layers'' of additional information, including the DEM-calculated drainages. The downstream endpoint of these segments is an example of the sampling point along the stream. In practice, the point that is actually sampled will be determined by additional factors, including geology, accessibility, and the characteristics of the stream as determined in the field.

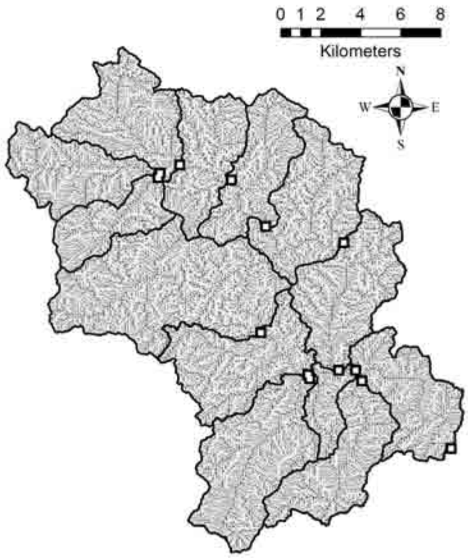

Figure 11: Upstream catchment area for a certain node which can be used to asses the quality of the water and to isolate the possible areas from which the pollutant comes.

4. Discussion

Since its construction, Haji Dam has been important as source of water and electricity, entertainment, wildlife management for *Anas formosa, Mergus squamatus*, protection against floods and more over, helped the economical growth of the town (Green et al., 2000; Kuriki, 2000). But after more than three decades of the dam completion, Yachiyo Lake (Dam Lake) is facing several problems in relation to the water quality; due to human impact which makes it a center of intensive investigation, in a huge effort to understand, control, and later on, eradicate the source of the problem.

We will discuss the relevance of an accurate base map, in order to study appropriately the structure of the stream network in Haji Dam watershed.

Accuracy

When considering DEM source, of particular concern for these closed-drainage landscapes, it's the poor ability of the 100m DEM to represent the position of the local depressions. Differences in terrain attributes are more significant in 10m DEM and the greater discrepancy observed between 100m DEM and 10m DEM likely occur because the 100m represent certain landscape features less discernibly (Figure 5a and Figure 5b).

It is important to remark the fact that all the research in high resolution carries a high accuracy in its results. In a previous research it was reported that patches larger than the area of a cell, on a vector-based map, could be kept almost certainly on any map, but many patches of less than the cell size were lost (Nakagoshi et al., 1998). Now, 10m DEM is a very high resolution data, not available yet in any other country, and gives detail of 10x10m^2 (0.01ha) of area which represent a remarkable difference with the usual research done using 100m DEM, which gives a poor resolution of only 100x100m^2 (1ha) as shows Figure 2.

Figure 4a shows the Drainage Direction Matrix (DDM) obtained from a 100m DEM of Haji Dam

Watershed, which was constructed to demonstrate the poor resolution of 1ha grid sizes (Figure 4b), and another from 10m DEM with 0.01ha grid sizes (Figure 4c). It is easy to observe the difference in accuracy for the study. From Figure 4, the enlarged areas, measure about 1.5 x 1.5 km^2 (225 ha). Also from the Figure 5a and Figure 5b it's simple to appreciate the detail in 3D each resolution introduces. In Figure 5a the overall curves of the ground are more visible and they follow the DEM-field surveyed pattern, there are also no steps, the mountains look sharper as the relief goes, and no discontinuity in the height, the size of the grid make a visible difference in observation.

From the Figure 2 it is possible to understand the amount of error introduced by the program, when it eliminates a "pit" from the study area. Of course the more accurate the topography map is, the more number of pits will appear, but each one carrying significantly less error than in a poor resolution map.

River Basin Assessment

The use of a DEM implies an interest in some spatial extensive characteristic of the terrain. The practical applications presented here are to use a DDM to help in the design phase of a stream water sampling, that involve the assessment of water quality in Haji dam-lake.

Analytically, complex three-dimensional surfaces can be tractable with computer processing of digitizing the surface at discrete points on a regular grid. Due to the high resolution of the 10m DEM, the results have comparatively more accuracy than other similar studies (Liang and Mackay, 1999; Jones 2002), which usually have 100m DEM as a base map.

Figure 6 shows the results for the stream order calculations (only from the order 5^{th} to 10^{th} in order to preserve the clarity of the figure). The usefulness of the stream order system is directly proportional to the size of the watershed, the stream dimensions and the stream discharge. Because the order number is dimensionless, it can be use to compare two different drainage networks (Strahler, 1964).

