Fuzzy Identification and Manipulation of Source Channels in Channel Network Derived from Digital Elevation Model

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Abstract

The accuracy of channel networks extracted automatically from a grid digital elevation model (DEM) generally relies on the selection of a Critical Source Area (CSA) threshold. Using an unique CSA within an entire DEM will lead to the assumption that all source (1st order) channels have an equal contributing area. Thus, overshoot and undershoot problems, excessive and deficient representation of source channels, appear frequently in the channel network, especially for a DEM of a hydrologically heterogeneous region. This research focused on these problems by introducing fuzzy set theory for source channel identification and manipulation. A comprehensive valley morphology membership function is employed to calculate the CSA for each individual source channel. The function depends on the relationship between the contributing area and valley morphology. A new approach, Fuzzy Identification Channel Network Model (FICNM), is proposed and developed in the research. The main procedure of FICNM includes: (1) generating an extremely dense channel network by DEDNM (Digital Elevation Drainage Network Model) to avoid undershoot problems; (2) collecting valley morphology information for each source channel; (3) calculating valley morphology membership grade and converting the grade to CSA for each source channel; and (4) eliminating some source channels partly or totally to solve the overshoot problems. Performance of FICNM has been tested in three DEMs. The results indicate that FICNM works well in heterogeneous regions and can set flexible CSA for individual source channels. Therefore, FICNM can enhance the potential reliability of channel network derived from DEM.

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Finally, this thesis is dedicated to my wife, Aiqi, and my son, Ziqi. Without their consistent support and extra patience, this thesis might never have been completed.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

A Digital Elevation Model (DEM) is an ordered array of numbers that represents the spatial distribution of terrain elevations (Moore *et al.*, 1991). Three major methods to structure a DEM are commonly used: raster-type DEM, triangulated irregular network (TIN), and contour-based DEM. The distinction among them lies in their organizations of elevation data for the land surface imitation. The raster-type DEM represents the ground by an evenly spaced grid to hold elevation data (Doyle, 1978). TIN portrays the terrain surface by many piecewise linear facets (Jones *et al.*, 1990). Contour-based DEM's symbolize the land surface by clusters of irregular shaped polygons (Moore *et al.*, 1988). The use of grid DEMs is dominant fashion because they are more easily used to derive features of a land surface. They are also a more available source of digital elevation data, and more compatible structurally with computer storage, remotely sensing data and GIS techniques (Tribe, 1991). In this research, only grid DEMs are involved.

Techniques for automated recognition of landform and extraction of topographic information from DEMs have been developed in recent decades (Moore *et al.*, 1991). At present, DEM analysis techniques are available to delineate channel networks and drainage divides, to extract slope properties, and to determine total and direct drainage area, length, slope, and Strahler order of each channel network links from DEM (Martz and Garbrecht, 1992). Such techniques have been applied in geology (Beaver and Eliason, 1992), geomorphology (Moore and Mark, 1992), climatology (Adomeit and Austin, 1987), hydrology (Wiche *et al.*, 1992), soil science (Su and Kanemasu, 1990), agriculture (Smith *et al.*, 1987), land use management (Burrough and Macmillan, 1992), rural and urban planning (Reutebuch and Twito, 1985; Djokic and Maidment, 1991), cartography (Allam, 1988), remote sensing (Niemann, 1988) and geographic information systems (Derenyi and Pollock, 1990; Weibel and DeLotto, 1988).

Research on the automated extraction of topographic information from DEM has predominantly concentrated on slope properties, ridges, channels, and drainage networks (Martz and Garbrecht, 1993). The issue of recognizing valley heads is seldom studied independently (Tribe, 1991). Here, the term valley head refers to the upstream end of a first order channel. Tribe (1990, 1991, 1992) first addressed this issue of location of valley heads and undertook research on valley head recognition from DEM. She concluded that the positions of valley heads in a channel network must be given specific consideration and treatment to improve the reliability of channel network derived from DEM.

The problem of valley head recognition is an outgrowth of channel network delineation. That is, a valley head position is defined arbitrarily at an upstream end of a first order (source) channel by some kind of a threshold when delineating a channel network from a DEM. However, it is not enough to study only the issue of the valley head position to pursue Tribe's purpose, for valley head recognition is closely related to source channel validity. Any modification in source channels can lead to a new arrangement in the whole channel system order. For the current approaches of delineating the channel network from a DEM, the positioning of source channels is critical, but it is more questionable than any other order channels. Because valley head recognition is highly associated with the morphology of the source channel, the characteristic of source channel morphology must be inspected thoroughly. Therefore, special manipulation should be offered for source channel validity rather than for valley head position only.

This research extends the issue of valley head recognition to the issue of source channel validation for a channel network system derived from a grid DEM. The characteristics of source channel morphology and the concepts of valley and channel will be discussed. A new method will be approached systematically for inspecting and modifying source channels in channel networks derived from DEMs.

1.2 Problems:

The position of a valley head is commonly recognized and delineated by applying a single threshold or sample combined thresholds for all source channels within an entire DEM. This kind of threshold includes Critical Source Area (CSA), Minimum Source Channel Length (MSCL), upstream channel slope or side slope, or any combination of them (e.g. O'Callaghan and Mark, 1984; Tribe, 1991; Martz and Garbrecht, 1992). In O'Callaghan and Mark's (1984) approach of runoff simulation (see details in next chapter) the threshold of inflow accumulation area is a key parameter for deriving channel network.

However, the use of a single threshold for all source channel delineation in an entire DEM may lead to the assumption that each source channel has the same characteristics specified by the threshold. For instance, the use of a single catchment area threshold (also true for other thresholds) to all source channels will suggest that every source channel has an equal catchment area. Thus, if the threshold of catchment area is defined larger than the contributing area of a real source channel, the source channel will not be delineated completely. That is, it will be shorter than the length that the real source channel would have. This is termed the undershoot problem. Conversely, if the threshold is defined smaller than the contributing area of a real source channel, a problem of excessive representation for the source channel will occur. That is, the delineated source channel is longer than what it should be (termed overshoot problem). Figure 1-1 illustrates the problems of undershoot and overshoot, which are dependent on the relationship between the contributing area of a real source channel and the catchment area defined by the inflow accumulation threshold.

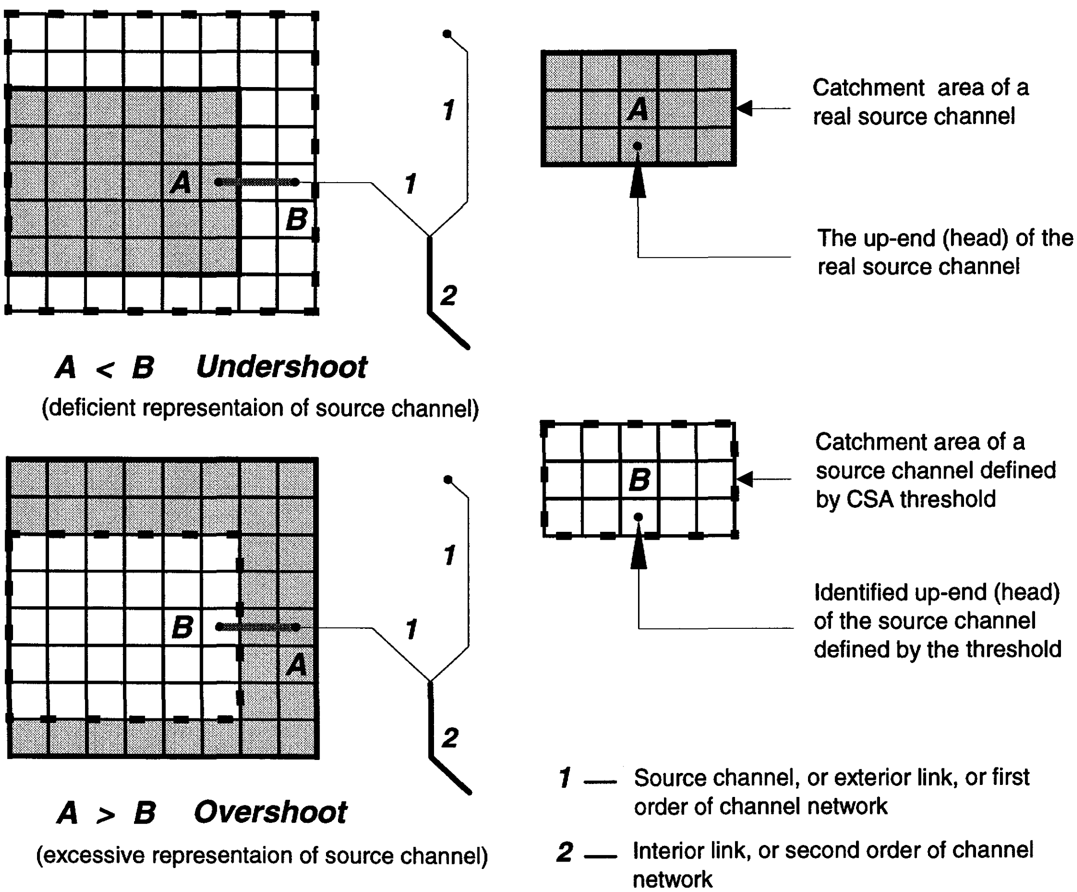


Figure 1-1 Problems of source channel delineation resulted from threshold selection

It is commonly expected that not all source channels have the same size of catchment area, due to the local disparity within a same drainage basin. However, the results may appear satisfactory if an appropriate single threshold is defined for an approximately homogeneous region (Garbrecht and Martz, 1993). In this case, the magnitude of undershoots and overshoots would be small and would tend to compensate for one another. However, the problems of overshoots (delineated excessively) and undershoots (delineated inadequately) of the source channels occur often seriously when the channel network is extracted from a DEM of an approximately heterogeneous region. This is why the threshold of catchment area works well in some case and not in others (Tribe, 1991).

The critical question is where exactly the valley heads should occur when delineating the starting points of the source channels? What kind of landform features can be measured to mark the valley heads? Is there any method to set a flexible threshold for each individual source channel rather than a unique threshold on a whole DEM? Some factors make these questions more complex. One is that the concept of valley is not quantitative and operable but quite ambiguous for automated channel recognition from DEM. For instance, what kind of quantitative characteristics in morphology can be used to distinguish valleys from the hollows upslope of the source channels on DEMs? Another situation is often confronted in the field: source channel heads in a rugged area are easy to distinguish but in a very gentle relief area are less distinctive. This is also the case with DEM. For some source channels, morphologic information is quite limited, whatever on DEM or on the site. This implies that there is some limitation on the recognition of all the valley heads from DEMs.

1.3 Purpose and Objectives

In order to improve the reliability of channel networks derived from DEMs, a new method is proposed and developed in this research. The new method incorporates the advantages of all existing approaches on channel network delineation by introducing a valley morphology membership function for source channel treatment. The new method attempts to enhance the reliability of source channels and their heads derived from DEM.

The objectives of the research are:

1) examine the conceptual difference between valley and channel and its effect on the approaches of channel network delineation from a DEM; analyze the relationship between contributing area and valley morphology; and develop a new framework for source channel verification and treatment.

2) introduce fuzzy set theory to deal with the quantification of valley morphology; create a comprehensive membership function of valley morphology to evaluate the characteristic of valley morphology for each source channel; and apply a flexible threshold to manipulate each source channel individually.

3) develop a special program for the new approach to execute the tasks of data collection from DEM, assessment of source channel morphology and modification of the channel network system; and verify the functions of the new approach in a range of topographic settings among three different DEM data sets.

1.4 Scope of the Thesis

In this research, three DEM data sets are involved. They are Bill's Creek in Oklahoma, Johnson Creek in Vermont and Wolf Creek in Yukon. The criterion for choosing these data was based on the data availability and regional diversity. These DEMs have a same spatial resolution (30m x 30m) but they locate in different region with different landforms. The detailed geographic characteristics of them are listed in Table 3-1. The difference among them will be applied for testing the function of the proposed methods.

Due to no special treatment for source channels delineated from DEM and the use of a fixed threshold in an entire DEM, problems of overshoot and undershoot of source channels are unavoidable. A new approach is proposed and developed in this work to deal with the problems. Fuzzy set theory is introduced for source channel identification and manipulation by creating valley morphology membership function, which depends on the relationship between contributing area and typicality of valley morphology. A new model, Fuzzy Identification Channel Network Model (FICNM), is developed for setting flexible threshold for each individual source channel. Finally, the performance of FICNM is verified in the selected three DEMs, and the results prove that the new approach possesses a good adaptation in application for the DEM of a heterogeneous region.

Chapter 2

Literature Review and Theoretical Basis

2.1 Automated Channel Network Delineation and Valley Head Recognition

There are two general conceptual models presently used to extract information on channel networks from grid DEM. The first model is the local morphology approach. It is based on a 'higher than' comparison. Peuker and Douglas (1975) initially suggested passing a 2 by 2 window over a DEM. At each position of the window, the highest cell of the four is flagged. After the window has passed over the entire DEM, the unflagged cells are defined as the valley lines. Jenson (1985) improved the method by passing a 3 by 3 window over a DEM. At each position, the elevation of the centre cell is compared to each elevation of its eight neighbour cells respectively. If the elevations of an opposing neighbour pair are greater than that of the centre cell, the cell has `V'-shaped profile and is thus likely to channel water (Figure 2-1). If all such `V'-shaped cells are marked, the resultant map shows the valley network (Tribe 1992). While this method has an explicit basis in morphologic information on the land surface, its main disadvantage is that it generates discontinuous network segments. Many variations on this type of general approach have been developed by Johnston and Rosenfeld (1975), Grender (1976), Toriwaki and Fukumura (1978), Carroll (1983), Mark (1984), Jenson (1985), Douglas (1986), Burrough (1986), and Tribe (1990, 1991), etc.

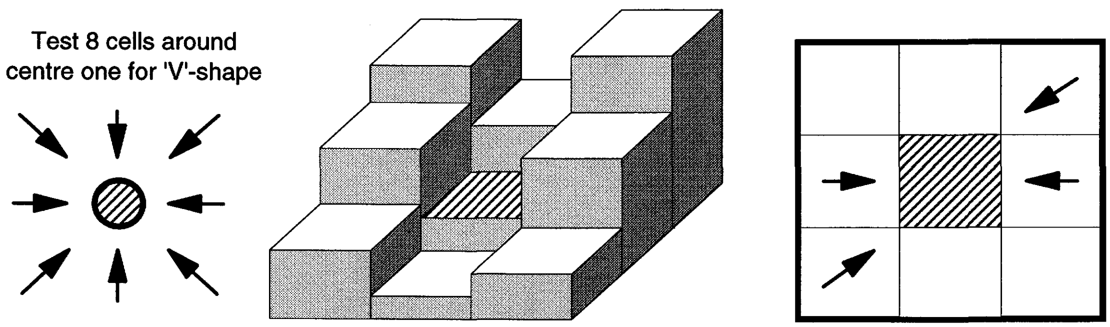
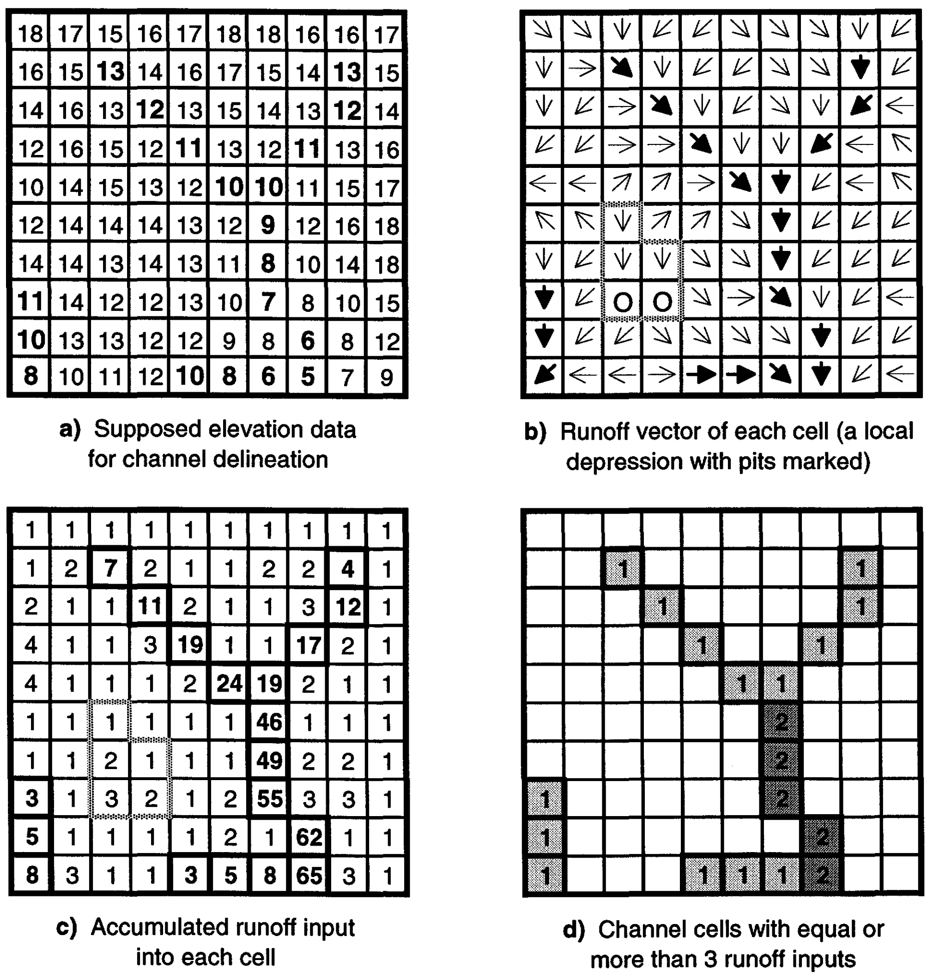


Figure 2-1 Local morphology approach for channel network delineation from DEM

The second model, based on the surface runoff simulation, was first presented by O'Callaghan and Mark (1984). Using grid elevation data (Figure 2-2a), the maximum elevation interval between each centre cell and its eight neighbour cells is found by scanning a 3 by 3 window. The centre cell is assigned a drainage direction which points to its lowest neighbour cell (Figure 2-2b). The directions are then used to simulate surface runoff so as to calculate the number of upstream cells contributing flow to each cell (Figure 2-2c). A flow accumulation threshold is used to evaluate each cell such that any cell with an accumulation value greater than this threshold is identified as part of the valley network (Figure 2-2d). Here, the derived channel network pattern (or density) is dependent on the selection of the accumulation area threshold. Due to its basis in hydrology, this method is considered a better approach than the first and has been utilized dominantly in recent years (Tribe, 1992). The main problem of the approach is the existence of pits in DEM. Pits are cells in DEM for which the elevations of all neighbour cells are equal to or greater than that of the central cell and, therefore, no drainage direction can be assigned to them. Many methods on this type of general approach to the pit problem have been developed in recent years by Mark (1984), Band (1986, 1989), Carrara (1986), Yuan and Vanderpool (1986), Weibel et al. (1987), Jenson and Domingue (1988), Martz and de Jong (1988), Morris and Heerdegen (1988), Yoshiyama (1989), Skidmore (1990), Tribe (1991), and Martz and Garbrecht (1992, 1993).



a) Supposed elevation data for channel delineation

b) Runoff vector of each cell (a local depression with pits marked)

c) Accumulated runoff input into each cell

d) Channel cells with equal or more than 3 runoff inputs

Figure 2-2 Runoff simulation approach for channel network delineation from DEM

Research on valley head recognition from DEMs has been undertaken recently by Tribe (1991, 1992). Her method is based on O`Callaghan and Mark's (1984) runoff simulation algorithm. After testing a single flow accumulation threshold and obtaining an unsatisfactory result, she then applied two thresholds to locate valley heads. The first is a small area threshold which is used to mark all of the cells with many (e.g. >3) flow inputs as channel cells. Because not all the marked cells are valley head cells, she then uses a slope threshold to identify the cells with a slope value greater than a threshold value as valley head cells. She identifies all valley heads successfully on a small artificial landscape (only ten valley heads involved), but her method is less successful on real data (100 km^2), due to the variability of the landscape. She believes that this was caused by using single threshold for the entire DEM and that the best way is to enable computer to `learn' thresholds suitable for the recognition of valley heads in particular parts of a DEM.

2.2 Channel and Valley Concepts

It is necessary to discuss the conceptual difference between channel and valley, for this difference will affect what technique should be employed and how an appropriate threshold is defined for valley head recognition and source channel delineation.

A channel is "a long, narrow, troughlike depression occupied and shaped by a stream moving to progressively lower levels" (Strahler and Strahler 1992). Generally, all channels of a drainage system connect to each other and constitute a channel network. There are commonly three types of ordering systems for channel networks; those introduced by Horton (1945), Strahler (1952), and Shreve (1966). The most widely used method of ordering streams is that developed by A. N. Strahler. He defined all channels which have no tributaries as first order channels. Where two first order channels join, they form a second order channel; where two second order channels meet they form a third order channel, and so forth. The concept of the first orders of channels is exactly equivalent to Shreve's concept of `exterior links' (Mark, 1988). In this research, the term source channel is used to refer to first order channels, or exterior links.

The concept of valley has broad meaning. A valley is an elongated depression with an outlet, between ranges of hills (Stamp, 1966). Sometimes, it can be used to refer an area of a great river system, such as St. Lawrence valley. But sometimes, it can refer to a very small local depression with steep sides, like a gully. The term gully is used to refer to a deep, V-shaped trench with steep walls, carved by a stream in rapid headward growth during accelerated soil erosion (Strahler and Strahler 1992). Gully heads are the points at which overland flow converges into stream flow. Therefore, a gully can be viewed as a first order channel in a stream network system.

The common features of the two concepts, channel and valley, are that both are landscape depressions through which flowing water can move as streams. The difference is that the concept of channel stresses the flow path in hydrology while the concept of valley is more concerned with the shape of the depression in geomorphology.

Spatially, a channel network system coincides roughly with its corresponding valley system, especially in the middle reaches of a river. In the lower reaches, there is often only channel and the corresponding valley is not readily apparent. Therefore, in the middle and lower of network reaches, it is necessary to explicitly identify the channel and not the valley. For the upper reaches, especially for first order channels, any small valley or gully corresponds to a source channel. However, not all source channels possess a typical V-shape side slope. Not all source channels can be defined to gullies. In this case, using a valley concept is appropriate to identify a source channel. Clearly the morphology of the source channel should be considered, because if a gully head is recognized, the head of the source channel is identified precisely. If a source channel appears without typical valley morphology, special treatment is needed to confirm the validity of the source channel delineated.

The change of the conceptual model for extracting channel networks from DEM, from the local morphology approach to the runoff simulation approach, involves a shift of the central concept from valley to channel. In the local morphology approach, looking for a V-shape cross-section, typical of a small stream or gully, is the key point. In the runoff simulation approach, the flow direction for every cell, or unimpeded path for a channel, is most important. Even if a pit or local depression or flat area is confronted, the technique of filling to overflow (Martz and Garbrecht 1992) can be employed to create an unblocked path, regardless of whether a real v-shape profile exists. Because a channel network system, especially the source channels, is actually a mix of both channel and valley, their characteristics should be considered altogether when creating a model or algorithm for channel network delineation from DEM. However, due to no careful distinction of the concepts, either of the current two approaches uses one strategy to treat the all of the channel network. Information on valley morphology in DEM is not utilized fully in the popular runoff simulation approach even though it deserves more attention in assessing source channel validity.