Figure 7 represents the relation between the stream order and the areas covered by them; it also gives us an idea of the length of the streams corresponding to each order. The relation is expressed by Horton's Law of area and length, the lower the order, the smaller the area and the shorter the length of each stream.

Accuracy reflected by Horton's Bifurcation ratio

In order to construct a precise drainage model, the DEM have to contain information that directly locates drainages, also the capability to obtain the locations of drainages by computational analysis from the elevation grid data is important. This article addresses techniques that work with rasterized elevation data to located drainage areas. Once a drainage network has been defined, the problem of analysis can proceed to the next step. This study shows the accuracy of the DDM makes a big contribution to the reliability of future studies.

Figure 8a and Figure 8b shows the average of the bifurcation ratio (R_b) for 100m DEM and 10m DEM respectively, which are obtained from the fitted regression of the number of streams vs. the stream order. In a similar way we obtained the area ratio R_a and the length ratio R_l (Figure 9 and Figure 10). Table 2 shows the summary for the values corresponding to the Horton's parameters.

From Table 2 we observe the great difference in value that each resolution map brings. As we have showed before, the accuracy of the DEM used in the study will be translated in the reduction of the errors for the parameters obtained from them. Also, it has been reported before the sensitivity of Horton's parameter to the resolution of the base map used for the study (Walker, 1999; Musa, 2004).

Normally bifurcation rations could vary from 3 to 5, and they reflect the flatness or steepness of the watershed topography (Kirchner, 1993, 1994a and 1994b; Costa-Cabral, 1997). High bifurcation ratios are associated with elongated watersheds, while more rounded watershed have lower bifurcation ratios (Strahler, 1964).

Based on Previous studies of Japan's singular topography, the results on Table 2 could be assume both as valid, but one of them not reflecting the reality of the watershed.

To give a clear explanation of the importance of the bifurcation ration in relation to the resolution of the base map, we have gathered several results of Horton's parameter from other papers. All the values are summarized on Table 3. From Figure 12 we can observe the frequency of appearance for the bifurcation ratio, and the Gaussian fitting to obtain the mean value as $R_b = 3.89$, and from Figure 13 we obtained the average of length ratio as $R_l = 2.28$. Figure 14 shows the low dispersion in the value of length ratio R_l when is plot against the total area of the watershed, the values were taken from Table 3.

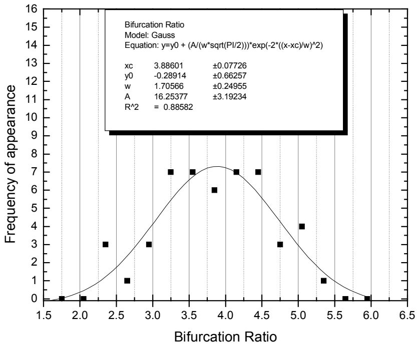

Figure 12: Frequency of appearance of the Bifurcation Ratio (Rb) and the Gaussian fitting, data from Table 3.

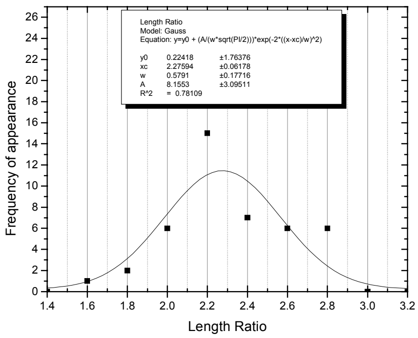

Figure 13: Frequency of appearance of the Length Ratio (Rl) and the Gaussian fitting, data from Table 3.

According to Figure 12, the results from 100m DEM ($R_b = 3.90$) will be taken as correct because it goes with the average (world average), but certainly the topography in Japan is different, is abrupt and with steep mountains (Oguchi, 2001a and 2001b). Following the relation of R_b and the relief, one could expect that the corresponding value for a watershed in Japan will fall on the right part of the Figure 12 (with values higher than the average). But the value given from 100m DEM does not. On the other hand, the value obtained from 10m DEM ($R_b = 4.45$) perfectly describes the topography of Haji Dam watershed, as the average R_b for any watershed with steep mountains in Japan. This assumptions are corroborated by Oguchi (2001), were he explains that in steep Japanese mountains, the Horton parameters such as the bifurcation ratio (R_b) and the stream length ratio (R_l) have different values (mean $R_b = 4.5$, mean $R_l = 1.9$) from those in less steep Japanese mountains (mean $R_b = 4.0$, mean $R_l = 2.4$) and from those in mountains in other countries (mean $R_b = 3.7$, mean $R_l = 2.6$). All these values have been summarized on Table 4.

Table 3: Horton's parameters of watersheds around the world

Watershed	Location	Type	Order	Area (ha)	R_b	R_l	
Haji Dam Watershed	Japan	Mountain	10	30750	4.45	1.93	
Esopus creek1	US	Mountain	5	60600	3.12	2.31	a
Esopus creek2	US	Plain	7	110000	2.27	1.84	a
Rondout Creek	US	Mountain	4	27200	3.30	2.64	a
Putnam Brook	US	Glacial	4	6990	2.46	2.74	a
Cold Spring Brook	US	Glacial	4	4090	2.62	2.66	a
Crane Creek	US	Glacial	5	11800	2.22	2.30	a
Ganargua Creek	US	Glacial	6	77400	2.89	2.30	a
Keuka Lake	US	Hilly	5	41700	3.25	1.96	a
Seneca Lake	US	Hilly	6	124000	3.15	2.20	a
Owasko Lake	US	Hilly	5	51800	3.91	2.22	a
Thunder Bay River	US	Glacial	4	-	3.00	-	a
Almanzora River	Spain	Mountain	4		4.75	2.25	b
Real Collobrier	France	Mountain		7500	4.2	2.1	c
Gardon	France	Hilly		54600	5.1	2.5	c
L'Adour	France	Plain		1630000	5.1	2.6	c
Number 1	Italy	Mountain	5	1180	3.35	1.62	d
Number 2	Italy	Mountain	6	11470	4.00	2.24	d
Number 3	Italy	Mountain	5	4250	4.28	2.26	d
Number 4	Italy	Mountain	6	11360	4.41	5.51	d
Number 5	Italy	Mountain	5	5400	4.70	2.87	d
Number 6	Italy	Mountain	6	4800	3.42	1.88	d
Number 7	Italy	Mountain	6	5300	4.18	2.29	d
Number 8	Italy	Mountain	6	17770	4.90	2.71	d
Number 9	Italy	Mountain	6	5540	3.87	2.08	d
Number 10	Italy	Mountain	7	8120	3.82	2.03	d
Number 11	Italy	Mountain	5	3453	4.33	2.35	d
Number 12	Italy	Mountain	5	4300	4.60	2.49	d
Number 13	Italy	Mountain	5	4120	5.22	2.84	d
Number 14	Italy	Mountain	5	1950	3.56	2.19	d
Number 15	Italy	Mountain	7	14300	3.40	1.91	d
Number 16	Italy	Mountain	6	7700	4.17	2.24	d
Number 17	Italy	Mountain	5	1940	3.58	2.07	d
Vermilion River	US	Hilly, plain	6	344900	3.55	2.00	e
Mackinaw River	US	Hilly	6	287100	4.55	2.54	e
Arcidiacotana Basin	Italy	Hilly	5	12390	4.12	2.39	f
Lapilloso	Italy	Hilly	4	2850	4.34	2.28	f
Vulgano	Italy	Hilly	5	9410	3.79	2.26	f
S. Maria	Italy	Hilly	5	5810	3.72	2.57	f
Salsola	Italy	Hilly	5	4410	3.28	2.29	f
Casanova	Italy	Hilly	5	5730	3.44	2.55	f
Calone S.V.	Italy	Hilly	5	9250	3.38	2.73	f
Celone a P.F.	Italy	Hilly, mountain	5	23350	4.1	2.74	f
Akikawa	Japan	Mountain	5	4640	4.9	3.4	g
Okuri	Japan	Mountain	5	2730	4.3	2.4	g
Shiketi	Eritrea	Plain	5	585	3.9	-	h
Emni-Tzellim	Eritrea	Hill	5	1172	3.5	-	h
Deccan basalt	India	Valley	4	1908	3.00	2.49	i
Danda watershed	India	Mountains	3	450	4.58	-	j

(a) Horton 1945; (b) Garcia-Ruiz 1992; (c) Moussa 1996; (d) Veltri 1995; (e) Saco 2002; (f) Claps 1996; (g) Yoshinomori 1974; (h) Colombo 1995; (i) Pakhmode 2003; (j) Jain 1996

From 100m DEM the bifurcation and length ratios are R_b = 3.9 and R_l = 2.03; according to Oguchi this values are close to those of a "less steep Japanese mountain", which is not the case for Haji Dam watershed. This explains that a poor resolution DEM can not reflect the real relief for steep mountains in Japan. A poor resolution DEM such as 100m DEM will show the topography as "hilly" areas, which does not happened with a 10m DEM fine grid, which shows a great concordance with the reality (Figure 5).