2.3 Contributing Area and Valley Morphology

The generation and development of source channels are controlled by different geographic factors including relief, climatic conditions, hydrologic properties, vegetation cover, soil type and surface material. The catchment area and morphology of each source channel depend on the integrated operation of these factors.

The link between the contributing area and the typicality of the source valley morphology is the size of the contributing area. Here, the term of *typicality* of valley morphology is used to refer to *how typical a source channel appears in valley form*, and the term of contributing area refers the section of the catchment area located directly above a source channel head. Under particular geomorphologic, climatic, vegetative and edaphic conditions, the size of the contributing area determines the amount of overland flow converging into a source channel and overland flow provides the material and energy to modify the morphology of a source channel (valley),. The relationship between the size of the contributing area and typicality of the source valley morphology can be observed: the more distinctive (e.g. steep side slope) morphology of a valley, such as a gully, the smaller its contributing area or the higher the upward extend position of its head, under similar conditions; the less typical (e.g. shallow or gentle side slope) the morphology of a valley, the larger the catchment area is required to accumulate adequate energy to support it.

The slope condition of the contributing area controls the potential and kinetic energy of overland flow. Although it is not mentioned in the relationship above, it has been represented actually by the size of the contributing area indirectly. For instance, if the slope is steep, a small size contributing area can provide sufficient energy to sustain a source channel. Therefore, the relationship can also be expressed that the steeper the slope, the smaller the contributing area, and the more typical the valley morphology of a source channel. Because the size data of contributing area are more easily obtained from DEM than slope data of contributing area, the slope condition of it will not be involved directly in this study.

The relationship between contributing area and valley morphology can be observed in reality and supported by the following analysis based on a hypothesized situation. There are two source channels with very similar characteristics on their valley morphology. If they are located closely together in a small region over which climatic and edaphic controls are homogeneous, they should have approximately the same contributing area in view of the similar basis on material and energy. If the two source channels do not have approximately the same contributing area, they may be located in different regions or generated in different geologic time. If they are in a same region indeed but with different contributing area, the source channel with the smaller contributing area must have a scarce vegetation or easy erodible surface in its catchment area. Conversely, the source channel with the larger contributing area must have a abundance vegetation or resistant surface. Therefore, it needs more energy to shape it through a large catchment area to accumulate sufficient overland flow. In this case, they must locate in a heterogeneous region.

Generally, for a certain region (not very large), there is an approximately same annual precipitation and history in geology. The local difference in the region is in local relief, local vegetation and local surface material. Therefore, a minimum contributing area for a non-typical valley and a maximum contributing area for a most typical valley can be expected for that region. Different region possesses different minimum and maximum contributing area. This discussion is the basis of creation of comprehensive CSA threshold.

2.4 Quantification for Valley Morphology

To specify the characteristics of source channel (valley) morphology an effective quantitative method must be adopted to distinguish the morphologic typicality for each source channel. The proposed new method should be able to measure the degree of the morphologic typicality, so that an appraised value of the typicality can be assigned to each source channel. Due to imprecision of the valley concept, fuzzy set theory is introduced in the research for the purpose of morphologic quantification.

2.4.1 Fuzzy Set Theory

Fuzzy set theory is different from classical set theory or crisp set theory. In crisp set theory, an element can either belong to a set or not with complete certainty. Elements are differentiated in a dichotomous fashion (e.g. yes-or-no, true-or-false, rather than more-or-less) (Zimmermann, 1991). There is no ambiguity in assignment and unequivocality, certainty and precision are assumed. However, this is not adequate to depict much of the real world. Rather, imprecision and uncertainty exist everywhere in reality and are often used in daily life to represent our perception of the real world. For instance, concepts of hot weather, steep slope, beautiful flower, keen ear, clear picture, and serious headache, describe understandable situations. But these concepts are difficult to model by classical mathematics. In geography, fuzziness often characterizes many factors, features and their relationship. In fact, the more complex the geosystem involved, the lower the extent or precision of quantification for modelling by classical methods (Leung, 1988).

Fuzzy set theory can deal with the quantification and modelling of such things in terms of imprecision, uncertainty, vagueness and complexity. Actually, fuzzy set theory is an expansion of the classical set theory and it provides the counterpart operations to those of classical set theory. The theory was introduced thirty years ago (Zadeh, 1965) and now is broadly applied in various fields, such as fuzzy logic and fuzzy reasoning, pattern recognition and fuzzy control, artificial intelligence and expert system, and spatial analysis in geography (Leung, 1988).

2.4.2 Membership Grade and Membership Function

One basic and important concept in fuzzy set theory is that of membership grade, which can measure how near or close one thing is to another thing defined by our perception. The grade of membership of a fuzzy set is a real number in a [0, 1] domain, where 0 presents no membership and 1 presents complete membership (Zimmermann, 1991).

A membership function is used to calculate the membership grade of an object; for instance, the membership grade of valley morphology of a source channel. The value of membership grade falls among zero to one. If a source channel's membership grade is one, the channel possesses a typical valley morphology defined by our perception (e.g. two side slopes are greater than 30 degrees). If the number is zero, it means that the source channel is only a flow path or local depression and has no typical valley morphology (e.g. two side slopes are less than 3 degrees). If the value is 0.6, it indicates that the source channel exhibits only 60 % of typicality of valley morphology. Therefore, the membership grade of valley morphology is employed in this research for measuring the typicality for all source channels. The detail on creating the membership function of valley morphology will be discussed in next chapter.

2.5 Conceptual Framework of a New Approach

A new approach, a combination of the runoff simulation approach and the local morphology approach by introducing the membership function of valley morphology, is proposed to deal with the problem of valley head recognition and source channel delineation. The approach includes two main procedures.

Firstly, the runoff simulation technique is utilized to complete such tasks as assigning flow direction; accumulating flow inputs for each cell in a DEM; and delineating the channel network. When delineating all channel cells from the DEM, very low CSA (Critical Source Area) and MSCL (Minimum Source Channel Length) thresholds are applied so as to guarantee no undershoot problems in all source channels. As a result, an extremely dense channel network is obtained in this step and only overshoot problems exist on the derived channel network.

Second, a membership function of valley morphology is employed for assessing the valley morphology typicality for each individual source channel generated from the first step. This new approach first collect the morphologic data for all source channels from DEM. Then, a valley morphology membership function is used to calculate the valley morphology membership grades from the data. The membership grades are then converted to CSA threshold values for each individual source channel. Next, all source channels are examined and all the cells with the catchment area lower than their CSA thresholds are marked. These marked cells will be eliminated downward continuously from channel heads until stopped where the calculated CSA thresholds are matched. This is actually to get rid of some overshoot sections of source channels. After some source channels are eliminated completely, the remained channel network may not fit the Strahler's ordering system and must be reordered again. Therefore, some new source channels are produced. Then, the second procedure is executed repeatedly until no overshoot problems exist and all the source channels have their proper contributing area which corresponds to their morphology typicality.

Chapter 3

Methodology

3.1 Study Sites and Data Sets

To test the new approach, three data sets are manipulated in this research. They are Bill's Creek in Oklahoma, Johnson Creek in Vermont and Wolf Creek in Yukon. These were selected on the criteria of the data availability and regional diversity. The first two are already 7.5" USGS DEMs. The third is digitized from 1:50,000 topographic map and is processed by SURFER software to generate a DEM in the resolution of 30m by 30m. The detail characteristics are listed in Table 3-1.

Table 3-1 General Features of Three DEM Data Sets

DEM Data Sets	Bill's Creek	Johnson Creek	Wolf Creek
Centroid Position	N $34^0 57'$ W $98^0 04'$ Oklahoma	N $44^0 40'$ W $72^0 41'$ Vermont	N $60^0 32'$ W $135^0 06'$ Yukon
Number of Rows	351	342	335
Number of Columns	500	474	435
Resolution (cell size)	30m x 30m	30m x 30m	30m x 30m
DEM Area	157.95 km^2	145.90 km^2	131.15 km^2
Minimum Elevation	33m	140m	1006m
Maximum Elevation	183m	869m	2073m
Elevation interval	150m	729m	1067m
E. interval / Area	0.95 m/km^2	5.0 m/km^2	8.14 m/km^2
Land Relief	Low Relief	Moderate Relief	High Relief

Obviously these DEMs are located in different climatic zones. From the table it is clear that they cover approximate same area and that the elevation ranges of these regions are considerably different. In Bill's Creek, the topography is mainly hills with very gentle slope. In Johnson Creek, the landform is also hills but with moderate slope. In Wolf Creek, the landform includes both some steep hills and broad flat regions. Therefore, the DEM of Bill's Creek represents a very gentle relief and a hydrologically homogeneous region whereas the DEM of Wolf Creek represents a high relief and heterogeneous region.

3.2 Initial Network Extraction

Before the new approach is used to treat the channel network derived from DEM, two kinds of channel networks are required. One is a "normal" channel network that appears similar to the blue line of topographic map in terms of overall pattern or density; the other is an extremely dense channel network that will be assessed by membership function. Both of them are generated initially by DEDNM.

3.2.1 DEDNM and IDRISI

Program DEDNM, Digital Elevation Drainage Network Model, is a software package developed by Martz and Garbrecht (1991). The purpose of this program is for hydrologic and geomorphic analysis. It performs the following tasks: DEM aggregation; depression identification and treatment; relief increment of flat areas; flow vector determination; watershed boundary delineation; drainage network and subcatchment area definition and systematic indexing; tabulation of channel and subcatchment area properties; and evaluation of drainage network composition (Martz and Garbrecht, 1992).

DEDNM is based on the "runoff simulation approach" with ten specific algorithms for all of its tasks. The main operation of DEDNM comprises the following steps: It first reads in a parameter and option file and DEM data. These DEM data are then aggregated or resampled when these treatments are required. Next, the DEM data are smoothed to reduce some noise in them. Then, DEDNM fills the depression sections and increases the local relief in a minimum amount for flat area, so that the flow vectors can be assigned to all DEM cells. Next, the program calculates the upstream drainage areas for each cell and determines the boundary of the watershed. DEDNM then identifies the drainage network, orders all channels and records the attributes on every order channel. Finally, DEDNM identifies all of the subwatershed areas and their parameters and produces a series of images and attribute tables for the DEM region. Clearly the program deals with a wide range of general issues for extracting channel network and drainage basin parameters from DEMs.

The reason for applying DEDNM in the research is threefold: 1) DEDNM is a tool to generate extremely dense channel networks without undershoot problems by using drainage flow direction for all cells; 2) DEDNM's standard outputs are a prototype of the "runoff simulation approach" in channel network delineation from DEM without special treatment of source channels. This standard output is compared with the results of the proposed new approach; and 3) DEDNM provides raster data for the research that focuses only on the issue of source channel treatment and avoids the involvement of the common problems on DEM, such as pits or flat area treatment.

In addition to tabular outputs of the program on main watershed and individual network links and individual subwatersheds, DEDNM raster output files consist of the following images:

bound.dat -- drainage basin boundary on DEM

flovec.dat -- flow direction at each grid cell

fildep.dat -- extent of depressions and flat areas

inelev.dat -- DEM with depressions

netw.dat -- channel network: links by Strahler order

relief.dat -- DEM with depressions filled and relief imposed on flat areas

smooth.dat -- smoothed DEM

subwta.dat -- template of main watershed

uparea.dat -- drainage area at each grid cell

IDRISI is a grid-based geographic information and image processing system developed by the Graduate School of Geography at Clark University. It is an inexpensive and education-oriented GIS software package and is widely used. In this research, the output of DEDNM is converted by its file utilities to input for IDRISI. The IDRISI image display and data conversion modules are employed for testing and visualizing results.

3.2.2 Extremely Dense Channel Network

Before running DEDNM to treat the original three DEM data sets, two user-defined channel network parameters are defined. One parameter is the Critical Source Area (CSA) and the other is the Minimum Source Channel Length (MSCL). The CSA is a threshold value that defines a minimum catchment area for supporting a permanent source channel. The choice of the value is generally dependent on the regional characteristics, such as climatic conditions, vegetation cover, surface material, and morphology. The MSCL defines the threshold of the source channel length. Any source channel with a length shorter than the threshold will be pruned.

Applying this kind of parameters to source channel delineation is quite common in many of current models. In DEDNM, the two parameters will define the locations of the upstream ends of source channels in the DEM. First, DEDNM recognizes all the cells that have a catchment area larger than the parameter CSA as channels. Next, DEDNM orders all channels using the Strahler ordering system (1952). Then, DEDNM calculates the length of all source channels and deletes those with a length shorter than the parameter MSCL. The program requires that CSA must be equal to or bigger than 3 by 3 cell units and MSCL equal to or bigger than 2 cell units. The channel network derived from a DEM by DEDNM varies with the choice of the two parameters. According to Garbrecht and Martz (1993), the channel network generated from the DEM of Bill's Creek is most similar to the blue line network on the corresponding topographic map if the CSA is set to 90 cell units (8 hectares) and the MSCL is set to 5 cell units (150 meter).

In this research, an extreme condition is adopted by choosing very small CSA and MSCL when running DEDNM. The purpose is to avoid the appearance of undershoot problems for source channels in all of the pre-processed data and to get a good base for further evaluation of valley morphology feature. The CSA is set to 4 by 4 cell units and the MSCL is set to 3 cell units of DEMs. Under this condition, an extremely detailed channel network is generated for the DEMs of Bill's Creek, Johnson Creek and Wolf Creek (Figure 3-1, Figure 3-2, Figure 3-3). In these figures, the "normal" networks refer to that when running DEDNM under the selected CSA and MSCL parameters, the overall patterns or densities of the generated channel networks appear similar to the blue lines in their corresponding topographic maps. After running DEDNM, four image data files, out of nine DEDNM output files, are used in further analysis for the three studied regions:

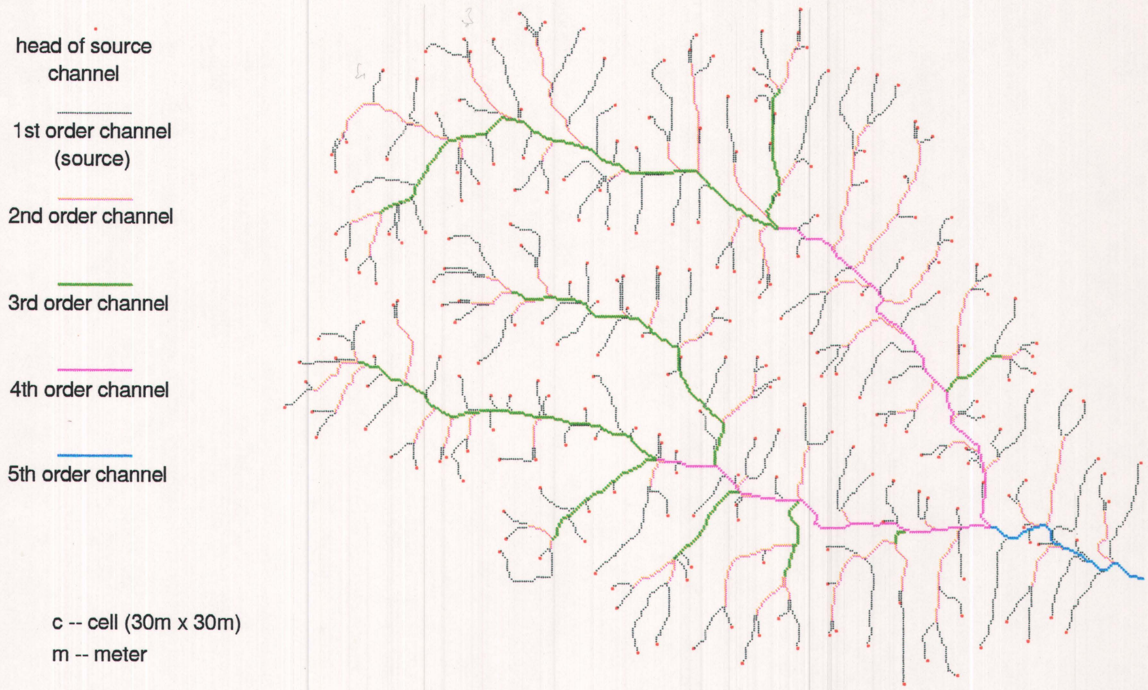


Figure 3-1a Normal DEDNM Network (CSA=64c, MSCL=150m), Bill's Creek

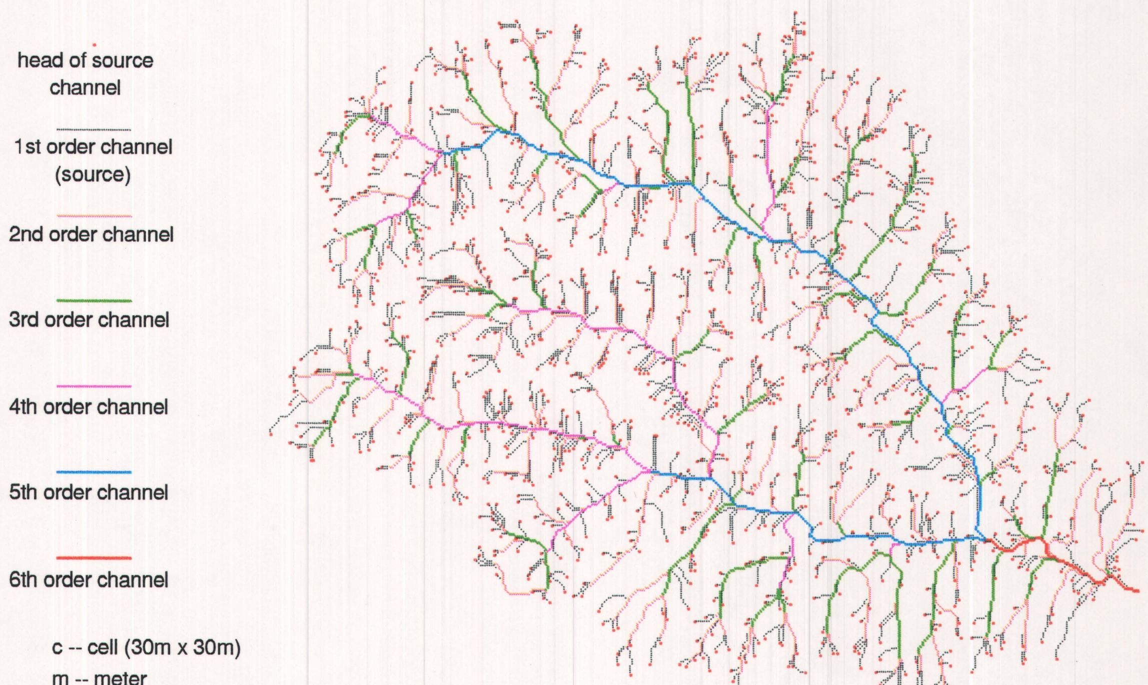


Figure 3-1b Extremely dense DEDNM Network (CSA=16c, MSCL=90m), Bill's Creek

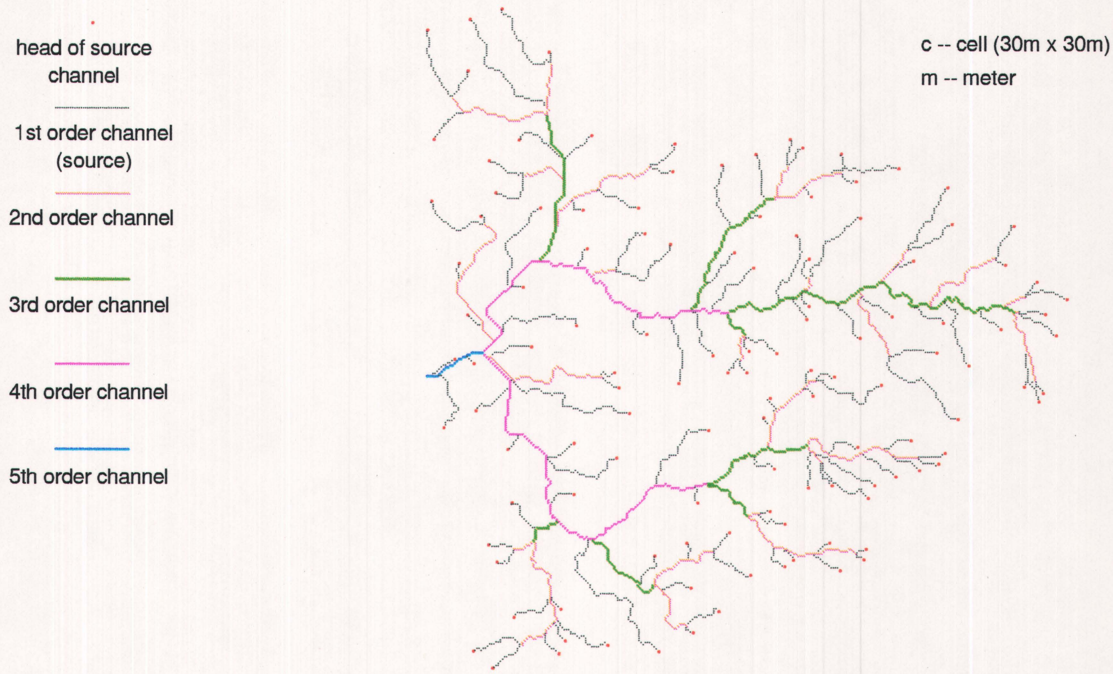


Figure 3-2a Normal DEDNM Network (CSA=144c, MSCL=150m), Johnson Creek

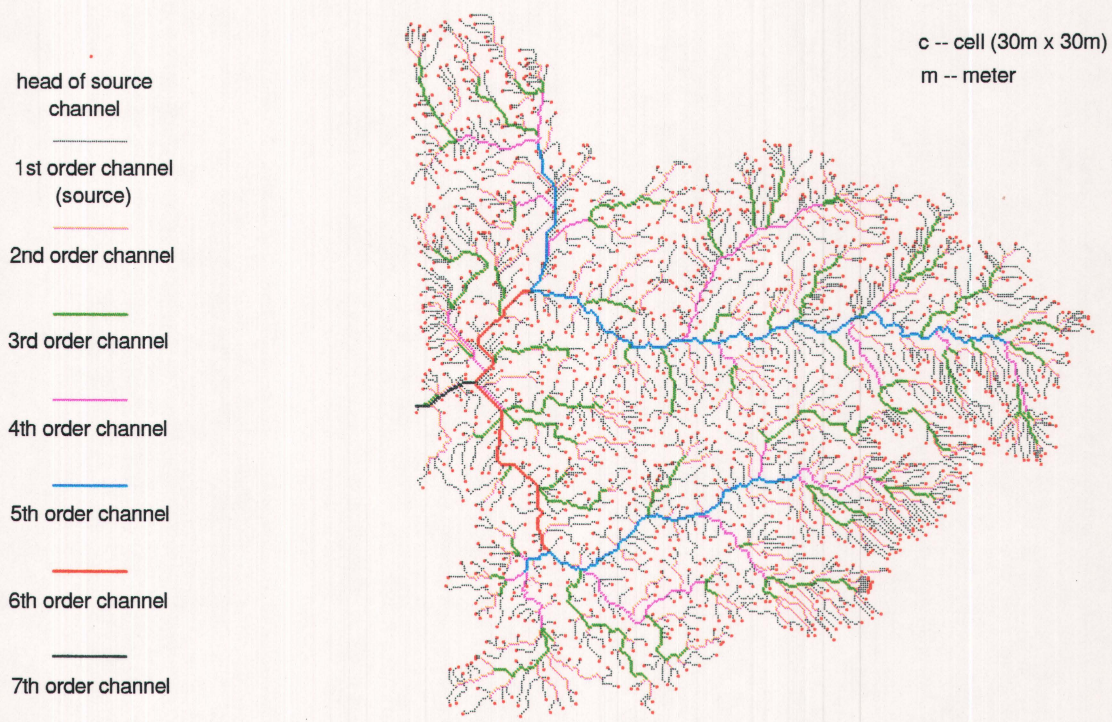


Figure 3-2b Extremely dense DEDNM Network (CSA=16c, MSCL=90m), Johnson Creek

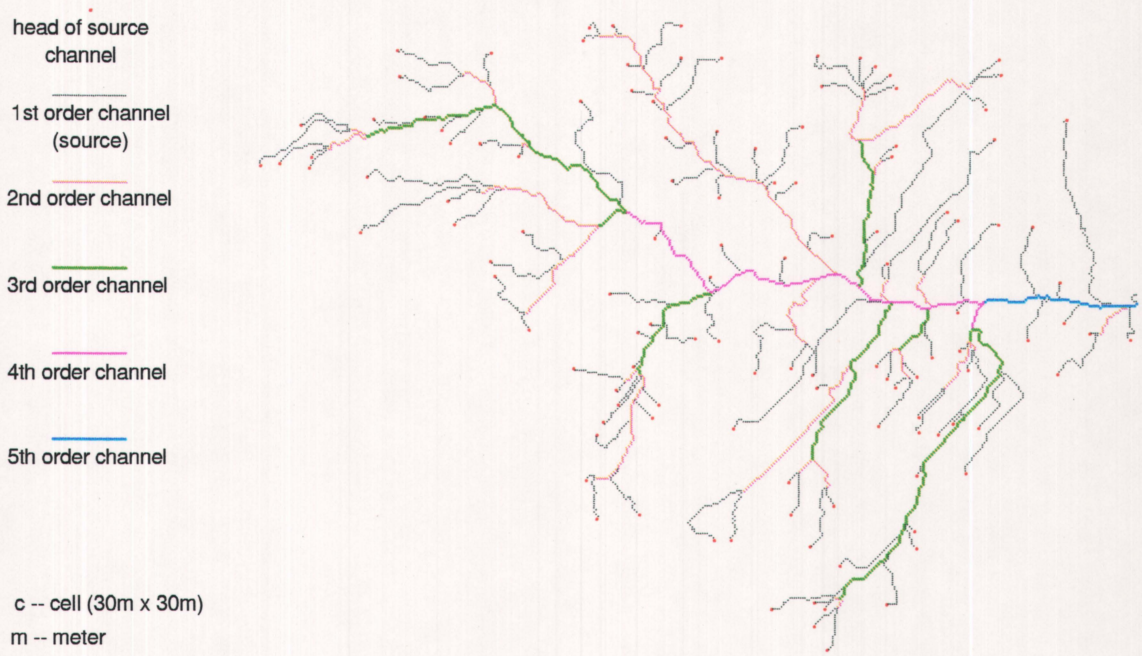


Figure 3-3a Normal DEDNM Network (CSA=196c, MSCL=150m), Wolf Creek

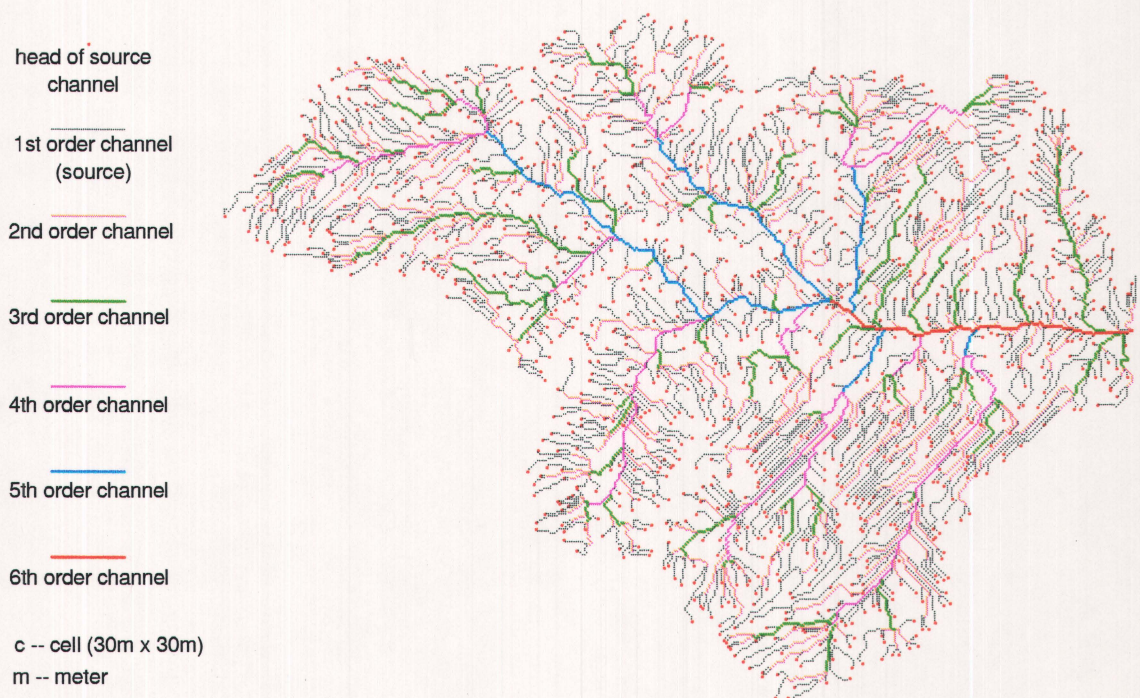


Figure 3-3b Extremely dense DEDNM Network (CSA=16c, MSCL=90m), Wolf Creek

Netw.img -- ordered channel network data file,

Relief.img -- relief data without pits,

Flovec.img -- continuous surface runoff vector data and

Uparea.img -- catchment area data.

3.3 Data Collection: Source Valley Morphology

After extremely dense channel networks are produced by DEDNM, information on source valley morphology is needed for further evaluation of source valley morphology. The procedure consists of three steps: the first is to collect information about the source valley morphology; the second is to calculate variables used to measure morphologic typicality; and the third is to correct some problems raising from the extremely dense channel network.

3.3.1 Data Collection about Valley Morphology

The procedure of data collection actually uses a small 3 by 3 window to scan the four images of channel network, drainage flow vector, local relief (elevation) and accumulated catchment area to collect morphologic data. The main steps are as follows:

1) Identify all the valley heads of source channels;

2) At each valley head position, collect data on it and the neighbouring cells;

3) Move along a source channel cell-by-cell from its upstream end (head cell) to its downstream end to collect the morphologic information on it and all neighbour cells of its two sides;

4) Check all the source channels and mark the problematic channels for further treatment.

When scanning the four image files, the following information is recorded:

1) X, Y co-ordinates: the positions of columns and rows on the head cells, the downstream end cells, and the minimum and maximum channel gradient point cells. All of them are recorded from the network image file;

2) Elevation data: all elevation data on the head cells, the downstream end cells, the minimum and maximum channel gradient point cell, and all cells along the two sides of each source channel. This is done by reading elevation data from the relief image file;

3) Catchment area: the catchment area data on all head cells, downstream end cells, and the minimum and the maximum channel gradient point cells are collected from the accumulated catchment area image file.

3.3.2 Morphologic Variables Calculation

From the morphologic data the following variables are calculated.

1) The average two side slopes of each source channel are calculated from the elevation intervals between source channel cells and their two side neighbour cells;

2) The average channel gradients of each source channel are calculated from the elevation intervals between the head cells and downstream end cells;

3) The lengths of source channels are calculated from the X, Y co-ordinates between head cells and downstream end cells;

4) The average depths of source channels are calculated from their average side slopes and the length of the DEM grid size (30 meters);

5) The absolute value of maximum and minimum vertical angle change on extraordinary points along some source channels (Figure 3-4).

6) The number of cells of a source channel which are parallel to other channels. The detail about it will be described in next section.

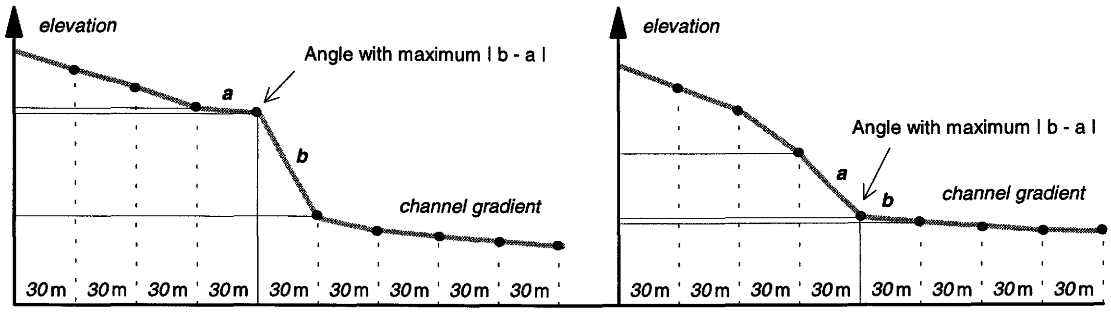


Figure 3-4 Extraordinary point on channel gradient with maximum absolute value of vertical angle change (maximum elevation difference between two adjoining segments)

3.3.3 Problem Correction

Some problematic source channels arise from the extremely dense channel network and the collected data need to be checked and corrected before their valley morphology membership grades are calculated. The problems and special treatment for them include:

1) Negative or zero degree side slope(s): Due to appearance of a large number of parallel source channels, some source channels possess a negative or zero (Figure 3-5) degree side slope. The treatment for them is that if one side slope of a source channel is negative, a zero value will be assigned to replace the negative value. The channel will be marked for further treatment. If two side slopes of a source channel are zero, the channel is located in a flat area and it will be marked for elimination later on. If only one side slope of a source channel is zero, the channel will be treated in next step.

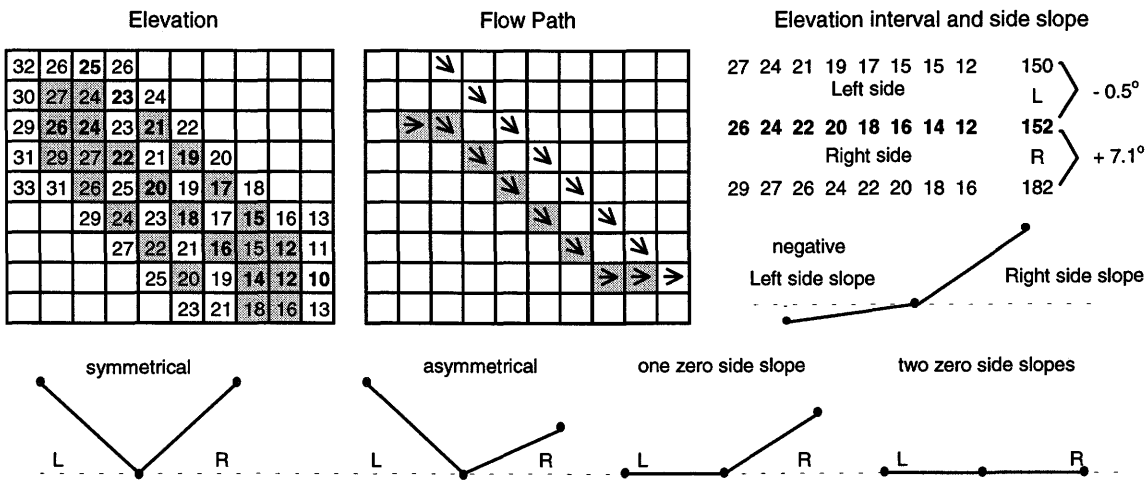


Figure 3-5 Problems on symmetrical property of the two side slopes of source channels

2) Asymmetric side slope: Generally, a typical source valley is expected to exhibit an approximately symmetrical V-shape profile. Actually, a large number of source channels demonstrate one side slope steeper more or less than the other side slope. In particular, some source channels have even one or two side slope(s) with zero degree (Figure 3-5), based on the method used in data collection. Because the slope index is important for evaluating valley morphology membership grade, the case of asymmetry of side slope should be differentiated from the symmetry case. For this purpose, an asymmetric coefficient is introduced for side slope standardization, so that every calculated average side slope has a same basis on valley morphology (Table 3-2). The function of the coefficient is to modify the arithmetic mean of two side slopes, so that if a source channel has an asymmetric side slope, its average side slope will be less than that of a symmetrical source channel. Therefore, for an asymmetric (not typical) source channel, its typicality of valley morphology in term of average side slope will be reduced slightly to differentiate it from

symmetrical (typical) source channel, although they possess a same arithmetic mean side slopes. The selection of the coefficient number relies on what percentage is required to decrease the arithmetic mean for the most asymmetric source channel. The more asymmetric a source channel, the more percentage of modification on its arithmetic mean of side slopes.

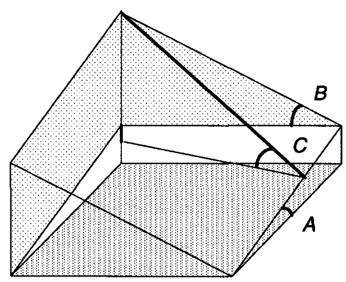
Table 3-2 Corrected means for asymmetrical side slopes

Samples	Left side slope (**Ls**)	Right side slope (**Rs**)	Arithmetic mean (**AM**)	Corrected mean (**CM**)	Modification
1	20	20	20	20	0%
2	25	15	20	18.75	6.25%
3	30	10	20	17.5	12.50%
4	35	5	20	16.25	18.75%
5	40	0	20	15	25.00%
6	53.33	0	26.17	20	25.00%

$$\mathbf{AM} = \frac{\mathbf{Ls + Rs}}{\mathbf{2}} \qquad \mathbf{CM} = \frac{\mathbf{Ls + Rs}}{\mathbf{2}} - \frac{\mathbf{|\,Ls - Rs\,|}}{\mathbf{2}} \times \mathbf{25.00\%}$$

3) Average side slope with channel gradient: during data collection, the side slope is calculated from the elevation interval between a channel cell and its two side cells. In a grid DEM, only eight drainage directions are used and the effect of channel gradient is neglected. Due to the action of gravity, surface runoff always converges along the path from the maximum slope to minimum slope. Therefore, the real side slope is different from the side slope directly collected from a grid DEM. This side slope needs to be corrected so that the effect of channel gradient can be taken into account. Considering the spatial relationship between current side slope (collected from DEM without combining channel gradient) and real side slope (corrected by combining channel gradient), all the real side slope values can be obtained from the equation that incorporates the channel gradient index. Table 3-3 displays the equation and the difference between the real side slope with channel gradient and the current average side slope initially obtained from data collection.

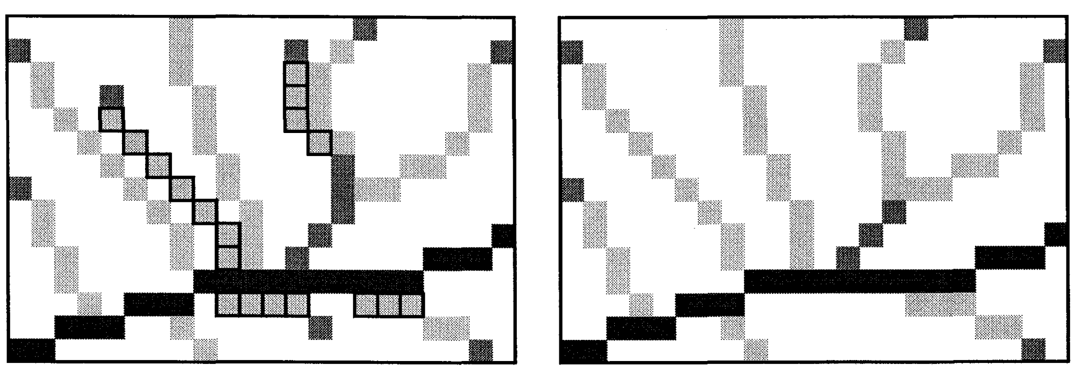
Table 3-3 Real side slope calculated from collected side slope and channel gradient



Real Side Slope (*C*)		Channel Gradient (**A**)			
		10	20	30	40
	10	11.55	16.18	23.82	34
Collected	20	21.26	25.01	31.13	39.29
Side	30	30.93	33.7	38.26	44.47
Slope	40	40.6	42.4	45.44	49.77
(**B**)	50	50.29	51.21	52.87	55.45
	60	60.06	60.28	60.79	61.82

$$TAN(C) = TAN(B) \times COS(A) + TAN^2(A) \times COS(A)$$

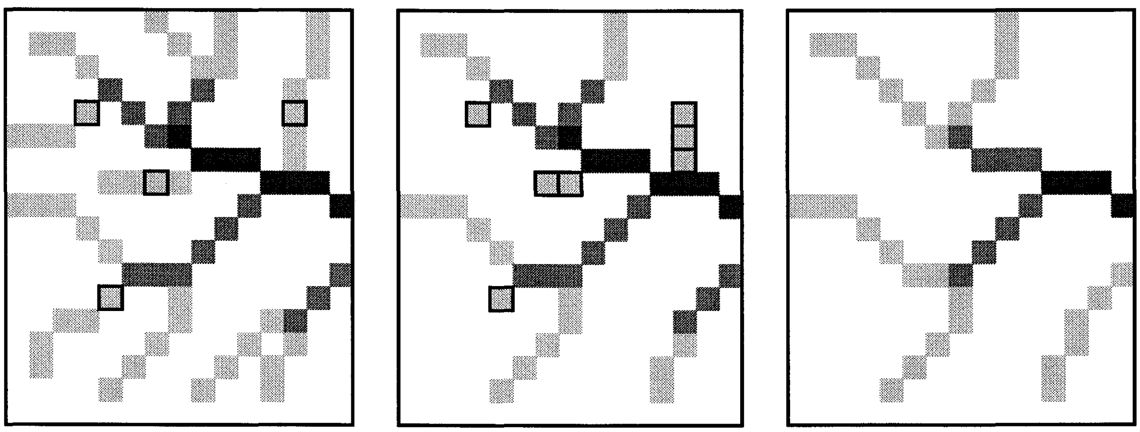
4) Parallel channels: This is a shorter source channel parallel to a longer source channel or higher order channel (Figure 3-6). Commonly, the channel network is depict in one cell width for all its sections, whatever or not a real wide flat bottom may exists. When moving along a source channel cell by cell from its head down to its end for data collection, the channel cells will be counted if their side cells are other channel cells. The recorded cells of the source channel are actually parallel with other channel cells and the length of this section is compared to the total length of the source channel. If more than the two third length of a source channel is abreast with other source channel or high order channel, the source channel will be cleared up totally.



a) some channel cells parallel to others **b)** after removing the parallel channels

Figure 3-6 Problem of parallel source channels

5) Short stub of source channel: This problem does not result from the original extremely dense channel network but instead from the process of morphological reduction. After calculating the morphologic typicality and modifying the source channels, some source channels are eliminated partly to where the calculated CSAs are matched (Figure 3-7). In some cases, only part of a source channel is removed. If the remained section (stub) is too short, it seems inconsistent with the conventional representation of the channel network derived from DEM. Therefore, the remained short section will be removed. The rule for this treatment is that if the remaining stub of a source channel is less than four cells, the stub will be eliminated.



a) removing some untypical source channels upon□ **b)** after removing them partly and generating some "stubs" **c)** removing these "stubs" and reordering channels

Figure 3-7 Problem of short "stubs" of source channels and treatment for them

3.4 Creation of Membership Functions

It is practice to create a membership function by defining a conceptual model for a studied issue firstly and quantifying the model to a mathematical model (He, 1984; Li, 1994).

3.4.1 Conceptual Model of Typical Valley Morphology

To derive the membership function of valley morphology to calculate the typicality of valley morphology, the conceptual model of what is typical valley morphology needs to be defined. Generally, a typical valley morphology characterizes some morphologic properties on steep side slopes with some depth and gradient. Although there is no absolute amount for them to define how steep or deep they are, relative amount is determined by our perception about it. For instance, if the average two side slopes of a source channel are greater than 30 degrees, the channel exhibits a typical valley morphology. It is a typical source valley with a complete membership. If the side slopes are less than 3 degrees, the channel is only a local depression or runoff path and can be defined as a non-typical source valley without valley membership. The relative amount for the average side slopes with complete membership is not necessarily associated with the value of 30 degree, but the amount does relate to the value that we are confident by our knowledge to use it for recognizing source valley. The same reason is applicable to the case without membership. Therefore, this kind of marginal conditions defines a border for the conceptual model of a typical valley morphology and only uncertainty section within the border needs to be calculated for membership grade through morphologic indices. From this cause, the quantification for the conceptual model is actually the quantification for the morphologic indices used in morphology membership function.

3.4.2 Indices for Valley Morphology

There are different indices which can be computed to represent morphologic characteristics of a source channel, such as length, width, depth, side slope, longitudinal (channel) gradient, and catchment area (Mark, 1975; Evans, 1986). In order to simplify the final membership function of valley morphology, only key indices are involved in membership grade calculation. The selection of these indices is dependent on their significance for valley morphology and the availability from DEM. For this reason, side slope, channel gradient, and depth are selected for the quantification of valley morphology. As for the length of source channel, because all of them are generated initially in the minimum length of 90 meters, further distinction in length for valley morphology evaluation has no meaning. For instance, a source channel of 200 meters has no more apparent effect on the membership grade of valley morphology than a source channel of 300 meters. Therefore, the length index can be ignored. For the width of source channel, the main algorithm for morphologic data collection is based on only one cell width from the two sides of each channel cell. Therefore, no width data are available for assessing valley morphology.

From the three indices (side slope, channel gradient, and depth), two sub-membership functions of source valley morphology are developed: one is the ratio of average side slope to channel gradient and the other is average depth of the source channel. Then, these two sub-functions are combined into one comprehensive membership function to measure the typicality of valley morphology for each source channel.

3.4.3 Slope and Gradient Membership Function

A typical source valley is expected to possess a "v"-shape, steep side slopes with certain channel gradient, and the side slopes should be distinctly greater than channel gradient. If the channel gradient is very close to or equal to side slope, the direction of side slope runoff will be parallel to the channel gradient and there will be no slope runoff converging into the channel. According to the conceptual model of typical valley morphology, the following marginal conditions define the border for the sub-membership function, based on the relationship between side slope (X) and channel gradient (Y), and on the properties of side slopes:

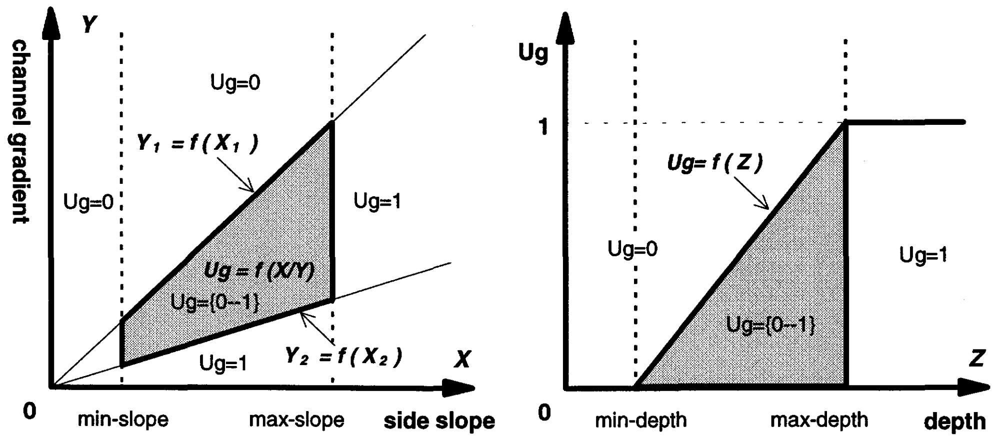
1) If the average side slope of a source channel is less than a minimum slope (min-slope, Figure 3-8 a), e.g. 3 degrees, the source channel does not possess a typical valley morphology and therefore its slope and gradient membership grade Ug(X,Y) is zero (function <1>);

2) If the average side slope (X) of a source channel is greater than a maximum slope (max-slope, Figure 3-8 a), e.g. 30 degrees, the channel possesses a typical valley morphology and its slope and gradient membership grade Ug(X,Y) is one (function <3>);

3) If the ratio of channel gradient to average side slope is equal to Hc, e.g. 1.0 (channel gradient equals to average side slope), its membership grade Ug(X,Y) is zero (function<1>); if the ratio is less than a value Lc, e.g. 0.3 (channel gradient is less than 30% of average side slope), its membership grade Ug(X,Y) is one (function<3>) (Figure 3-8 a).

These marginal conditions are illustrated in Figure 3-8a. They encircle an area outside of which the valley morphology membership grade is predefined by the knowledge about it. For the centre region, the Ug(X,Y) needs to be calculated by the function <2>. This function ensures that any point (ratio of channel gradient Y to side slope X) between the line $Y_1 = f(X_1)$ and line $Y_2 = f(X_2)$ will have a membership grade value within 0 to 1.

The side slope and channel gradient membership function is defined as in Figure 3-8a and the equations <1>,<2>,<3>. Where Ug(X,Y) is membership grade; X is average side slope; Y is channel gradient; max-slope is maximum average side slope at which membership grade is equal to 1; min-slope is minimum average side slope at which



a) Membership function of slope/gradient

b) Membership function of depth

Valley morphology membership functions

I. Ratio of Gradient to Slope of Valley Morphology Membership Function

$Y_1 = f(X_1) \longrightarrow Y_1 = Hc \times X_1$ ***Hc*** -- high coefficient, slope of the linear equation

$Y_2 = f(X_2) \longrightarrow Y_2 = Lc \times X_2$ ***Lc*** -- low coefficient, slope of the linear equation

$$Ug\ (gradient/slope) = \begin{cases} 0 & \text{If } X < \text{min-slope or } Y/X >= Hc \\ (Hc - Y/X)/(Hc - Lc) & \text{If min-slope} < X < \text{max-slope, } Lc < Y/X < Hc \\ 1 & \text{If } X > \text{max-slope or } Y/X <= Lc \end{cases}$$

<1> <2> <3>

II. Depth of Valley Morphology Membership Function

$$Ug\ (depth) = \begin{cases} 0 & \text{If } Z < \text{min-depth} \\ (Z - \text{min-depth})/(\text{max-depth} - \text{min-depth}) & \text{If min-depth} < Z < \text{max-depth} \\ 1 & \text{If } Z > \text{max-depth} \end{cases}$$

<4> <5> <6>

min-depth = tan(min-slope) x cellsize, max-depth = tan(max-slope) x cellsize

III. Integration of Valley Morphology Membership

$$Ug\ (gradient/slope, depth) = w1 \times Ug(gradient/slope) + w2 \times Ug(depth) \qquad \text{<7>}$$

w1, w2 ---- weights for the two sub-membership functions

Figure 3-8 Membership function of source valley morphology on slope/gradient and depth
(Ug -- membership grade, X -- side slope, Y -- channels gradient, Z -- depth)

membership grade is equal to 0; Hc is a high coefficient or ratio of side slope to channel gradient; and Lc is a low coefficient or ratio between side slope and channel gradient. Actually, Hc and Lc are the slopes of the two linear equations which specify the range for calculating membership grade. In all of these variables, X and Y come from the morphologic data collection from DEM while min-slope, max-slope, Hc and Lc are the user-defined marginal conditions for the conceptual model of typical valley morphology . It is clear from the function <2> in an extreme case that

if $Y / X = Hc$, then $Ug (X, Y) = (Hc - Y/X) / (Hc - Lc) = 0$;

if $Y / X = Lc$, then $Ug (X, Y) = (Hc - Y/X) / (Hc - Lc) = 1$;

if $Lc < Y /X < Hc$, then $Ug (X, Y) = \{0, 1\}$.

3.4.4 Depth Membership Function

The slope and gradient membership function discussed above is a ratio value. In some cases, the same membership grade value may result from different combinations of side slope and channel gradient. For example, one source channel has $X = 10$ and $Y = 4$, and the other has $X = 20$ and $Y = 8$. They will have the same membership grade in terms of the ratio of side slope (X) to channel gradient (Y). Therefore, the conceptual model of typical valley morphology must be further specified by another valley morphologic index. Average depth of source channel is introduced for creating the second sub-membership function. Two marginal conditions are pre-set for this index (Figure 3-8b):

1) If the average depth (Z) of a source channel is less than a minimum depth, the channel processes a unclear depth for a typical source valley. Therefore, its depth membership grade Ug(Z) is pre-set to zero (function <4>);

2) If the average depth (Z) of a source channel is greater than a maximum depth, the channel processes a distinct depth for a typical source valley. Therefore, its depth membership grade Ug(Z) is set to one (function <6>).

These marginal conditions also enclose an area in that the depth membership grade is calculated by the function <5>. Where Z is the average depth of a source channel. Max-depth is the maximum depth at which membership grade is equal to 1 and min-depth is the minimum depth at which membership function is equal to 0. Here, the value Z is calculated from the morphologic variables during the data collection. The values of min-depth and max-depth are decided by the value of min-slope and max-slope, respectively, and the value of cell size of a grid DEM.

Min-depth = tan (min-slope) x cellsize;
Max-depth = tan (max-slope) x cellsize.

It is also clear from the function <5> in an extreme case that

if Z = min-depth, then Ug(Z) = (Z - min-depth) / (max-depth - min-depth) = 0;
if Z = max-depth, then Ug(Z) = (Z - min-depth) / (max-depth - min-depth) = 1;
if min-depth > Z > max-depth, then Ug(Z) = {0, 1}.

3.4.5 Combined Valley Morphology Membership Function

The comprehensive valley morphology membership function Ug(X,Y,Z) is derived by combining the slope and gradient sub-membership function Ug(X,Y) with the depth sub-membership function Ug(Z) as a weighted average. The combined membership function is shown in equation <7>. Where w1 is the weight of Ug(X,Y) while w2 is the weight of

Ug(Z). To ensure that value of Ug(X,Y,Z) is within 0 to 1, the sum of w1 and w2 must be one. The selection of the w1 and w2 values relies on which sub-membership function is more important than the other for the combined membership function. For this combined membership function, Ug(X,Y) is main sub-function and w1 = 2/3 whereas Ug(Z) is secondary sub-function and w2 = 1/3. This function of Ug(X,Y,Z) will be employed in the calculation of the catchment area threshold for each source channel.

To illustrate how the combined membership function works on source channels under the different morphologic characteristics, Table 3-4 shows the sub-membership grades and combined membership grades for five hypothetical source channels. Obviously, some sample channels have same Ug(X,Y) or Ug(Z), but they have different Ug(X,Y,Z) values. The greater the Ug(X,Y,Z) value, the more typical the morphology of the source channel.

Table 3-4 Samples of sub-membership grades and integrated membership grades

Samples	Side Slope	Channel Gradient	Ug(X/Y)	Depth	Ug(Z)	Ug(X,Y,Z)
1	10	4	0.875	5.29	0.236	0.662
2	20	4	1	10.92	0.594	0.865
3	20	8	0.875	10.92	0.594	0.781
4	25	8	0.971	13.99	0.789	0.91
5	25	20	0.286	13.99	0.789	0.454

It should be stressed that the values adopted for the marginal conditions and the weights in the above functions are arbitrary. In fact, they are defined by our realization of what is typical of source valley morphology. The results obtained from the functions can be evaluated by our knowledge and the values of the marginal conditions can be modified repeatedly by the feedback of the results. Therefore, such subjectivity is actually knowledge-driven (Bonham-Carter 1994). Although the choice of the values may vary between different people, they can be adjusted until a common standard acceptable by majority is achieved. For instance, a high certainty can be secured for the condition of slope/gradient membership grade starting to equal to 1.0 by choosing 35 degree rather than choosing 25 degree as a typical average side slope. The most important thing is that a special sequence, a sorting all of source channels, can be obtained by this method. This sequence is objective and its order is free from whatever the values of marginal conditions are chosen initially. This sequence is actually data-driven. Based on the derivation of the valley morphology membership function, only uncertain sections circled by pre-defined marginal conditions are calculated by membership function.

3.5 Threshold Determination

In the new approach, the CSA threshold value is not fixed for all source channels but instead varies for each individual source channel, based on its morphologic characteristics. The new CSA threshold is actually a transformation of the valley morphology membership grade. After calculation of the membership grade, all source channels are sorted based on valley morphology typicality. Typical source channels with a valley morphology membership grade one will have a minimum CSA (MinCSA) value assigned to them. Non-typical source channels, with a valley morphology membership grade zero, will have a maximum CSA (MaxCSA) value. The minimum CSA and maximum CSA are predefined by user based on the relief features of the studied region. For those source channels with the grades between zero and one, calculated CSA values between minimum CSA and maximum CSA will be assigned to them. Due to existence of special situation on source valley morphology, the CSA threshold is decided in three priority levels :

1) For problematic source channels, if the average side slope or the maximum channel gradient of a source channel equals zero, the source channel is a pseudo-channel and it will be removed entirely. Therefore, its CSA threshold value is directly set to the catchment area at its downstream end cell and is not calculated from its valley morphology membership grade;

2) For normal source channels, special points on the longitudinal channel profile are examined first. If the maximum absolute value of vertical angle change along the channel profile (Figure 3-4) is greater than the average side slope (the average side slope must be greater than 25 degree), a valley head is locate at that point. Therefore, its CSA threshold value will be directly set to the catchment area of the special point. Its valley morphology membership grade is not converted to CSA;

3) For normal source channels without a distinct special point, the average side slope, channel gradient and depth are determined. Then, the membership grades of source valley morphology are calculated from the collected information and the grades are converted to CSA by the function: $CSA = MaxCSA - Ug(X,Y,Z) \times (MaxCSA - MinCSA)$.

From the three level priority threshold selections, two things are achieved: First, the valley morphology membership function is not applied everywhere. Channels with distinct morphologic features are always taken into account first to decide their catchment area threshold. Only those without typical valley morphology are the subject to membership grade calculation. Second, no single catchment area threshold is utilized for the whole DEM. The magnitude of the catchment area threshold for each individual source channel relies on the typicality of each source valley morphology.

3.6 FICNM

Using all of the considerations discussed above, a program, Fuzzy Identification Channel Network Model (FICNM), was designed and developed for the source channel manipulation. The program was written in standard FORTRAN 77 (Appendix B) and its main steps on treating channel network are illustrated in Figure 3-9. The steps are:

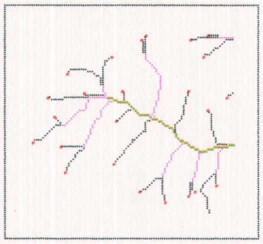
1) Use very small CSA and MSCL parameters in DEDNM to generate extremely dense channel networks (Figure 3-9b). Read in a user-defined parameter file, output options, and four image files (network, flow vector, elevation, and catchment area).

2) Scan the DEM data using 3 * 3 window; test network data and flow vector data; and define all the channels cells with only non-channel flow inputs pointed to them as the source channel head cells (Figure 3-9c).

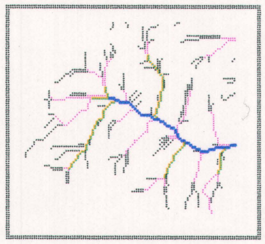
3) Collect the information on each source channel morphology by reading from the four image data files. Calculate all variables of the source channel morphology. Identify and mark all problematic source channels (Figure 3-9d).

4) Calculate the valley morphology membership grade for each source channel and convert the value to a CSA threshold (Figure 3-9e).

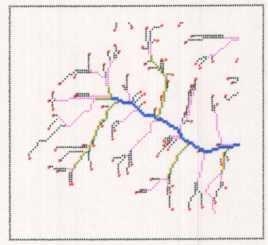
5) Eliminate those cells with a catchment area lower than the channel's CSA threshold and set a new valley head where the cell's catchment area equals to the CSA threshold. Remove all problematic source channels (Figure 3-9f).



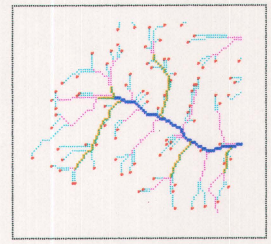
a) Normal DEDNM channel network



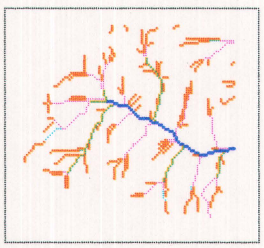
b) Extremely dense DEDNM network treated by FICNM



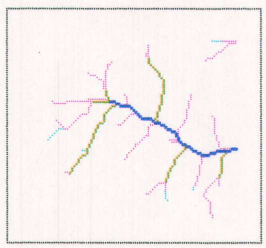
c) Find all source channel heads



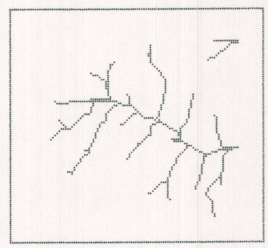
d) Collect data on each source channel morphology



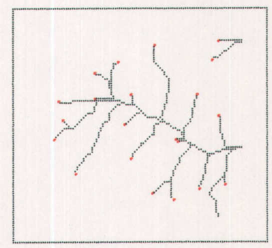
e) Calculate grade of membership and corresponding CSA



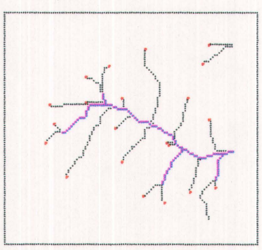
f) Eliminate all sections lower than CSA



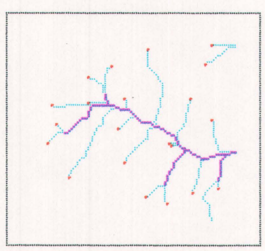
g) Rewrite the remaining channel network



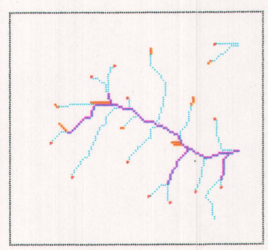
h) find all source channel heads



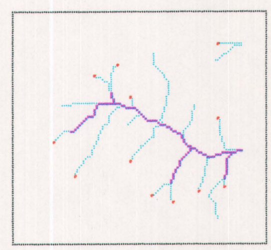
i) Separate 1st order channels from other order channels



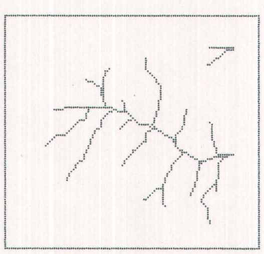
j) Collect data on each source channel morphology



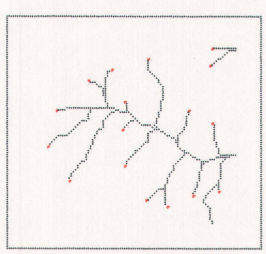
k) Calculate grade of membership and corresponding CSA



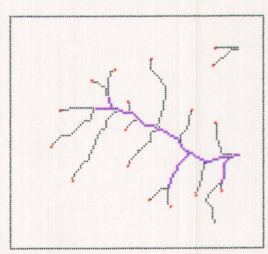
l) Eliminate all sections lower than CSA



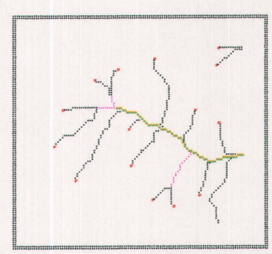
m) Rewrite the remaining channel network



n) find all source channel heads



o) ---- Repeat step **g)** to step **m)** until the last delete is less than 2%



p) Reorder final remaining channel network system

Figure 3-9 Procedure of FICNM Treatment on DEDNM Channel Network

6) Set all of the remaining channels to the same value (Figure 3-9g); find all heads of source channels (Figure 3-8h); separate source channels from other channels (Figure 3-8i).

7) Go back to the step d) for next round of the manipulation and continue until the number of modified source channel is less than 2 percent of the number of the total source channels in the last treatment. Now, all the source channels will have their proper catchment area which coincide to the extent of typicality of their valley morphology;

8) Reorder the final remaining channel network (Figure 3-9p), write the output files and terminate the procedure.

Chapter 4

Results and Discussion

4.1 Comparison of Results

Commonly, the evaluation of a channel network derived from a DEM is based on a visual comparison between the network and the blue line network on the corresponding topographic map. Overlay or statistical comparison is sometimes also applied to verify results (Garbrecht and Martz, 1993). In this research, all of these techniques are applied to three kinds of channel networks. The first channel network is the channel network derived by DEDNM from DEMs. The second is the extremely dense channel networks first generated by DEDNM and then treated by FICNM. The third is the blue line network digitized from corresponding topographic maps and then rasterized by IDRISI so as to obtain a compatible data format for the comparison.

To improve the visual comparison, DEDNM channel networks and FICNM channel networks are generated in series using different parameter values. These series of network images are then grouped and overlaid to find the variations of network pattern with the change of parameters. Next, the coordinates of the blue line images are adjusted so that the maximum spatial match between blue line and DEDNM network or FICNM network can be obtained. Finally, these images are overlaid with each other and the results are recorded statistically, forming new images for easy visual comparison. Comparisons are made between DEDNM networks and DEDNM networks, DEDNM networks and blue line, FICNM networks and FICNM networks, FICNM networks and blue line and DEDNM networks and FICNM networks.

4.2 DEDNM Network and Blue Line Comparison

4.2.1 Comparison of DEDNM Network to DEDNM Network

To understand how the channel network changes when running DEDNM under different values of parameters, a series of images of DEDNM channel network was generated using four CSAs and four MSCLs. The parameter values were as follows:

CSA = 64 cells (8 by 8 cells) (a cell = 30m x 30m)

CSA = 100 cells (10 by 10 cells)

CSA = 144 cells (12 by 12 cells)

CSA = 196 cells (14 by 14 cells)

MSCL = 3 cells (90m)

MSCL = 4 cells (120m)

MSCL = 5 cells (150m)

MSCL = 6 cells (180m)

The selections of CSA and MSCL values are based on the relief features in the three DEM data sets. These values cover a wide range so that the change of channel networks using different parameters can be valuated. A total of 16 DEDNM network images were generated for each data set, using all combinations of the four CSA values and the four MSCL values (Table 4-1). Then these images are overlaid in group by holding one parameter constant so that any change of channel network pattern with the other parameter change can be detected.

Table 4-1 Generation of the new overlaid DEDNM images for comparison

New Overlaid Images	Every four DEDNM images overlaid each other (one parameter constant and another parameter change)			c - cell size m - meter
1	CSA= 64c / MSCL= 90m	CSA= 64c / MSCL=120m	CSA= 64c / MSCL=150m	CSA= 64c / MSCL=180m
2	CSA=100c / MSCL= 90m	CSA=100c / MSCL=120m	CSA=100c / MSCL=150m	CSA=100c / MSCL=180m
3	CSA=144c / MSCL= 90m	CSA=144c / MSCL=120m	CSA=144c / MSCL=150m	CSA=144c / MSCL=180m
4	CSA=196c / MSCL= 90m	CSA=196c / MSCL=120m	CSA=196c / MSCL=150m	CSA=196c / MSCL=180m
5	CSA= 64c / MSCL= 90m	CSA=100c / MSCL= 90m	CSA=144c / MSCL= 90m	CSA=196c / MSCL= 90m
6	CSA= 64c / MSCL=120m	CSA=100c / MSCL=120m	CSA=144c / MSCL=120m	CSA=196c / MSCL=120m
7	CSA= 64c / MSCL=150m	CSA=100c / MSCL=150m	CSA=144c / MSCL=150m	CSA=196c / MSCL=150m
8	CSA= 64c / MSCL=180m	CSA=100c / MSCL=180m	CSA=144c / MSCL=180m	CSA=196c / MSCL=180m

Eight new images are generated in this manner. When overlaying these images, their absolute spatial match (number of cells matched exactly in column and row) is calculated and the results are displayed in Figure 4-1(a-c) and Table 4-2. From the Figures and the Table, three points can be concluded:

1) When holding the MSCL constant and increasing the CSA value, the density (in terms of number of cells) of channel networks decreases distinctly. The variation of channel network pattern is very sensitive to the change of parameter CSA.In Table 4-2, all variations of the spatial match between each channel network are greater than 10 percent. Therefore, carefully choosing a proper CSA for channel network delineation from DEM is critical.