Table 4: Comparison of Horton's parameters

	Bifurcation Ratio	Area Ratio	Length Ratio
100m DEM	3.90	4.19	2.03
10m DEM	4.45	4.56	1.93
Steep Mountain in Japan*	4.5		1.9
Less Steep Mountain in Japan*	4.0		2.4
Average of the world*	3.7		2.6
Values from Figure 12 and Figure 13	3.85		2.28

(*Oguchi, 2001)

Fractal Dimension

The fractal dimension quantifies the complexity or irregularity of a fractal object. An object with a low fractal dimension is less complex than an object with a higher fractal dimension.

It is generally anticipated that the fractal dimension of a stream network is less than 2.0. It is estimated to be between 1.5 and 2 with an average between 1.6 and 1.7 (La Barbera and Rosso, 1989; Schuller et al., 2001). But several other researchers have related also the fractal value to be sensitive to the scale (Tarboton et al. 1990). They contended that the dimension should be 2.0 since, at high resolutions; one could imagine a network that drains every point and thus fills the area it drains. Our calculation from the Eq. (2) and (3) of the fractal dimension of individual stream (d) and the fractal dimension of the stream network (D) gave us a value of d = 1 and D = 1.97, which is in good concordance with the expected value for a typical watershed structure analyzed with a high resolution DEM.

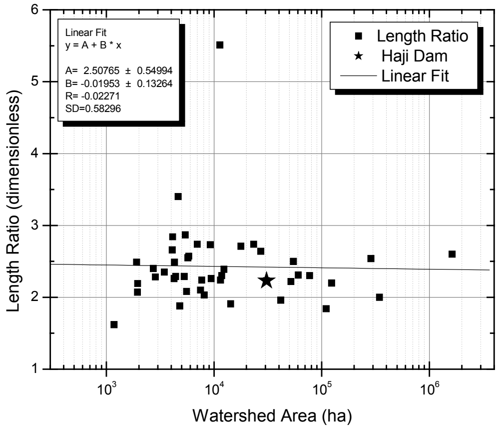

Figure 14: Length ratio (Rl) vs. watershed area for several reported values around the world.

Optimal point selection

One of the possible applications of DDM was presented in this research. It is related to the calculation of upstream areas for water quality studies, and possible pollutant origin. These will be done by considering several factors, both, naturals and humans, such as landuse, vegetation, population, industrial areas, etc. In other words, the human impact on the watershed and it consequence in the nutrient load into the water.

The method consist on selecting the high risk areas according to the landuse segments (crop land, build up areas, paddy field, etc) and overlapping them with the stream network calculated from 10m DEMs. By using this method, it will be possible to identify ‘‘optimal’’ sample sites as shown in Figure 11.

5. Conclusion

The results described above show conclusively that it is possible to derive topographic data from 10m DEM and give more accurate topographic information compared to the 100m DEM normally used at the study site. The overall curves of the ground are more visible and they follow the DEM-field surveyed pattern. We also have proven that the Horton’s parameters (R_b = 4.45 and R_l = 1.93) obtained from 10m DEM are correct and reflect the relief of Haji Dam Watershed. This comes to conclusion that a good quality DDM can be created from 10m fine grid resolution of 10m DEM.

Natural landscape structure of river basin was assessed as well as the geometric designed topography and it was possible to study the watershed from the scale-free point of view. This is reflected by the fractal analysis results that classify it as a typical high resolution structured watershed (d = 1 and D = 1.97).

Based on the results obtained in this study, it appears that 10m DEM fine grid images prove to be suitable for a range of environmental mapping tasks involving the use of DDM. One of those task is the great accuracy in the sub watershed delineation and the selection of the optimal point to which each area drains, and that will be use for the water quality assessment projected for the future.

The function of each sub watershed is act as the analytical unit; due to the fine resolution DDM each area can be study in a micro-scale range. Also, for future studies we will have to calculate the landscape indexes such as, topographic, soil and hydrological indexes.