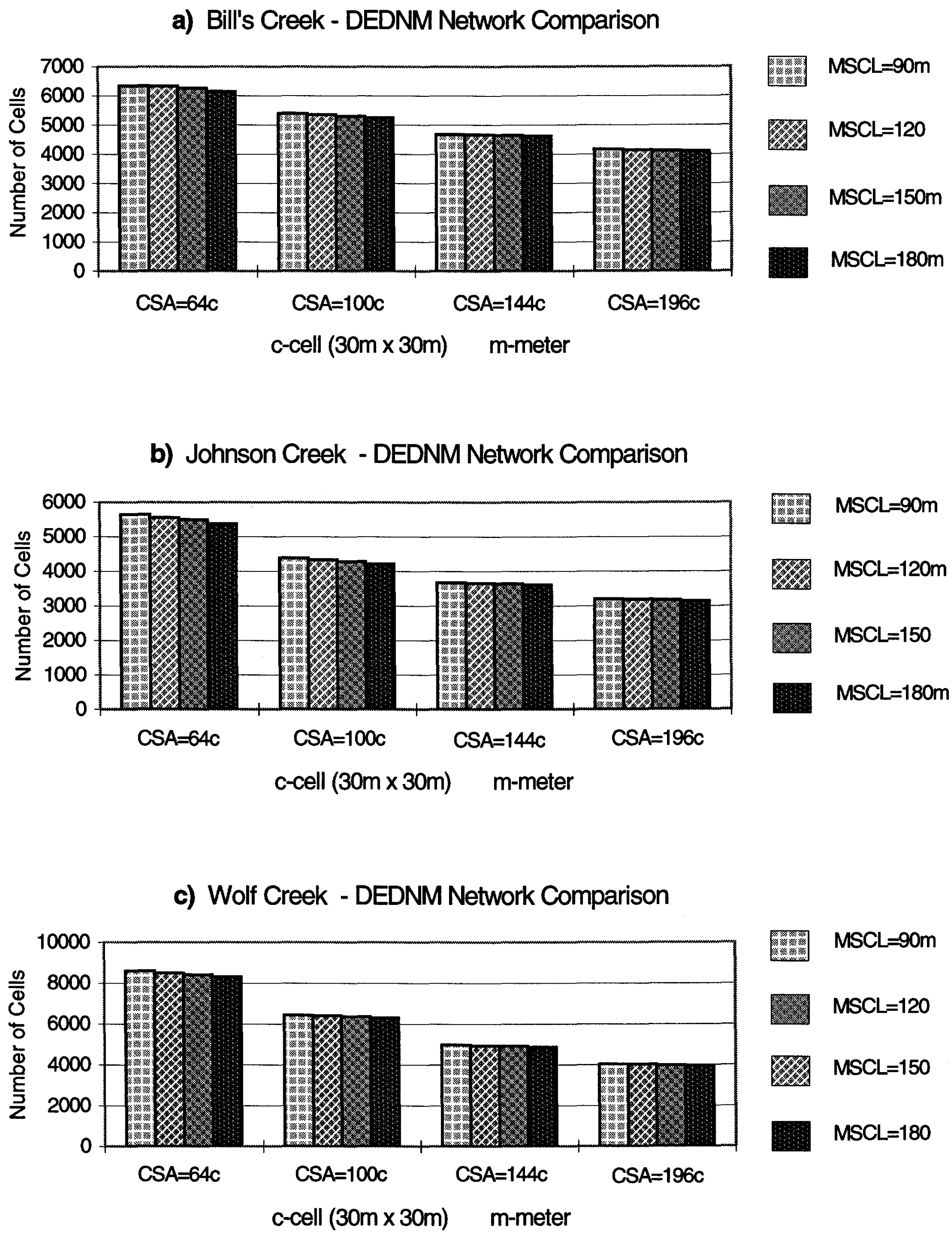


Figure 4-1 Comparison of DEDNM networks with different CSAs and MSCLs

Table 4-2 Comparison among DEDNM networks with different CSA and MSCL

Data Set	CSA(A) / Diff%	MSCL (L) / Diff% L= 90m	Diff%	L=120m	Diff%	L=150m	Diff%	L=180m
Bill's Creek	**A= 64c**	6343	*1.68* >	6328	*0.93* >	6269	*1.91* >	6149
	Diff%(A)	*16.31* V		*15.46* V		*15.67* V		*14.65* V
	A= 100c	5386	*0.67* >	5350	*1.07* >	5293	*0.85* >	5248
	Diff%(A)	*13.15* V		*12.79* V		*12.22* V		*12.14* V
	A=144c	4678	*0.26* >	4666	*0.43* >	4646	*0.75* >	4611
	Diff%(A)	*11.05* V		*11.21* V		*11.34* V		*11.08* V
	A=196c	4161	*0.43* >	4143	*0.58* >	4119	*0.46* >	4100
Johnson Creek	**A= 64c**	5649	*1.65* >	5556	*1.13* >	5493	*2.18* >	5373
	Diff%(A)	*22.48* V		*21.98* V		*22.08* V		*21.53* V
	A= 100c	4379	*1.03* >	4334	*1.25* >	4280	*1.5* >	4216
	Diff%(A)	*16.01* V		*15.48* V		*14.88* V		*14.37* V
	A=144c	3678	*0.41* >	3663	*0.55* >	3643	*0.91* >	3610
	Diff%(A)	*12.89* V		*12.78* V		*12.74* V		*12.99* V
	A=196c	3204	*0.28* >	3195	*0.5* >	3179	*1.2* >	3141
Wolf Creek	**A= 64c**	8598	*1.12* >	8502	*1.02* >	8415	*1.21* >	8313
	Diff%(A)	*25.1* V		*24.75* V		*24.46* V		*23.96* V
	A= 100c	6440	*0.65* >	6398	*0.64* >	6357	*0.57* >	6321
	Diff%(A)	*22.72* V		*22.87* V		*22.79* V		*22.97* V
	A=144c	4977	*0.84* >	4935	*0.55* >	4908	*0.79* >	4869
	Diff%(A)	*19.09* V		*18.89* V		*19.13* V		*19.04* V
	A=196c	4022	*0.6* >	4003	*0.85* >	3969	*0.68* >	3942

4022	Channel density in term of number of cells in a DEDNM channel network
19.09 > V	Percentage decrease of channel density between two images (one parameter constant and the other change)

2) When keeping the CSA constant and increasing the MSCL value, the density of channel networks generated is reduced slightly. The channel network pattern is not responsive to the change in parameter MSCL. In Table 4-2, almost all of the variation between the channel networks are less than 2 percent. Therefore, the change of MSCL value has no significant effect on the derived channel density when running DEDNM.

3) The variation of channel network pattern differs between data sets. In a relatively flat region (e.g. Bill Creek), the variation of channel density with CSA is less than in a relatively high relief region (e.g. Wolf Creek). Therefore, the CSA value has a larger effect in a high relief region than in a low relief region.

4.2.2 Comparison of DEDNM Network to Blue Line

The blue line is the channel network drafted in blue colour on a topographic map. It is compiled by cartographer as a representation of the stream and river system. It is commonly regarded as a standard reference for the channel network delineated from DEM. In this research, all the blue lines of the three date sets were digitized from topographic maps. Then all the data files were converted to image files by IDRISI with the same resolution as other DEMs.

When overlaying two kinds of channel images for comparison, their spatial match in terms of shared cells exactly in row and column needs to be recorded for the overall pattern assessment. The two images should have the same co-ordinate system and the numbers of row and column. There are some differences between the DEDNM network images and blue line images. The co-ordinates of the blue line images are adjusted by shifting or removing some of rows and/or columns, so that the maximum numbers of channel cells matched both images can be achieved for this purpose.

Based on the results of the DEDNM network comparison (conclusion 1 and 2 above), four DEDNM channel network images in each date set were selected to compare to the corresponding blue line network (Figure 4-3a,b,c). These four images had the same MSCL but different CSA values:

CSA = 64cell	MSCL = 150m
CSA = 100cell	MSCL = 150m
CSA = 144cell	MSCL = 150m
CSA = 196cell	MSCL = 150m

Table 4-3 Overlay comparison between DEDNM network and blue line

Data Set	CSA (cell)	MSCL (m)	DEDNM Netw	blue line	Shared C	Shared %
(Fig 4-3a)	64		6269		2029	35.37
Bill's Creek	100	150	5293	5737	1846	34.88
	144		4646		1670	35.94
	196		4119		1489	36.15
	64		5493		993	29.89
Johnson Creek	100	150	4280	3322	903	27.18
(Fig 4-3b)	144		3643		852	25.65
	196		3179		794	24.98
	64		8415		388	26.01
Wolf Creek	100	150	6357	1492	344	23.06
	144		4908		315	21.11
(Fig 4-3c)	196		3969		283	18.97

It is clear from the Table 4-3 that the absolute spatial matches between DEDNM networks and blue line are not very high, although the overall patterns matched well (Figure 4-3a,b,c), especially when the density of DEDNM network is close to that of blue line. The two networks differed substantively in detail. The reason for this will be discussed in section 4.5 of the chapter.

4.3 FICNM Network and Blue Line Comparison

4.3.1 Comparison of FICNM Network to FICNM Network

The FICNM channel networks come from the extremely dense of channel networks generated by DEDNM and then treated by the program FICNM. Some parameters need to be pre-set before running FICNM. The most important two parameters are minimum CSA (MinCSA) and maximum CSA (MaxCSA). The minimum CSA is defined for the typical source channels with valley membership grade 1 while the maximum CSA is for the no-typical source channels with valley membership grade 0 (maximum CSA). For different regions or data sets, different MinCSA and MaxCSA values should be adopted, depending on the relief characteristics. In order to understand how MinCSA and MaxCSA to affect the channel network pattern, eight images are produced from one extremely dense channel network by FICNM, using the following parameters:

MinCSA = 25c / MaxCSA = 50c	MinCSA = 50c / MaxCSA = 100c
MinCSA = 25c / MaxCSA = 100c	MinCSA = 50c / MaxCSA = 200c
MinCSA = 25c / MaxCSA = 150c	MinCSA = 50c / MaxCSA = 300c
MinCSA = 25c / MaxCSA = 200c	MinCSA =100c / MaxCSA = 300c

The eight images are overlaid in two groups with the same MinCSA to exhibit the change of channel network pattern in these series of images. From the Table 4-4 and Figure

4-2, the main trend of variations of channel network patterns appears similar to the variations of DEDNM network pattern.

Table 4-4 Comparison among FICNM network images with different MinCSA and MaxCSA

Data Set	MinCSA / Diff%	MaxCSA / Diff% 50c	Diff%	100c	Diff%	150c	Diff%	200c	Diff%	300c
Bill's Creek	25c	5849	17.25 >	4840	13.08 >	4207	10.89 >	3749		
	Diff%			0.21 ∨				0.11 ∨		
	50c			4830	22.46 >		>	3745	17.12 >	3104
	Diff%									0.39 ∨
	100c									3092
Johnson Creek	25c	5704	20.09 >	4558	12.86 >	3972	9.14 >	3609		
	Diff%			8.51 ∨				5.51 ∨		
	50c			4170	<18.23 >		>	3410	12.86 >	2988
	Diff%									6.36 ∨
	100c									2798
Wolf Creek	25c	6560	26.01 >	4854	15.43 >	4105	15.79 >	3457		
	Diff%			2.8 ∨				1.42 ∨		
	50c			4718	<27.77 >		>	3408	12.12 >	2995
	Diff%									1.14 ∨
	100c									2961
4718	---- Channel density in term of number of cells in a FICNM channel network									
27.77 > ∨	---- Percentage decrease of channel density between two images (with parameter constant and the other change)									

When comparing the images with same minimum CSA but different maximum CSA, nearly all of the variations of the channel network pattern in terms of number of cells are greater than 12 percent. However, when comparing the images with same maximum CSA but different minimum CSA, the variations become small, especially in the data sets of Bill's Creek and Wolf Creek. This suggests that when running FICNM, choosing maximum CSA is more important than choosing minimum CSA. For the minimum CSA, the value can be defined for a known or supposed typical source valley. It is, therefore, relatively easy

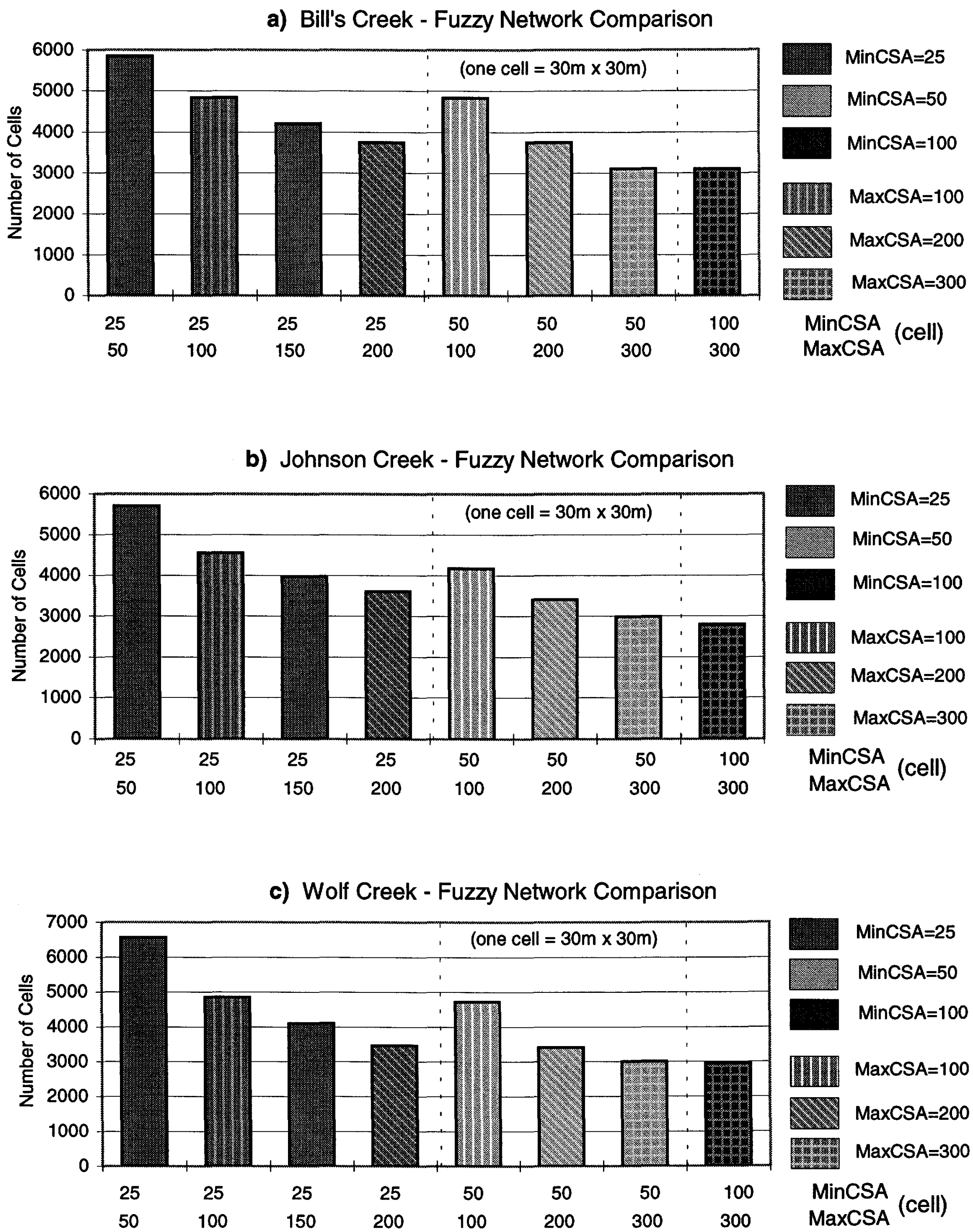


Figure 4-2 Comparison among FICNM networks with different MinCSA and MaxCSA

to be predetermined. However, the Maximum CSA is strongly associated with the geographic characteristics of the region rather than with the morphologic characteristics of source valleys. It should be chosen carefully and modified repeatedly by feedback of the results.

4.3.2 Comparison of FICNM Network to Blue line

When these eight images are overlaid with blue line, the results of channel network overlay and spatial match are similar to the results between DEDNM network and blue line. The Table 4-5 and Figure 4-4a,b,c illustrates the comparison. It is also clear that the overall network pattern matched well, but that the absolute spatial match is not high. The difference in detail is obvious.

Table 4-5 Overlay comparison between FICNM network and blue line

CSA parameter		**Bill's Creek** (blue line=5737c)			**Johnson** (blue line=3322c)			**Wolf Creek**(blue line=1493c)		
MinCSA	MaxCSA	cells	shared c	shared%	cells	shared c	shared%	cells	shared c	shared%
25	50	5849	1912	32.69	5704	1011	17.72	6560	385	5.87
25	100	4840	1721	35.56	4558	918	20.14	4854	342	7.05
25	150	4207	1524	36.23	3972	876	22.05	4105	318	7.75
25	200	3749	1366	36.44	3609	841	23.3	3457	304	8.79
50	100	4830	1721	35.63	4170	896	21.49	4718	338	7.16
50	200	3745	1365	36.47	3410	821	24.08	3408	297	8.71
50	300	3104	1143	36.82	2988	765	25.6	2995	285	9.52
100	400	3092	1134	36.68	2798	737	26.34	2961	284	9.59
Figure		(Fig 4-4a)			(Fig 4-4b)			(Fig 4-4c)		

4.4 FICNM network and DEDNM network Comparison

Due to the low spatial match between blue line and DEDNM network or FICNM network, portions of the DEDNM and FICNM networks with different parameters need to

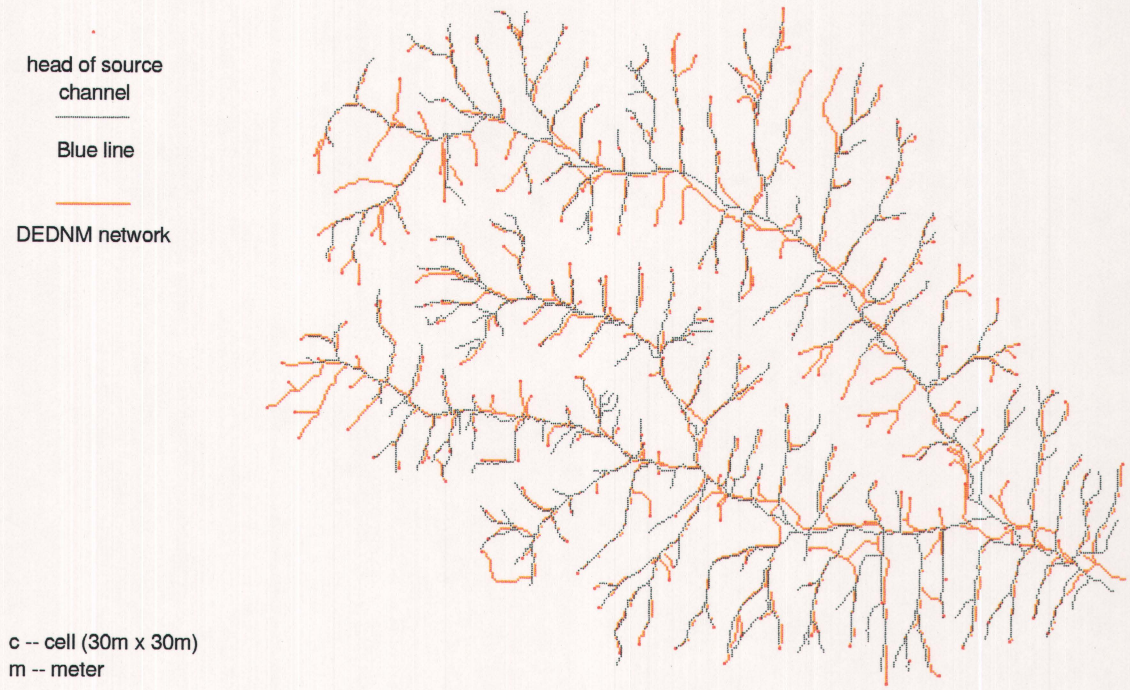


Figure 4-3a Overlay of Blue Line and DEDNM Network (CSA=64c, MSCL=150m), Bill's Creek

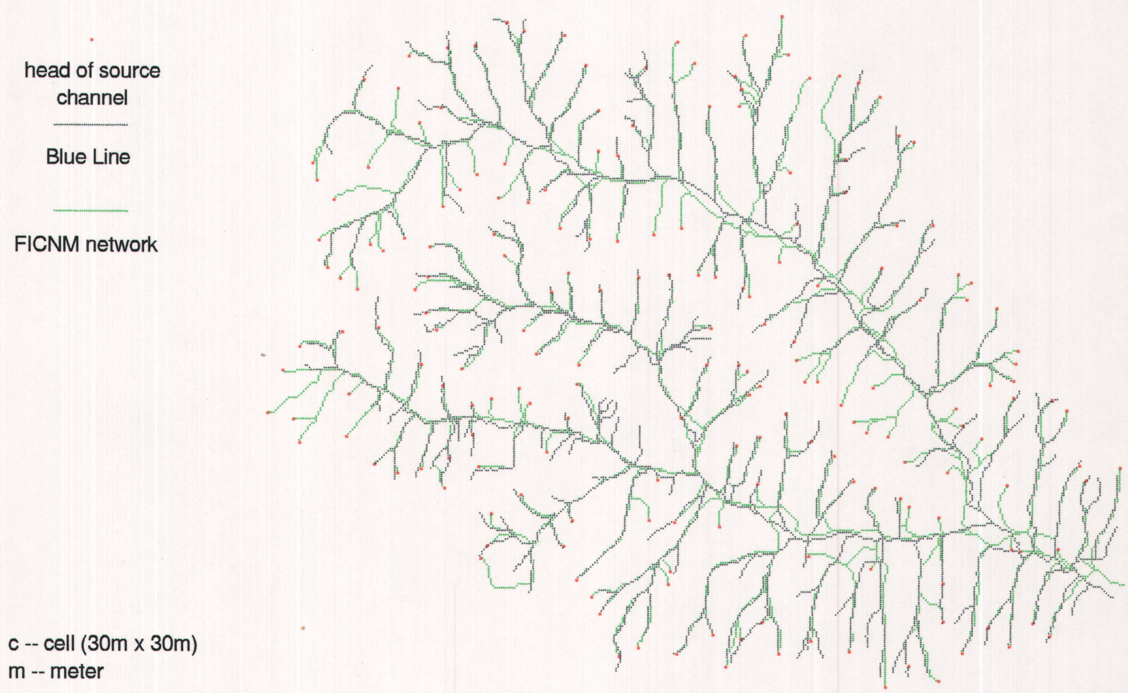


Figure 4-4a Overlay of Blue Line and FICNM Network (MinCSA=25c, MaxCSA=50c), Bill's Creek

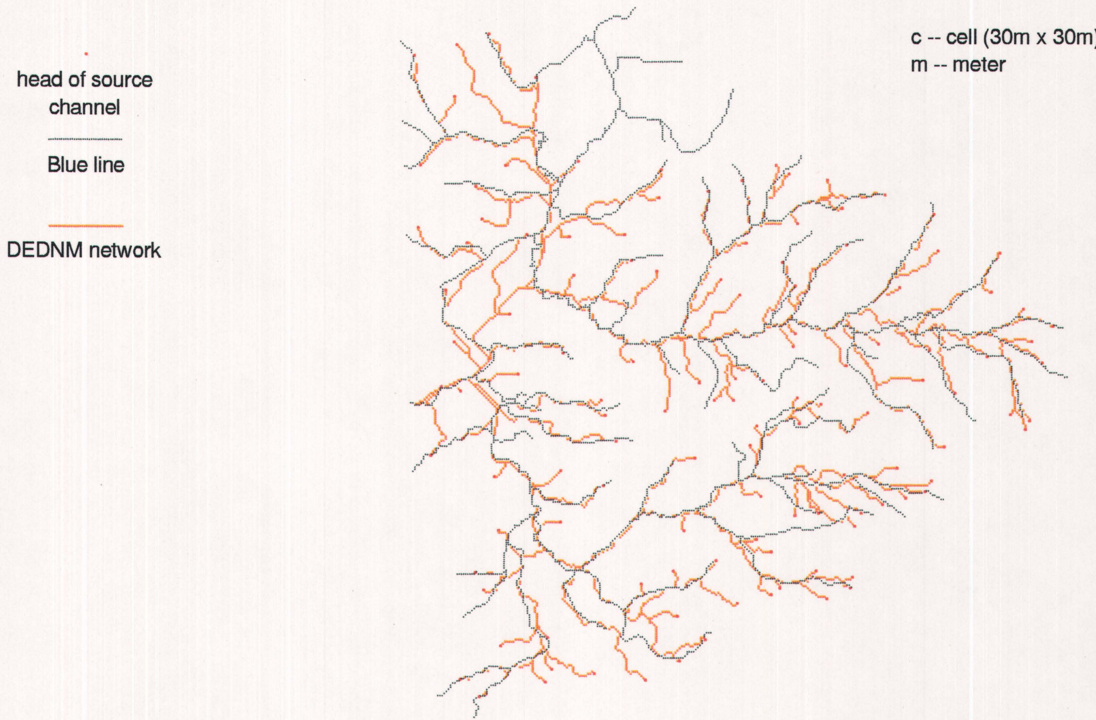


Fig 4-3b Overlay of Blue Line and DEDNM Network (CSA=144c, MSCL=150m), Johnson Creek