Acknowledgement

Authors would like to extend our gratitude to Haji Dam Management Office for providing me with the necessary data. Special thanks and acknowledge to Dr. Takao Yamashita of IDEC, Hiroshima University for his valuable suggestions that improve this manuscript.

References

Anas Formosa, Baikal Teal, Threatened birds of Asia. URL: http://birdbase.hokkaido-ies.go.jp

Brooks, K.N., H.M. Gregersen, P.F. Ffolliott, and K.G. Tejwani 1992; Watershed management: A key to sustainability. pp. 455-487 IN: N.P. Sharma (ed.) Managing the World’s Forests: Looking for Balance between Conservation and Development; Kendall/Hunt, Dubuque, Iowa.

Claps P., Fiorentino M. and Oliveto G., 1996; Journal of Hydrology, Vol. 187, pp. 145-156.

Colombo, R., Martucci, A., Rodolfi, G., Sarfatti, P., Kahsay, T. and Yohannes, A. 1995; Hydrological analysis of two sub-catchments of the Mareb River (Eritrea). *Atti VII Convegno Nazionale AIT*, Chieri (TO): 349-353.

Costa-Cabral M. C. and Burges S. J., 1997; Sensitivity of channel network planform laws and the question of topologic randomness. Water Resources Research, Vol. 33, No. 9, pp. 2179-2197.

Garcia-Ruiz J. M. and Otalora F., 1992; Fractal Trees and Horton's Law. Mathematical Geology, Vol. 24, No. 1, pp 61-71.

Garrote, L., Bras, R.L., 1995; A distributed model for real-time flood forecasting using digital elevation models, Journal of Hydrology, 167, 279–306.

Green, C.H., Parker, D.J., Tunstall, S.M. 2000; Assessment of Flood Control and Management Options, Thematic Review IV.4 prepared as an input to the World Commission on Dams, Cape Town, URL: www.dams.org.

Gyasi-Agyei Y., Willgoose G., Troch F., 1995; Effects of Vertical Resolution and Map Scale of Digital Elevation Models on Geomorphological Parameters Used in Hydrology, pp. 121-140. IN: John Wiley & Son (ed.) Scale Issues in Hydrological Modelling. Baffins Lane, Chichester, West Sussex, England.

Hogan D., Maltby E. and Blackwell M., 2000; Wetlands as a Buffer Zones in Catchment Water Resource Management, International Conference, Beijing, P.R. China: Ecosystem Service and Sustainable Watershed Management in North China.

Horton, R.E., 1945; Erosional development of streams and their drainage basins: Hydrological approach to quantitative morphology. Geological Society of America Bulletin 56.275-370.

Jain M. K., 1996; Geomorphologic & land use planning for Danda Watershed. National Institute of Hydrology, Roorkee, India.

Jones R., 2002; Algorithms for using a DEM for mapping catchment areas of stream sediment samples Computers & Geosciences 28, 1051–1060.

Kirchner, J.W., 1994a; Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks-Reply to Masek and Turcotte, *Geology*, 22, pp. 380-381.

Kirchner, J.W., 1994b; Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks-Reply to Troutman and Karlinger, *Geology*, 22, pp. 574-575.

Kirchner, J.W., 1993; Statistical inevitability of Horton's laws and the apparent randomness of stream channel networks, *Geology*, 21, pp. 591-594.

Kiss Richard, 2004; Determination of drainage network in digital elevation model, utilities and limitations. Journal of Hungarian Geomathematics, Vol, 2, **2**, pp. 16-29.

Kuriki M., 2000; Why Multipurpose Dams. Function in Japan. Prepared for Thematic Review IV.4: Assessment of Flood Control and Management Options, URL: www.dams.org.

Kusler J. A., Opheim T., 1996; *Our National Wetland Heritage: A Protection Guide, 2nd Edition,* Environmental Law Inst; 2nd edition, 149 pages.

La Barbera P. and Rosso R. 1989; On the fractal dimension of stream networks, Water Resources Research, 25(4), pp. 735–741.

La Barbera P. and Rosso R., 1990; Reply. Water Resources Research 26 (9), pp. 2245–2248.

Liang C. and Mackay D.C., 2000; A general model of watershed extraction and representation using globally optimal flow paths and up-slope contributing areas. Int. J Geographical Information Science, **14**, 4, pp.337-358.

Mandelbrot B.B., 1983; The Fractal Geometry of Nature. Freeman, New York.

Mark, D.M., 1984; Automatic Detection of Drainage Network from Digital Elevation Models. Cartographica, **21**, pp.168-178.

Martz, L.W., Garbrecht, J., 1998; The treatment of flat areas and depressions in automated drainage analysis of raster digital elevation models. Hydrological Processes 12, 843–855.

McCormack, J.E., Hogg, J., 1997; Virtual-memory tiling for spatial data handling in GIS, Computers and Geosciences, 23 (6), 659–669.

Miller, C. L, and Laflamme, R. A., 1958; The Digital Terrain Model Theory and Application. Photogrammetry Engineering. 24 (3): 433.

Moussa R. and Bocquillon C., 1996; Fractal analyses of tree-like channel networks from digital elevation model data. . Journal of Hydrology, Vol. 187, pp. 157-172.

Musa M. K. A., 2004; Accuracy assessment between DEM generated by Hypsographic data and Radarsat stereo images in the production of hilly forests road alignment map. 25th ACRS, Data Progressing, B-1.5, pp. 197-203.

Nakagoshi N., Hikasa M., Koarai M., Goda T., Sakai I., 1998; Grid Map Analysis and Its Application for Detecting Vegetation Changes in Japan. *Applied Vegetation Science*, Vol. 1, No. 2, pp. 219-224.

Nogami, M. 1995; Geomorphometric measures for digital elevation models. Z. Geomorph., N.F., Suppl., Vol. 101, pp. 53-67.

O'Callaghan, J.F., Mark, D.M., 1984; The extraction of drainage networks from digital elevation data. Computer Vision, Graphics and Image Processing. **28**, 323–344.

Oguchi T., Saito K., Kadomura H. and Grossman M., 2001a; Fluvial geomorphology and paleohydrology in Japan, Geomorphology, 39, pp. 3-19.

Oguchi T., 2001b; Geomorphology and GIS in Japan: Background and characteristics, GeoJournal, Vol. 52, pp. 195-202.

Pakhmode V., Kulkarni H. and Deolankar S. B., 2003; Hydrological-drainage analysis in watershed-programme planning: a case from the Deccan basalt, Idia. Hydrogeology Journal, 11:595-604.

Rosso R., Bacchi B. and La Barbera P., 1991; Fractal relation of mainstream length to catchment area in river networks. Water Resources Research 27 (3), pp. 381–387.

Saco P. M. and Kumar P., 2002; Kinematic dispersion in stream networks: 2. Scale issues and self-similar network organization. Water Resources Research, Vol. 38, No. 11, 1245.

Schuller D. J., Rao A. R. and Jeong G. D. 2001; Fractal characteristics of dense stream networks Journal of Hydrology, Volume **243**, Issues 1-2, pp 1-16

Strahler A. N., 1952; Hypsometry (area-altitud) analysis if Erosional topography. Bull. Geol. Soc. Am. **63**, pp. 117-1142.

Strahler A. N., 1964; Quantitative Geomorphology of Drainage Basin and Channel Networks. Handbook of Appl. Hydrology, ed. McGraw-Hill Book Company Inc., New York, pp. 4,39-4,79

Tarboton D. G., Bras R. L. and Rodriguez-Iturbe I., 1988; The fractal nature of river networks. Water Resources Research 24 (8), pp. 1317 – 1322.

Tarboton D. G., Bras R. L. and Rodriguez-Iturbe I., 1990; Comment on “the fractal dimension of stream networks”. Water Resources Research 26 (9), pp. 2243 – 2244.

Veltri M., Veltri P. and Maiolo M., 1995; On the fractal description of natural channel networks. Journal of Hydrology, Vol. 187, pp. 137-144 (Scale of 1:10000)

Walker J. P. and Willgoose G. R., 1999; On the effect of digital elevation model accuracy on hydrology and geomorphology. Water Resource Research, Vol. 35, No. 7, pp. 2259-2268.

Wiche, G.J.; Jenson, S.K.; Baglio, J.V.; Domingue, J.O., 1992; Application of digital elevation models to delineate drainage areas and compute hydrologic characteristics for sites in the James River Basin, North Dakota: U.S. Geological Survey Water-Supply Paper 2383, 23 p. abstract URL http://nd.water.usgs.gov/pubs/wsp/wsp2383/index.html

Yoshinori T., 1974; Study on the Stream Channel (V) On a Hypsometric curve synthesized from channel network in equilibrium stage. Journal of the Japan Society of Erosion Control Engineering, Vol. 93, pp. 19-29.

（2007.2.23 受理）