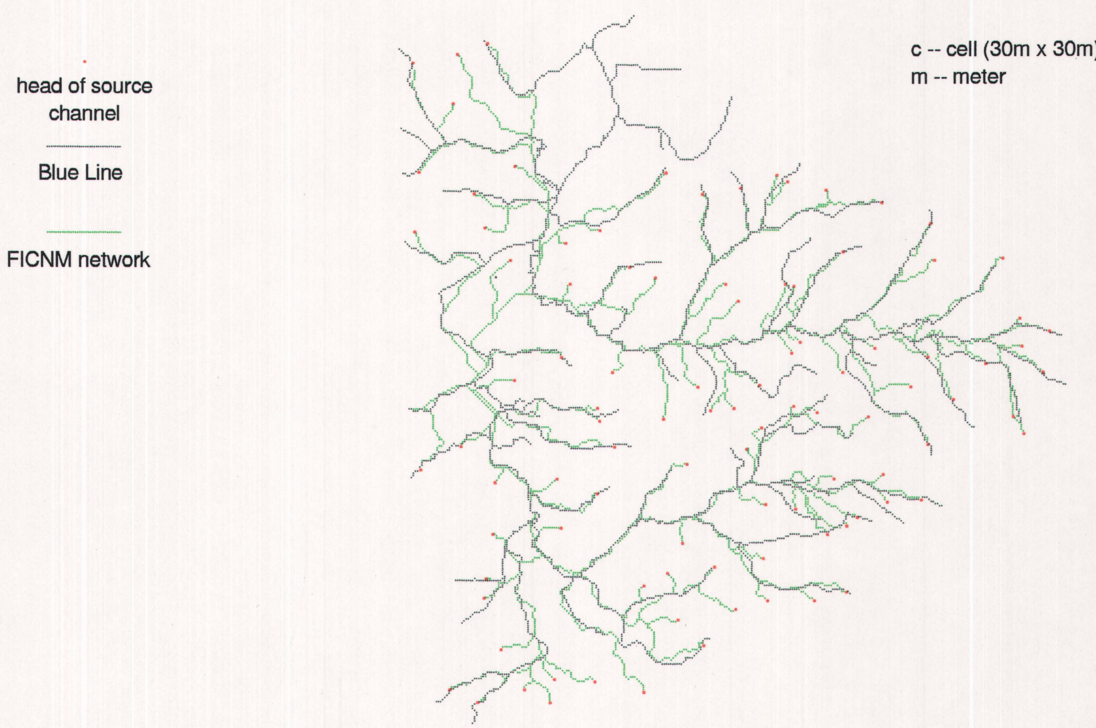


Figure 4-4b Overlay of Blue Line and FICNM Network (MinCSA=25c, MaxCSA=200c), Johnson Creek

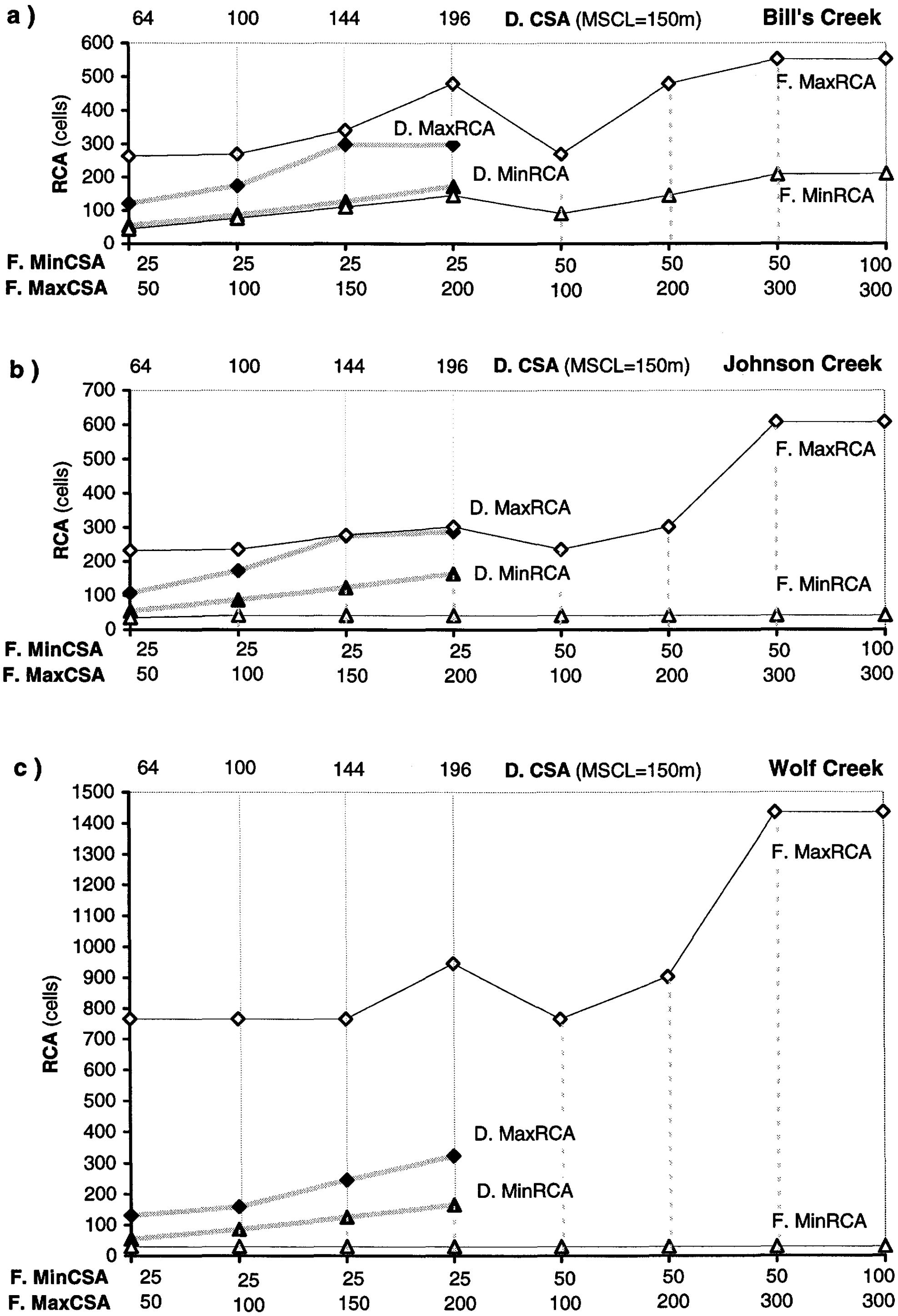
Figure 4-3c Overlay of Blue Line and DEDNM Network (CSA=196c, MSCL=150m), Wolf Creek

Figure 4-4c Overlay of Blue Line and FICNM Network (MinCSA=100c, MaxCSA=300c), Wolf Creek

be compared to each other, so that the improvement made by FICNM can be found (Figure 4-5). Four DEDNM network images and eight FICNM network images were chosen for overlay operation, which resulted in a total of thirty-two new images being generated for each data set (see appendix A). According to the total number of valley heads, total channel cells and occurrence of overshot and undershot cells, two best matched images were selected and illustrated in Figure 4-6a,b,c and Figure 4-7a,b,c. From the figures and the best matched images, the following three improvements can be identified:

1) The most distinctive difference between the DEDNM network and the FICNM network is the range values between MinRCA and MaxRCA. *RCA* is the abbreviation of *Recorded Catchment Area* that is registered on a valley head of a source channel. The Min RCA and MaxRCA are the minimum and maximum values among all RCAs recorded from all valley heads. The MinRCA and MaxRCA are different from the thresholds of MinCSA and MaxCSA. They are the results after FICNM treatment under the thresholds. From the Figure 4-5, all the MinRCA / MaxRCA ranges of FICNM networks are much wider than those of DEDNM networks. In the DEDNM networks, all of the data sets have a similar RCA range. In the FICNM networks, however, the RCA range varied with different date sets. The larger the relief of the date set region (e.g. Wolf Creek), the bigger its RCA range. This indicates that the new method has a good adaptation to different date sets and can be applied more widely in different geographic regions. This is due to introducing a membership function that allows each individual source channel to be treated under its own morphologic features.

2) FICNM can identify and correct the overshoot and undershoot problems and clear up some improperly parallel channels appeared in DEDNM networks. Because FICNM network is generated from the DEDNM network first, they are matched well in the high order channels. When these two kinds of channel networks are overlaid each other, any



CSA -- Critical Source Area threshold used when running DEDNM (D.) or FICNM (F.)

RCA -- Recorded Catchment Area from source channel heads

Figure 4-5 Comparison of the MinRCA / MaxRCA range between DEDNM and FICNM channel networks difference between them actually represents the problems of overshoot, undershoot and improper channels. If a FICNM channel is longer than the corresponding DEDNM channel, the excessive section represents the undershoot part of the DEDNM channel and it has been made up in FICNM channel. If a FICNM channel is shorter than the corresponding DEDNM channel, the uncovered section is the overshoot or improper source channel, which has been eliminated from DEDNM network after FICNM treatment (Figure 4-6a,b,c).

3) The results of the overlay comparison varied between data sets. In the best matched images of the Bill Creek data set, the FICNM network is very close to the DEDNM network. This suggests that in an approximately homogeneous region (e.g. Bill Creek), the new method can work as well as the current method and can draw out very close result from same data set. However, in the best matched images of the Wolf Creek data set, the FICNM network is quite different from the DEDNM network: the overshoot and undershoot problems appear substantially. This implies that in a heterogeneous region FICNM works in a different way and produces a different result from DEDNM. If this difference is closely inspected, it can be explained by the spatial distribution of the appearance of the overshoots or undershoots: most overshoot channels occur in relatively flat areas while the most undershoot channels appear near the peaks. In a flat area, source channels have low valley membership grades and large CSA thresholds. This brings about overshoot corrections. Typical source valleys (gullies) frequently happen near the peak areas. High valley membership grades and small CSA thresholds are assigned to them. This leads to undershoot correction. Clearly the success of the new method to resolve such problems results from the application of valley morphology membership function.

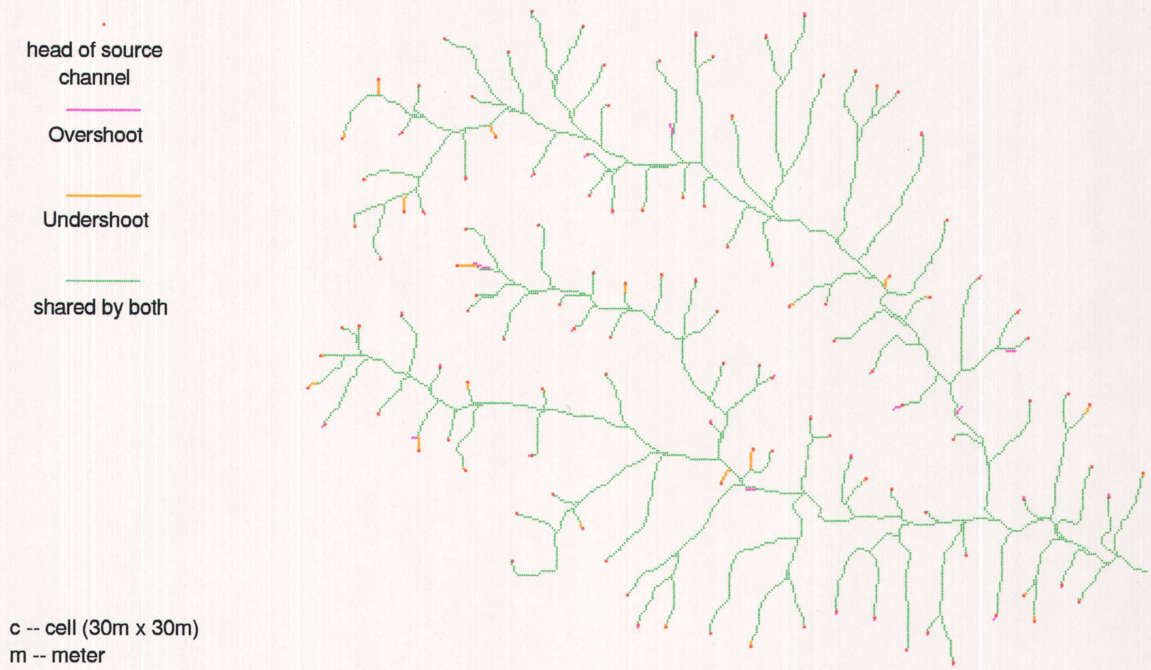


Figure 4-6a Overlay of DEDNM Network (CSA=196c, MSCL=150m) and FICNM Network (MinCSA=25c, MaxCSA=150c), Bill's Creek

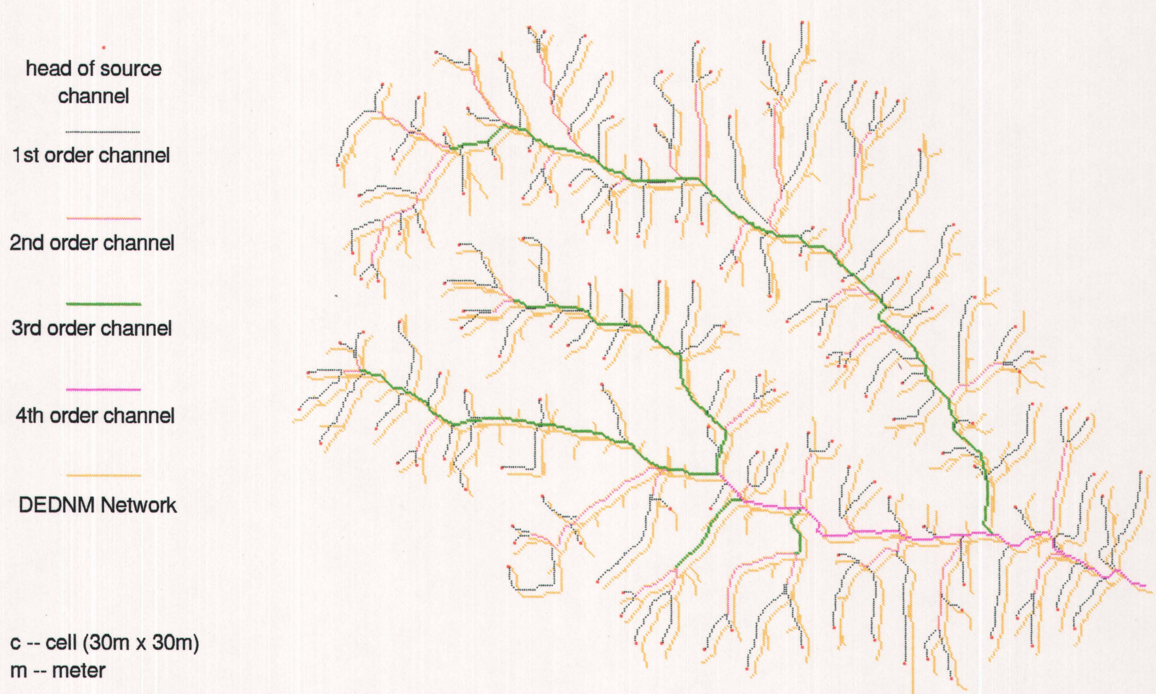


Figure 4-7a FICNM Network (MinCSA=50c, MaxCSA=100c) with background, DEDNM Network (CSA=64c, MSCL=150m), Bill's Creek

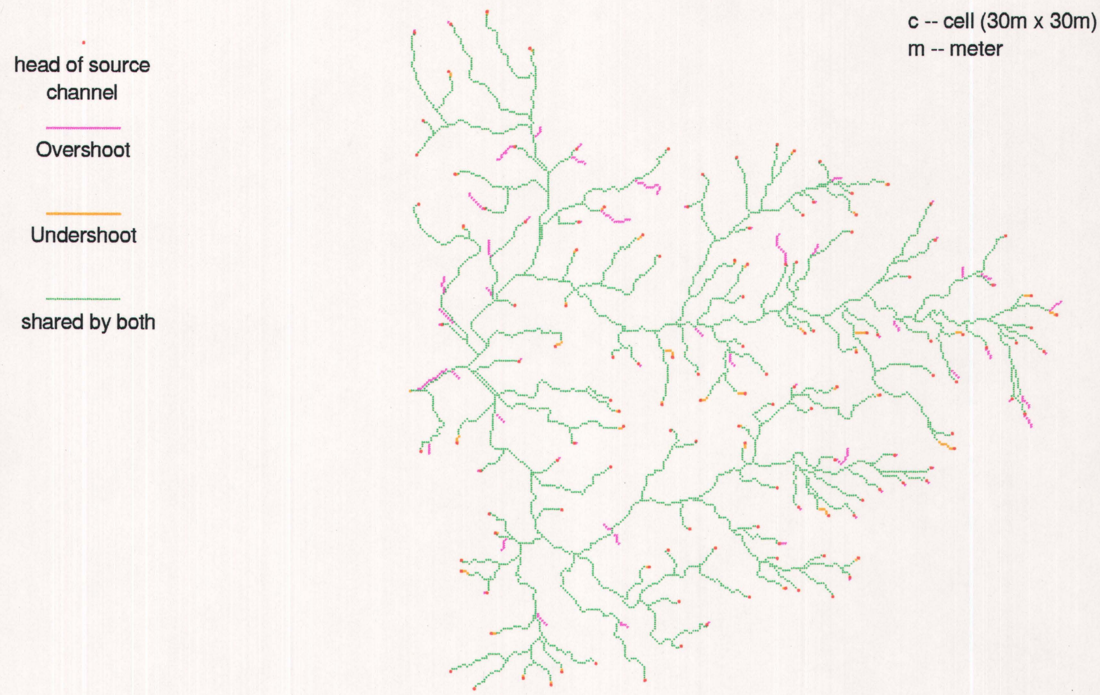


Figure 4-6b Overlay of DEDNM Network (CSA=100c, MSCL=150m) and FICNM Network (MinCSA=50c, MaxCSA=100c), Johnson Creek

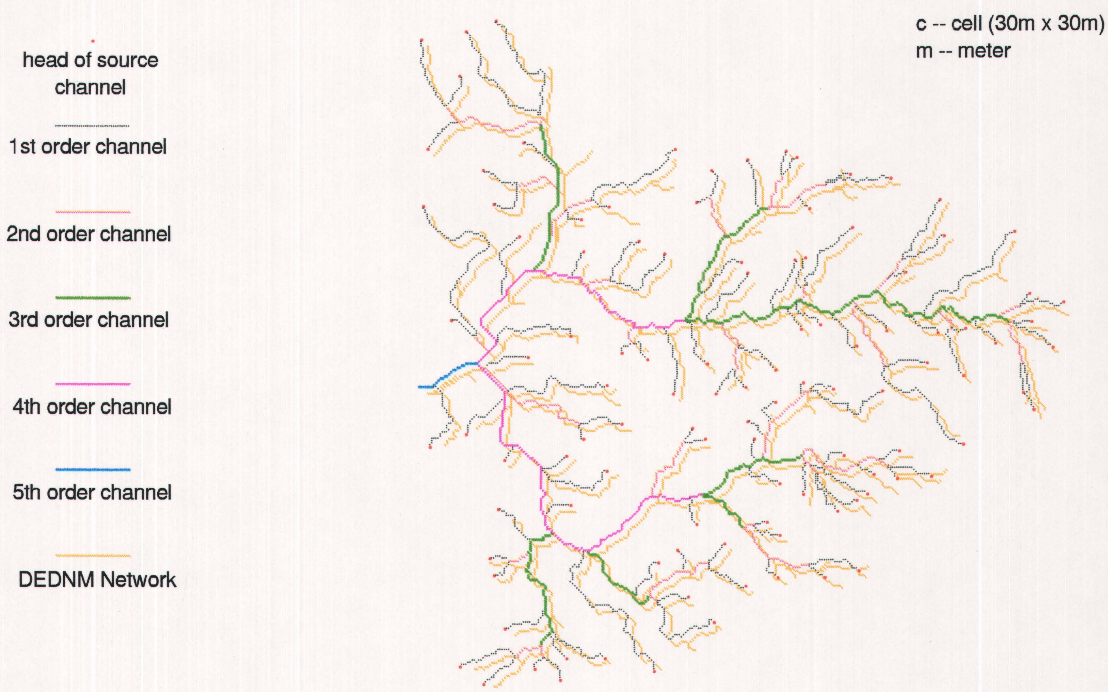


Figure 4-7b FICNM Network (MinCSA=25c, MaxCSA=200c) with background, DEDNM Network (CSA=144c, MSCL=150m), Johnson Creek

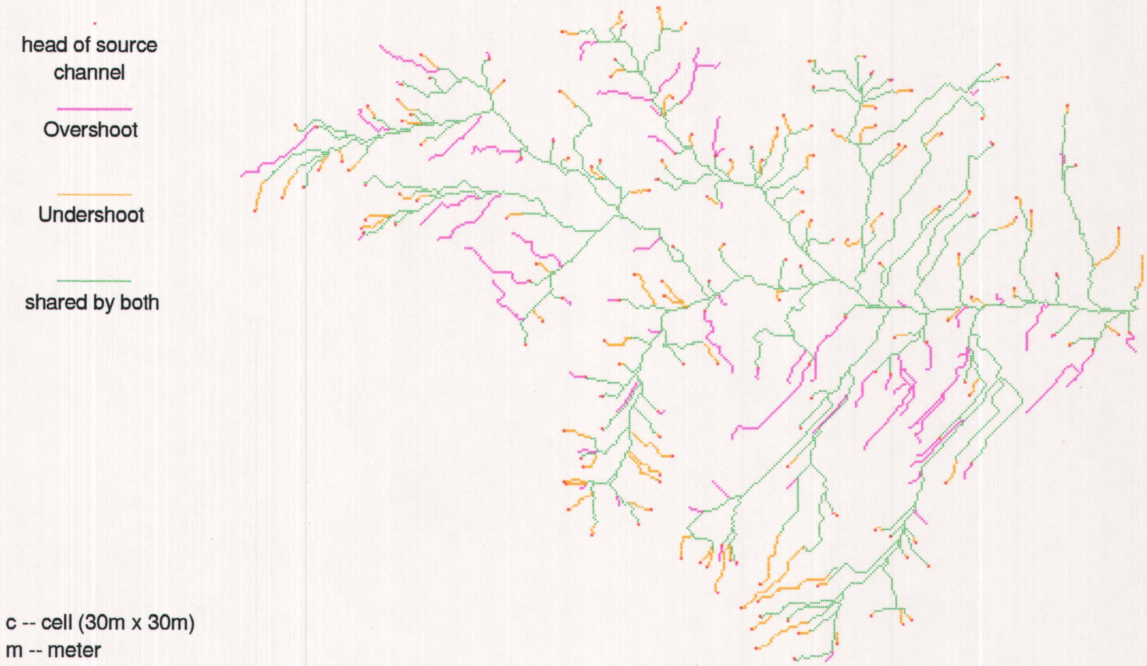


Figure 4-6c Overlay of DEDNM Network (CSA=144c, MSCL=150m) and FICNM Network (MinCSA=25c, MaxCSA=100c), Wolf Creek

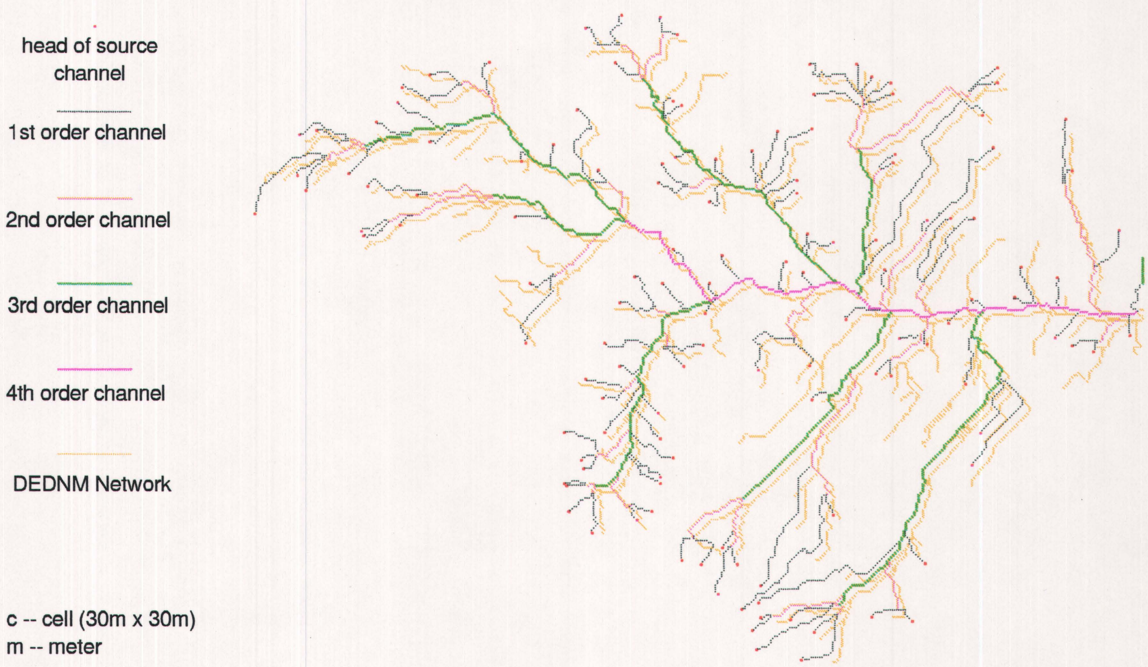


Figure 4-7c FICNM Network (MinCSA=25c, MaxCSA=150c) with background, DEDNM Network (CSA=196c, MSCL=150m), Wolf Creek

4.5 Summary of comparison analysis

The present results were examined by overlay analysis among different images. The absolute spatial match between DEDNM network and FICNM network is very high because the latter is derived from the former. However, both have a low maximum absolute spatial match with blue line, which is often used as a standard reference for the channel network derived from DEM. The explanation for the mismatch between blue lines and DEM channel networks is:

1) The method, maximum absolute spatial match, may not be suitable for comparing the results. Generally, the DEM channel network is visually compared with blue line network. The degree of similarity of the overall pattern between them is easily recognized. However, when comparing these two images point by point, the maximum absolute spatial match is actually very low, although the overall match looks good. Therefore, a precise comparison may not lead to a good conclusion for spatial pattern comparison.

2) It is difficult to compare the features between two different objects. DEM channel networks connect local lowest points that may form part of runoff path. The channel network is extracted using only elevation information from a DEM. Therefore, its generation relies only on the morphology information of earth surface. The blue line is derived from different data source. It is compiled from the data on landform morphology and hydrographic conditions as depicted on airphotos. Although blue line can be regarded as a standard reference stream and river system, the extensions of its exterior links are really not so fixed as shown on topographic map. However, because blue line and DEM channel network share approximately the same spatial position, blue line can work as a reference for DEM channel network but not as an absolute standard line for DEM channel network to match it completely.

3) The most serious mismatch between blue line and DEM channel networks frequently occur in flat areas, especially in the middle and lower reaches. This problem indicates that the grid DEM possesses an inherent deficiency: a fixed resolution in both horizontal and vertical directions. This will reduce the correction of channel position in flat area and make the precision of it varied in entire DEM or different date set. Therefore, It seems impossible that the derived channel network from DEM is fitted to blue line with very high absolute spatial match. This limitation may be improved well by introducing a variable resolution in DEM data structure rather than by some kind of new algorithm applied in current DEM data structure.

It seems that at present there is no a very reliable standard reference for evaluating the channel network derived from DEM. How to assess the new method suggested in the research? The FICNM channel network originated from DEDNM, and FICNM can be viewed as an extension or supplement of DEDNM in its function. Therefore, it can produce same reliable channel network on high orders as DEDNM. The improvement is that it offers a special consideration to deal with the most questionable channel order, the source channel. The framework of the new method is thorough, the applied techniques are reasonable, and the effect of its function is successful. Therefore, the channel network treated by FICNM are more reliable just as discussed and tested above. Although there is no evidence that the FICNM channel network is how close to some kind of standard reference, it can be argued that the FICNM channel network is more close to the objective realities of the channel network. Therefore, FICNM has improved the potential reliability of channel network derived from DEM.

CHAPTER 5
CONCLUSIONS

5.1 Current Achievements

1) This research reviews the current approaches applied in channel network delineation and valley head recognition from DEM; examines the problems of overshoot and undershoot in source channels which result from using single threshold for an entire DEM; discusses the concepts of channel and valley and points out the difference of the core concept used in the local morphology approach and runoff simulation approach; and extends the research scope from valley head recognition to all source channel validity. Therefore, this research has a considerate conceptual framework for the improvement of source channel validity.

2) This research examines the relationship between the contributing area of a source channel and the valley morphology typicality of a source channel. The relationship can play a link role between local morphology approach and runoff simulation approach and provides a theoretical basis for raising a new approach.

3) In this research, fuzzy set theory is introduced for the quantification of valley morphology. A comprehensive membership function of valley morphology is created to measure the valley morphology typicality and to assign a membership grade to each source channel. The membership grade will determine the threshold of contributing area and the head position for each source channel.

4) A dynamical threshold system for source channel evaluation and treatment is developed in this research. The determination of the catchment area threshold relies on the morphologic characteristics of each source channel. Some extraordinary points on valley morphology are included for threshold decision. Therefore, no single threshold is employed for a whole DEM data and all source channels have their own CSA thresholds that are corresponding with their individual valley morphology typicality.

5) A special program, Fuzzy Identification Channel Network Model (FICNM), is developed in the research. The program can collect the information on the valley morphology of source channels from DEM, calculate their membership grade and CSA threshold, get rid of any section that should not be represented as channel network. In particular, FICNM can treat each individual channel as whole rather than a very local section of a channel within a small window.

6) A systematic comparison is accomplished in this research to verify the function of the new approach. The parameters used in DEDNM and FICNM are examined by the overlay comparison so as to expose the rule of the variation of channel network pattern with the parameter change. The difference between blue line network and DEM channel network is explained. The performance of FICNM has been testified in three DEMs. The results verify that FICNM works well in heterogeneous region and can set flexible CSA for individual source channel. Therefore, FICNM has enhanced the potential reliability of channel networks derived from DEM.

5.2 Future Research

For the new approach developed in the research, some issues emerge which are worthy to be further explored.

1) The relationship between the contributing area and the typicality of source valley morphology is the basis of the new approach. However, the two factors appear close relative but the knowledge about it is actually a "black box". The exact relationship is unknown. Do they have a linear relationship or non-linear relationship? Does the relationship vary in different regions? Further discussing the relationship in detail is beyond the subject of the research. Nevertheless, the relationship between them exists indeed and is worthy to be investigated. Before understanding the exact relationship thoroughly, a simple linear relationship is supposed and adopted in this research.

2) The morphologic information of source channel is collected from its two sides with only one cell in width. It seems that it is too narrow for the information collection. Does the two or three cells in width along each side of source channel have an enough width for it? The answer is no. Due to the varieties of valley morphology, some section of a source channel may require quite a larger area to represent its morphologic features than others, such as a wide flat bottom of a source channel. Therefore, if only two or three cells in width are used for data collection, the result will not be improved too much, but the algorithm will become very complicated. A possible way may improve it by introducing a convertible width algorithm so that when the current width is not enough for data collection, the algorithm can change the current width automatically to meet the requirement.

3) At present, the new approach FICNM has been tested in three DEMs and has demonstrated a good adaptability applied in different regions or in a heterogeneous region.

However, the core of FICNM is a knowledge-driven empirical model. It needs to be further modified and optimized by the feedback of its results repeatedly from more DEM data sets of different regions, so that a more generalized format of it can be achieved.

4) The function of FICNM is merely an extension of the function of DEDNM in a new way. It can be integrated with such kind of runoff simulation model for drainage network extraction from DEM. Hence, some marginal conditions and geomorphometric parameters, such as minimum and maximum CSA and relief measures, can be obtained directly from DEM during the channel network extraction. This can avoid extra input/output process and might result in creating a more intellectualized model for the analysis of geomorphologic and hydrologic characteristics from DEM. A more considerate, intellectual, and multifunctional model for automated analysis and extraction of drainage properties is more useful in practice.

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Appendix A

Tables on comparison of DEDNM networks to FICNM networks

Table-A1 Overlay comparison between DEDNM network and FICNM network, Bill's Creek

Table-A2 Overlay comparison between DEDNM network and FICNM network, Johnson Creek

Table A3 Overlay comparison between DEDNM network and FICNM network, Wolf Creek

Table-A1 Overlay comparison between DEDNM channel network and FICNM channel network, Bill's Creek

DEDNM channel network image data						FICNM channel network image data						New overlaid image data			
CSA(A)	MSCL(L)	head	cell	MinRCA	MaxRCA	MinCSA	MaxCSA	head	cell	MinRCA	MaxRCA	shared c	shared %	overshoot	undershoot
						25	50	197	5849	44	263	5805	99.25	464	44
						25	100	148	4840	76	269	4839	99.98	1430	1
						25	150	121	4207	110	340	4206	99.98	2063	1
A=64c	L=150m	253	6269	54	121	25	200	105	3749	145	479	3749	100	2520	0
					(Fig 4-7a)	50	100	147	4830	90	269	4829	99.98	1440	1
						50	200	105	3745	145	479	3745	100	2524	0
						50	300	79	3104	208	553	3104	100	3165	0
						100	300	78	3092	210	553	3092	100	3177	0
						25	50	197	5849	44	263	5209	89.06	84	640
						25	100	148	4840	76	269	4832	99.83	461	8
						25	150	121	4207	110	340	4207	100	1086	0
A=100c	L=150m	178	5293	86	174	25	200	105	3749	145	479	3749	100	1544	0
						50	100	147	4830	90	269	4825	99.9	468	5
						50	200	105	3745	145	479	3745	100	1548	0
						50	300	79	3104	208	553	3104	100	2189	0
						100	300	78	3092	210	553	3092	100	2201	0
						25	50	197	5849	44	263	4640	79.33	6	1209
						25	100	148	4840	76	269	4569	94.4	77	271
						25	150	121	4207	110	340	4201	99.86	445	6
A=144c	L=150m	146	4646	127	298	25	200	105	3749	145	479	3747	99.95	899	2
						50	100	147	4830	90	269	4569	94.6	77	261
						50	200	105	3745	145	479	3743	99.95	903	2
						50	300	79	3104	208	553	3104	100	1542	0
						100	300	78	3092	210	553	3092	100	1554	0
						25	50	197	5849	44	263	4118	70.41	1	1731
						25	100	148	4840	76	269	4095	84.61	24	745
					(Fig 4-6a)	25	150	121	4207	110	340	4051	96.29	68	156
A=196c	L=150m	120	4119	172	298	25	200	105	3749	145	479	3741	99.79	378	8
						50	100	147	4830	90	269	4095	84.78	24	735
						50	200	105	3745	145	479	3740	99.87	379	5
						50	300	79	3104	208	553	3104	100	1015	0
						100	300	78	3092	210	553	3092	100	1027	0

(MinRCA / MaxRCA -- The maximum / minimum value of Recorded Catchment Area upon source channel heads)

Table-A2 Overlay comparison between DEDNM channel network and FICNM channel network, Johnson Creek

DEDNM channel network image data						FICNM channel network image data						New overlaid image data			
CSA(A)	MSCL(L)	head	cell	MinRCA	MaxRCA	MinCSA	MaxCSA	head	cell	MinRCA	MaxRCA	shared c	shared %	overshoot	undershoot
						25	50	242	5704	35	232	5206	91.27	287	498
						25	100	162	4558	42	235	4530	99.39	963	28
						25	150	127	3972	42	277	3961	99.72	1532	11
A=64c	L=150m	253	5493	55	107	25	200	109	3609	42	302	3598	99.7	1895	11
						50	100	136	4170	42	235	4158	99.71	1335	12
						50	200	99	3410	42	302	3407	99.91	2086	3
						50	300	83	2988	42	608	2985	99.9	2508	3
						100	300	72	2798	42	608	2795	99.89	2698	3
						25	50	242	5704	35	232	4190	73.46	90	1514
						25	100	162	4558	42	235	4065	89.18	215	493
						25	150	127	3972	42	277	3870	97.43	410	102
A=100c	L=150m	159	4280	87	173	25	200	109	3609	42	302	3568	98.86	712	41
					(Fig 4-6b)	50	100	136	4170	42	235	4017	96.33	263	153
						50	200	99	3410	42	302	3394	99.53	886	16
						50	300	83	2988	42	608	2978	99.67	1302	10
						100	300	72	2798	42	608	2791	99.75	1489	7
						25	50	242	5704	35	232	3611	63.31	32	2093
						25	100	162	4558	42	235	3573	78.39	70	985
						25	150	127	3972	42	277	3505	88.24	138	467
					(Fig 4-7b)	25	200	109	3609	42	302	3368	93.32	275	241
A=144c	L=150m	123	3643	123	274	50	100	136	4170	42	235	3541	84.92	102	629
						50	200	99	3410	42	302	3314	97.18	329	96
						50	300	83	2988	42	608	2971	99.43	672	17
						100	300	72	2798	42	608	2785	99.54	858	13
						25	50	242	5704	35	232	3171	55.59	8	2533
						25	100	162	4558	42	235	3154	69.2	25	1404
						25	150	127	3972	42	277	3126	78.7	53	846
A=196c	L=150m	100	3179	164	287	25	200	109	3609	42	302	3079	85.31	100	530
						50	100	136	4170	42	235	3136	75.2	43	1034
						50	200	99	3410	42	302	3066	89.91	113	344
						50	300	83	2988	42	608	2895	96.89	284	93
						100	300	72	2798	42	608	2777	99.25	402	21

(MinRCA / MaxRCA -- The maximum / minimum value of Recorded Catchment Area upon source channel heads)

Table-A3 Overlay comparison between DEDNM channel network and FICNM channel network, Wolf Creek

DEDNM channel network image data						FICNM channel network image data						New overlaid image data			
CSA(A)	MSCL(L)	head	cell	MinRCA	MaxRCA	MinCSA	MaxCSA	head	cell	MinRCA	MaxRCA	shared c	shared %	overshoot	undershoot
						25	50	266	6560	30	766	6089	92.82	2326	471
						25	100	176	4854	30	766	4610	94.97	3805	244
						25	150	131	4105	30	766	3862	94.08	4553	243
A=64c	L=150m	350	8415	55	131	25	200	98	3457	30	946	3214	92.97	5201	243
						50	100	169	4718	30	766	4477	94.89	3938	241
						50	200	95	3408	30	906	3167	92.93	5248	241
						50	300	75	2995	30	1436	2754	91.95	5661	241
						100	300	73	2961	30	1436	2720	91.86	5695	241
						25	50	266	6560	30	766	5115	77.97	1242	1445
						25	100	176	4854	30	766	4423	91.12	1934	431
						25	150	131	4105	30	766	3717	90.55	2640	388
A=100c	L=150m	245	6357	86	159	25	200	98	3457	30	946	3086	89.27	3271	371
						50	100	169	4718	30	766	4330	91.78	2027	388
						50	200	95	3408	30	906	3039	89.17	3318	369
						50	300	75	2995	30	1436	2628	87.75	3729	367
						100	300	73	2961	30	1436	2594	87.61	3763	367
						25	50	266	6560	30	766	4210	64.18	698	2350
					(Fig 4-6c)	25	100	176	4854	30	766	3845	79.21	1063	1009
						25	150	131	4105	30	766	3564	86.82	1344	541
A=144c	L=150m	172	4908	125	246	25	200	98	3457	30	946	2974	86.03	1934	483
						50	100	169	4718	30	766	3800	80.54	1108	918
						50	200	95	3408	30	906	2933	86.06	1975	475
						50	300	75	2995	30	1436	2519	84.11	2389	476
						100	300	73	2961	30	1436	2485	83.92	2423	476
						25	50	266	6560	30	766	3552	54.15	417	3008
						25	100	176	4854	30	766	3298	67.94	671	1556
					(Fig 4-7c)	25	150	131	4105	30	766	3187	77.64	782	918
A=196c	L=150m	123	3969	166	324	25	200	98	3457	30	946	2870	83.02	1099	587
						50	100	169	4718	30	766	3259	69.08	710	1459
						50	200	95	3408	30	906	2843	83.42	1126	565
						50	300	75	2995	30	1436	2450	81.8	1519	545
						100	300	73	2961	30	1436	2417	81.63	1552	544

(MinRCA / MaxRCA -- The maximum / minimum value of Recorded Catchment Area upon source channel heads)

Appendix B

Program of Fuzzy Identification Channels Network Model (FICNM)

```
C=====================================================================C
C                                                                     C
C          FUZZY IDENTIFICATION CHANNEL NETWORK MODEL (FICNM)         C
C                                                                     C
C                           By Kelin Zhao                             C
C         Department of Geography, University of Saskatchewan         C
C                                                                     C
C======================================================================

      write(*,*)'===================================================='
      write(*,*)'===================================================='
      write(*,*)'===  Fuzzy Identification Channel Network model  ==='
      write(*,*)'===     Writen by Kelin Zhao, 08/94 -- 10/95     ==='
      write(*,*)'===================================================='
      write(*,*)'===================================================='


C======================================================================

      parameter (mxr=400, mxc=500, degree=57.296)

      character filntw*8, filfvc*10, filrlf*10, filupa*10,
     +          fildat*8, filtab*8

      real minslp, maxslp, mindp, maxdp, lc, rlop

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

C--------------- read in user-defined parameter file -----------------

      open (20, file='userprmt.inp', status='old', err=1001)

      read (20, 7, err=121) irow
121   if(irow.eq.0) goto 1021
      read (20, 7, err=122) icol
122   if(icol.eq.0) goto 1022
      read (20, 8, err=123) csize
123   if(csize.eq.0) goto 1023
      read (20, 8, err=124) hc
124   if(hc.eq.0) goto 1024
      read (20, 8, err=125) lc
125   if(lc.eq.0) goto 1025
      read (20, 8, err=126) minslp
126   if(minslp.eq.0) goto 1026
      read (20, 8, err=127) maxslp
127   if(maxslp.eq.0) goto 1027
      read (20, 8, err=128) mindp
128   if(mindp.eq.0) goto 1028
      read (20, 8, err=129) maxdp
129   if(maxdp.eq.0) goto 1029
```

```
      read (20, 7, err=130) minupa
130   if(minupa.eq.0) goto 1030
      read (20, 7, err=131) maxupa
131   if(maxupa.eq.0) goto 1031
      read (20, 8, err=132) slpwt
132   if(slpwt.eq.0) goto 1032
      read (20, 8, err=133) dpwt
133   if(dpwt.eq.0) goto 1033
      read (20, 7, err=134) minlg
134   if(minlg.eq.0) goto 1034
      read (20, 7, err=135) mxflg
135   if(mxflg.eq.0) goto 1035

7     format(22x, i3)
8     format(22x, f5.2)

      close(20)

      goto 9

C----- User-defined parameter file found, but it is incomplete! ------

1021  write(*,*)
      write (*,*)'==== Number of Row ? : '
      read (*,*) irow
      goto 121
1022  write (*,*)'==== Number of Col ? : '
      read (*,*) icol
      goto 122

1023  csize=30.0
      goto 123
1024  hc=1.0
      goto 124
1025  lc=0.3
      goto 125
1026  minslp=3.0
      goto 126
1027  maxslp=30.0
      goto 127
1028  mindp=csize*tan(minslp/degree)
      goto 128
1029  maxdp=csize*tan(maxslp/degree)
      goto 129

1030  write(*,*)'==== Minimun uparea in # of cell (16 < X < 99) : '
      read (*,*) minupa
      if(minupa.lt.16.or.minupa.gt.99) then
      kretry1=kretry1+1
       if(kretry1.gt.2) then
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'====  Decide minimun uparea value (16 < X < 99) ===='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       goto 2000
       endif
      write(*,*)'===================================================='
      write(*,*)'!!!!  (16 <X< 99) of minimun uparea reconmanded !!!!'
      write(*,*)'===================================================='
      write(*,*)
      goto 1030
      endif
      goto 130

1031  write(*,*)'==== Maximun uparea in # of cell (50 < X < 999) : '
      read (*,*) maxupa
      if(maxupa.lt.50.or.maxupa.gt.999) then
      kretry2=kretry2+1
       if(kretry2.gt.2) then
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'==== Decide maximum uparea value (50 < X < 999) ===='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       goto 2000
       endif
      write(*,*)'===================================================='
      write(*,*)'!!!! (50 <X< 999) of maximun uparea reconmanded !!!!'
      write(*,*)'===================================================='
      write(*,*)
      goto 1031
      endif
      if(maxupa.lt.minupa) then
```

```
        kkk=minupa
        minupa=maxupa
        maxupa=kkk
       endif
       goto 131

 1032  slpwt=0.65
       goto 132
 1033  dpwt=0.35
       goto 133
 1034  minlg=3
       goto 134

 1035  write(*,*)'==== Minimum length for final source channel : '
       read(*,*) mxflg
       if(mxflg.lt.3.or.mxflg.gt.30) then
       kretry3=kretry3+1
        if(kretry3.gt.2) then
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       write(*,*)'==== Decide min length value (3 < X < 30 cells) ===='
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
        goto 2000
        endif
       write(*,*)'=================================================='
       write(*,*)'!!! (3 < X < 30 cells) of min length reconmanded !!!'
       write(*,*)'=================================================='
       write(*,*)
       goto 1035
        endif

       goto 135

C===== No user-defined parameter file found, default values used =====

 1001  write(*,*)'=================================================='
       write(*,*)'!!!!!!!   No  userprmt.inp  file  found  !   !!!!!!!'
       write(*,*)'=================================================='

 1041  write(*,*)
       write (*,*)'==== Number of Row ? : '
       read (*,*) irow
 1042  write (*,*)'==== Number of Col ? : '
       read (*,*) icol
 1043  csize=30.0
 1044  hc=1.0
 1045  lc=0.3
 1046  minslp=3.0
 1047  maxslp=30.0
 1048  mindp=csize*tan(minslp/degree)
 1049  maxdp=csize*tan(maxslp/degree)
 1050  write(*,*)'==== Minimun uparea in # of cell (16 < X < 99) : '
       read (*,*) minupa
       if(minupa.lt.16.or.minupa.gt.99) then
       kretry1=kretry1+1
        if(kretry1.gt.2) then
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       write(*,*)'====  Decide minimun uparea value (16 < X < 99) ===='
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
        goto 2000
        endif
       write(*,*)'=================================================='
       write(*,*)'!!!!  (16 <X< 99) of minimun uparea reconmanded !!!!'
       write(*,*)'=================================================='
       write(*,*)
       goto 1050
       endif
 1051  write(*,*)'==== Maximun uparea in # of cell (50 < X < 999) : '
       read (*,*) maxupa
       if(maxupa.lt.50.or.maxupa.gt.999) then
       kretry2=kretry2+1
        if(kretry2.gt.2) then
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       write(*,*)'==== Decide maximum uparea value (50 < X < 999) ===='
       write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
        goto 2000
        endif
       write(*,*)'=================================================='
       write(*,*)'!!!! (50 <X< 999) of maximun uparea reconmanded !!!!'
       write(*,*)'=================================================='
       write(*,*)
```

```
      goto 1051
      endif
      if(maxupa.lt.minupa) then
       kkk=minupa
       minupa=maxupa
       maxupa=kkk
      endif
1052  slpwt=0.65
1053  dpwt=0.35
1054  minlg=3
1055  write(*,*)'==== Minimum length for final source channel : '
      read(*,*) mxflg
      if(mxflg.lt.3.or.mxflg.gt.30) then
      kretry3=kretry3+1
       if(kretry3.gt.2) then
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'==== Decide min length value (3 < X < 30 cells) ===='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       goto 2000
       endif
      write(*,*)'===================================================='
      write(*,*)'!!! (3 < X < 30 cells) of min length reconmanded !!!'
      write(*,*)'===================================================='
      write(*,*)
      goto 1055
       endif

C------------- Display the parameters used in FICNM ----------------

9     write(*,*)
      write(*,*)'===================================================='
      write(*,*)'==========  User  Defined  Parameters :  =========='
      write(*,*)'===================================================='
      write(*,5)'|       Number of row  : ',irow,  '( <= 400 )      |'
      write(*,5)'|    Number of column  : ',icol,  '( <= 500 )      |'
      write(*,6)'| Dimension of a cell  : ',csize, '( 10 -- 100 )   |'
      write(*,6)'|     High coefficent  : ',hc,    '( 1.0 -- 5.0 )  |'
      write(*,6)'|      Low coefficent  : ',lc,    '( 0.0 -- 1.0 )  |'
      write(*,6)'|      Min side slope  : ',minslp,'( 0.0 -- 7.0 )  |'
      write(*,6)'|      Max side slope  : ',maxslp,'( 20.0 - 45.0 ) |'
      write(*,6)'|    Min valley depth  : ',mindp, '( 0.5 -- 3.8 )  |'
      write(*,6)'|    Max valley depth  : ',maxdp, '( 10.9 - 30.0 ) |'
      write(*,5)'|  Min uparea in cell  : ',minupa,'( 16 -- 99 )    |'
      write(*,5)'|  Max uparea in cell  : ',maxupa,'( 50 -- 999 )   |'
      write(*,6)'|  Weight of Ug-slope  : ',slpwt, '( 0.4 -- 0.8 )  |'
      write(*,6)'|  Weight of Ug-depth  : ',dpwt,  '( 0.2 -- 0.6 )  |'
      write(*,5)'|  Min length in cell  : ',minlg, '( 0 -- 5 )      |'
      write(*,5)'| Kp min lgth in cell  : ',mxflg, '( 3 -- 33 )     |'
      write(*,*)'===================================================='
5     format(1x, a26, i3, 5x, a17)
6     format(1x, a26, f5.2, 3x, a17)

      dfc=hc-lc
      dfupa=maxupa-minupa
      dfdp=maxdp-mindp

C------------------------- Output option ---------------------------

      write(*,*)
      write(*,*)'==== Writing output file in :'
      write(*,*)
      write(*,*)'     [1] series of all images (10 - 25 MB needed)'
      write(*,*)'     [2] several mid results  ( 4 - 10 MB needed)'
      write(*,*)'     [3] only a final result  [ 1 / 2 / 3 <- ? ] : '
      read (*,*) kfile

      if(kfile.lt.1.or.kfile.gt.3) then
       kretry3=kretry3+1
       if(kretry3.gt.2) then
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'====   Decide  what  result(s)  wanted  first   ===='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
       goto 2000
       endif
      write(*,*)'===================================================='
      write(*,*)'!!!!!!   Try  again  to choose  ( 1/ 2/ 3 )   !!!!!!'
      write(*,*)'===================================================='
       goto 9
      endif
```

```
C----------- Read in DEM data files generated from DEDNM -------------

      filntw='netw.img'
      filfvc='flovec.img'
      filrlf='relief.img'
      filupa='uparea.img'

      open (31, file=filntw, status='old', err=1002)
      open (32, file=filfvc, status='old', err=1003)
      open (33, file=filrlf, status='old', err=1004)
      open (34, file=filupa, status='old', err=1005)

C============ Reading data files from disk to main memory ============

      write (*,*)'==== Reading Netw.img Data ===='
      do 15 ir=1, irow
      do 15 ic=1, icol
15       read (31, *, err=1006) ntw(ir, ic)

      write(*,*)
      write (*,*)'==== Reading Flovec.img Data ===='
      do 16 ir=1, irow
      do 16 ic=1, icol
16       read (32, *, err=1006) nfl(ir, ic)

      write(*,*)
      write (*,*)'==== Reading Relief.img Data ===='
      do 17 ir=1, irow
      do 17 ic=1, icol
17       read (33, *, err=1006) relf(ir, ic)

      write(*,*)
      write (*,*)'==== Reading Uparea.img Data ===='
      do 18 ir=1, irow
      do 18 ic=1, icol
18       read (34, *, err=1006) nupa(ir, ic)

      kk=0
      do 19 i4=-1, 1
      do 19 j4=-1, 1
         kk=kk+1
         nfv(kk, 1)=i4
         nfv(kk, 2)=j4
19    continue

      close(31)
      close(32)
      close(33)
      close(34)

C----------------- Begin to process channel network ------------------

      ksw=0
      klop=1
      rlop=100
      write(*,*)
      write(*,*)'*****************************************************'
      write(*,27)'=====  Processing  the  network  in  loop ',klop,
     +           '  ======'
      write(*,*)'*****************************************************'
27    format(1x, a42, i2, a8)

C====================================================================
C          subroutine fhead (1)
C====================================================================
      write(*,*)
      write (*,*)'==== finding out heads of source channel ===='
      write(*,*)

      call fhead
C====================================================================
C          subroutine fprmt (2)
C====================================================================
111   write(*,*)
      write (*,*)'==== collecting morphologic parameters ===='

      call fprmt
C====================================================================
C          subroutine fzvalu (3)
C====================================================================
```

```
      write(*,*)
      write (*,*)'==== calculating CSA thresholds ===='

      call fzvalu
C======================================================================
C          subroutine remvch (4)
C======================================================================
      write(*,*)
      write (*,*)'==== Eliminating some source channels ===='

      call remvch
C======================================================================
C          subroutine rwelm (5)
C======================================================================
      write(*,*)
      write (*,*)'==== Re-write all channel value ===='

      call rwelm

      if(rlop.le.5) goto 333
C======================================================================
C          subroutine roder (6)
C======================================================================
      write(*,*)
      write (*,*)'==== Re-write 1st channel order system ===='

      call roder

      klop=klop+1
      write(*,*)
      write(*,*)'****************************************************'
      write(*,27)'=====  Processing  the  network  in  loop ',klop,
     +           '  ======'
      write(*,*)'****************************************************'
      if(rlop.gt.5) goto 111

C======================================================================
C          subroutine fnlod (7)
C======================================================================
      write(*,*)
      write (*,*)'==== Define final channel network order ===='

333   call fnlod

C======================================================================

      if(kfile.eq.1.or.kfile.eq.2) then
      write(*,*)
      write(*,*)'===================================================='
      write(*,*)'==== Byte data type and packed binary file type ===='
      write(*,*)'====    are recommended to all images created    ===='
      write(*,*)'===================================================='
      endif

      write(*,*)
      write(*,*)'===================================================='
      write(*,*)'===================================================='
      write(*,*)'====   Channel  network  treated  completely !  ===='
      write(*,*)'===================================================='
      write(*,*)'===================================================='

      goto 2000
C
C========================= Error massages =========================
C

1002  write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,1101)'===========   No  ',filntw,'  exists  ! ',
     +             '  ==========='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      goto 1995
1003  write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,1102)'==========   No  ',filfvc,'  exists  ! ',
     +             '  =========='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      goto 1995
1004  write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,1102)'==========   No  ',filrlf,'  exists  ! ',
     +             '  =========='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
```

```
      goto 1995
1005  write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,1102)'==========   No  ',filupa,'  exists  ! ',
     +            '  =========='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
1101  format(1x, a18, a9, a12, a13)
1102  format(1x, a17, a11, a12, a12)
      goto 1995

1006  write(*,*)
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'=======   Data transfor beyond end of file   ======='
      write(*,*)'=======   Check  No. of row and No. of col   ======='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'

1995  write(*,*)
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'
      write(*,*)'=======   Program terminated with error  !   ======='
      write(*,*)'!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!'

2000  end

C
C=====================================================================
C=====================================================================
C
C                        S U B R O U T I O N S
C
C=====================================================================
C  The subroutine(1) is to find valley heads for all source channels
C=====================================================================
C
      subroutine fhead
C
C---------------------------------------------------------------------

      parameter (mxr=400, mxc=500)

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      khd=0

      do 10 ir=1, irow
      do 20 ic=1, icol

      if (ir.eq.1.or.ir.eq.irow) goto 20
      if (ic.eq.1.or.ic.eq.icol) goto 20
      if (ntw(ir, ic).ne.1) goto 20

      kp=9
      k1=0

        do 30 i=-1, 1
        do 30 j=-1, 1

          if(i.eq.0.and.j.eq.0) goto 25
          if(kp.ne.nfl(ir+i,ic+j)) goto 25

          if(ntw(ir+i,ic+j).ge.1) then
            k1=k1+1
          endif

25       kp=kp-1
30       continue

          if (k1.eq.0) then
            ntw(ir, ic)=10
            khd=khd+1
          endif

20    continue
10    continue
```

```
C-------------------------------------------------------------------

      if(ksw.eq.0) then
      write(*,110)'==== The number of heads found : ',khd
110   format(1x, a33, i4)
        kwt=1
        call wrtdoc
      endif

      return
      end

C===================================================================
C
C===================================================================
C       The subroutine(2) is to collect morphologic parameters
C===================================================================
C
      subroutine fprmt
C
C-------------------------------------------------------------------

      parameter (mxr=400, mxc=500)

      real lngth, nor, non, nor1, non1, maxch, mxgd, lslp

      integer dfelv

      character fildat*10, filrpt*10, dat(9)

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      data        dat(1)/'1'/,dat(2)/'2'/,dat(3)/'3'/,dat(4)/'4'/,
     + dat(5)/'5'/,dat(6)/'6'/,dat(7)/'7'/,dat(8)/'8'/,dat(9)/'9'/

      if(kfile.eq.1) then
        fildat='prmt'//dat(klop)//'.dat'
        filrpt='prmt'//dat(klop)//'.rpt'
        goto 5
      endif

      if(kfile.eq.2.and.klop.eq.1) then
        fildat='prmt'//dat(klop)//'.dat'
        filrpt='prmt'//dat(klop)//'.rpt'
        goto 5
      endif

      if(kfile.eq.2.or.kfile.eq.3) then
        fildat='prmt-.dat'
        filrpt='prmt-.rpt'
      endif

5     open (35, file=fildat, status='unknown')
      open (36, file=filrpt, status='unknown')

C---- Finding a valley head and recording its around values ---------

      knmb=0
      kpage=0

      normal=0
      nonmal=0

      write(36,15)'  No. irh ich ire ice ncl  lngth dfelv hdslp ',
     +'asslp  lsslp  rsslp  depth  chlgd mxgd mxcr mxcc npc  upa mrk '
      write(36,15)'===^===^===^===^===^===^=====^=====^=====^===',
     +'==^======^======^======^======^=====^=====^===^===^====^===^=='
15    format(a45, a62)

C------- Found a valley head for collecting the head parameters ------

      do 10 ir=1, irow
      do 20 ic=1, icol
```

```
         if (ir.eq.1.or.ir.eq.irow) goto 20
         if (ic.eq.1.or.ic.eq.icol) goto 20
         if (ntw(ir, ic).eq.10) then

         knmb=knmb+1

         lngth=0
         sl=0
         sr=0
         sh=0

       goto (16,26,36,46,56,66,76,86,96) nfl(ir, ic)

16     sl=(relf(ir+1, ic-1)-relf(ir, ic))/1.414
       sr=(relf(ir-1, ic+1)-relf(ir, ic))/1.414
       sh=(relf(ir+1, ic+1)-relf(ir, ic))/1.414
       lngth=lngth+1.414
       goto 106

26     sl=relf(ir, ic-1)-relf(ir, ic)
       sr=relf(ir, ic+1)-relf(ir, ic)
       sh=(relf(ir+1, ic)-relf(ir, ic))
       lngth=lngth+1.0
       goto 106

36     sl=(relf(ir-1, ic-1)-relf(ir, ic))/1.414
       sr=(relf(ir+1, ic+1)-relf(ir, ic))/1.414
       sh=(relf(ir+1, ic-1)-relf(ir, ic))/1.414
       lngth=lngth+1.414
       goto 106

46     sl=relf(ir+1, ic)-relf(ir, ic)
       sr=relf(ir-1, ic)-relf(ir, ic)
       sh=(relf(ir, ic+1)-relf(ir, ic))
       lngth=lngth+1.0
       goto 106

56     goto 106

66     sl=relf(ir-1, ic)-relf(ir, ic)
       sr=relf(ir+1, ic)-relf(ir, ic)
       sh=(relf(ir, ic-1)-relf(ir, ic))
       lngth=lngth+1.0
       goto 106

76     sl=(relf(ir+1, ic+1)-relf(ir, ic))/1.414
       sr=(relf(ir-1, ic-1)-relf(ir, ic))/1.414
       sh=(relf(ir-1, ic+1)-relf(ir, ic))/1.414
       lngth=lngth+1.414
       goto 106

86     sl=relf(ir, ic+1)-relf(ir, ic)
       sr=relf(ir, ic-1)-relf(ir, ic)
       sh=(relf(ir-1, ic)-relf(ir, ic))
       lngth=lngth+1.0
       goto 106

96     sl=(relf(ir-1, ic+1)-relf(ir, ic))/1.414
       sr=(relf(ir+1, ic-1)-relf(ir, ic))/1.414
       sh=(relf(ir-1, ic-1)-relf(ir, ic))/1.414
       lngth=lngth+1.414
       goto 106

C----------------- Initilize all kind of variables -------------------

106      kcell=1
         csize=30

         irh=ir
         ich=ic

         el=0
         er=0

         ir1=ir
         ic1=ic

         ntpl=0
         ntpr=0
```

```
      kntl=0
      kntr=0

      sg1=sh
      sg2=0

      maxch=0
      mxcr=0
      mxcc=0
      mxupa=0

      dfch=0
      dfelv=0
      hl=0
      hr=0

C---- Do loop to change central cell and record the side values -----

12     kc=nfl(ir1, ic1)
      ir2=ir1+nfv(kc, 1)
      ic2=ic1+nfv(kc, 2)

      if(ntw(ir2, ic2).eq.1) then

      goto(14, 13, 14, 13, 18, 13, 14, 13, 14) nfl(ir2, ic2)

13     sg2=relf(ir1, ic1)-relf(ir2, ic2)
      goto 18
14     sg2=(relf(ir1, ic1)-relf(ir2, ic2))/1.414

      dfch=abs(sg2-sg1)

18     if(dfch.gt.maxch)then
        maxch=dfch
        mxcr=ir1
        mxcc=ic1
        mxupa=nupa(ir1, ic1)
      endif

      sg1=sg2

      goto (17,27,37,47,57,67,77,87,97) nfl(ir2, ic2)

17    el=(relf(ir2+1, ic2-1)-relf(ir2, ic2))/1.414
      er=(relf(ir2-1, ic2+1)-relf(ir2, ic2))/1.414
      ntpl=ntw(ir2+1, ic2-1)
      ntpr=ntw(ir2-1, ic2+1)
      lngth=lngth+1.414
      goto 107

27    el=relf(ir2, ic2-1)-relf(ir2, ic2)
      er=relf(ir2, ic2+1)-relf(ir2, ic2)
      ntpl=ntw(ir2, ic2-1)
      ntpr=ntw(ir2, ic2+1)
      lngth=lngth+1.0
      goto 107

37    el=(relf(ir2-1, ic2-1)-relf(ir2, ic2))/1.414
      er=(relf(ir2+1, ic2+1)-relf(ir2, ic2))/1.414
      ntpl=ntw(ir2-1, ic2-1)
      ntpr=ntw(ir2+1, ic2+1)
      lngth=lngth+1.414
      goto 107

47    el=relf(ir2+1, ic2)-relf(ir2, ic2)
      er=relf(ir2-1, ic2)-relf(ir2, ic2)
      ntpl=ntw(ir2+1, ic2)
      ntpr=ntw(ir2-1, ic2)
      lngth=lngth+1.0
      goto 107

57    goto 107

67    el=relf(ir2-1, ic2)-relf(ir2, ic2)
      er=relf(ir2+1, ic2)-relf(ir2, ic2)
      ntpl=ntw(ir2-1, ic2)
      ntpr=ntw(ir2+1, ic2)
      lngth=lngth+1.0
      goto 107
```

```
77     el=(relf(ir2+1, ic2+1)-relf(ir2, ic2))/1.414
       er=(relf(ir2-1, ic2-1)-relf(ir2, ic2))/1.414
       ntpl=ntw(ir2+1, ic2+1)
       ntpr=ntw(ir2-1, ic2-1)
       lngth=lngth+1.414
       goto 107

87     el=relf(ir2, ic2+1)-relf(ir2, ic2)
       er=relf(ir2, ic2-1)-relf(ir2, ic2)
       ntpl=ntw(ir2, ic2+1)
       ntpr=ntw(ir2, ic2-1)
       lngth=lngth+1.0
       goto 107

97     el=(relf(ir2-1, ic2+1)-relf(ir2, ic2))/1.414
       er=(relf(ir2+1, ic2-1)-relf(ir2, ic2))/1.414
       ntpl=ntw(ir2-1, ic2+1)
       ntpr=ntw(ir2+1, ic2-1)
       lngth=lngth+1.414
       goto 107

107    kcell=kcell+1

       sl=sl+el
       sr=sr+er

       if(ntpl.ge.1) kntl=kntl+1
       if(ntpr.ge.1) kntr=kntr+1

       endif

       if(ntw(ir2, ic2).eq.1) then
       ntw(ir2,ic2)=9
       ir1=ir2
       ic1=ic2
       goto 12
       endif

C---- Ended do-loop for data colection and then calculate them ------

       ire=ir1
       ice=ic1

       kplnt=max(kntl, kntr)

       hdslp=atan(sh/csize)*57.3
       mxgd=atan(maxch/csize)*57.3

       if(mxgd.eq.0) then
        mxcr=ire
        mxcc=ice
        mxupa=nupa(ire, ice)
       endif

       if(mxgd.gt.0.and.mxgd.lt.hdslp) then
        mxcr=irh
        mxcc=ich
        mxupa=nupa(irh, ich)
       endif

       dfelv=relf(irh,ich)-relf(ire,ice)
       chgd=atan(dfelv/(lngth*csize))
       chlgd=chgd*57.3

       if(sl.lt.0) sl=0.000
       if(sr.lt.0) sr=0.000

       hl=sl/kcell
       hr=sr/kcell

       slpl=atan((hl/csize)+tan(chlgd)*tan(chlgd))*cos(chlgd)
       slpr=atan((hr/csize)+tan(chlgd)*tan(chlgd))*cos(chlgd)
       lslp=slpl*57.3
       rslp=slpr*57.3

       if(lslp.eq.0.and.rslp.eq.0) then
         asslp=0.000
         goto 33
       endif
```

```
      avgslp=(lslp+rslp)/2
      asslp=avgslp*(abs(lslp-rslp)/8)

      if(asslp.lt.0.001) asslp=0

33    if(asslp.gt.0) then
      dpl=sqrt(csize*csize+hl*hl)*sin(slpl)/cos(chlgd)
      dpr=sqrt(csize*csize+hr*hr)*sin(slpr)/cos(chlgd)
      avgdp=(dpl+dpr)/2
      depth=avgdp*(abs(dpl-dpr)/8)
      else
        depth=0.0
      endif

        mrk1=1
        mrk2=1
        mrk3=1
        mrk4=1

        rt=kcell
        ratio=kplnt/rt

        if(asslp.eq.0) mrk1=0
        if(chlgd.eq.0.and.kcell.eq.3) mrk2=0
        if(ratio.ge.0.7) mrk3=0
        if(kcell.eq.3.and.kplnt.eq.2) mrk4=0

        minmrk=min(mrk1, mrk2, mrk3, mrk4)

        if(minmrk.eq.0) then
          mark=0
          nonmal=nonmal+1
        else
          mark=1
          normal=normal+1
        endif

C---- Finished one channel parameter calculation and record them ----

      write(35,35)knmb,irh,ich,ire,ice,kcell,lngth,dfelv,hdslp,asslp,
     + lslp,rslp,depth,chlgd, mxgd,mxcr,mxcc, kplnt,mxupa, mark
35    format(1x, 5i4, i3, f8.3, i4, 7f7.3, 2i4, i3, i5, i4)

      if(kpage.eq.70) then
      write(36,15)'  No. irh ich ire ice ncl  lngth dfelv hdslp ',
     +'asslp  lsslp  rsslp  depth  chlgd mxgd mxcr mxcc npc  upa mrk '
      write(36,15)'===^===^===^===^===^===^=====^=====^=====^===',
     +'==^======^======^======^======^=====^=====^===^===^====^===^=='
      kpage=0
      endif

      ir3=irh-1
      ic3=ich-1
      ir4=ire-1
      ic4=ice-1
      ir5=mxcr-1
      ic5=mxcc-1

      write(36,35)knmb,ir3,ic3,ir4,ic4,kcell,lngth,dfelv,hdslp,asslp,
     + lslp,rslp, depth, chlgd, mxgd,ir5,ic5, kplnt,mxupa, mark
      kpage=kpage+1

      endif

20    continue
10    continue

      nor1=normal
      non1=nonmal
      nor=(nor1*100)/knmb
      non=(non1*100)/knmb

      write(6,*)' '
      write (6,*)'============================================',
     +          '================================='
      write (6, 420) normal,knmb,nor, nonmal,knmb,non
      write (6,*)'============================================',
     +          '================================='

      write(36,*)' '
```

```
      write (36,*)'===============================================',
     +          '================================='
      write (36, 420) normal,knmb,nor, nonmal,knmb,non
      write (36,*)'===============================================',
     +          '================================='

420   format (3x,'Normal Channel:',i4,'/',i4,' (',f6.2,'%)',2x,
     +        'Non-normal Channel:',i4,'/',i4,' (',f6.2,'%)')

      close(35)
      close(36)

C-------------------------------------------------------------------
      if(kfile.eq.1) then
       kwt=2
       call wrtdoc
      endif

      return
      end
C===================================================================
C
C===================================================================
C   The subroutine(3) is to calculate CSA threshold and statistics
C===================================================================
C
      subroutine fzvalu
C
C-------------------------------------------------------------------
      parameter (mxr=400, mxc=500)

      character fildat*10, filtab*10, filstc*10, tab(9), dat(9)

      real lc, mindp, maxdp, minslp, maxslp, mxgd

      integer a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      data         tab(1)/'1'/,tab(2)/'2'/,tab(3)/'3'/,tab(4)/'4'/,
     + tab(5)/'5'/,tab(6)/'6'/,tab(7)/'7'/,tab(8)/'8'/,tab(9)/'9'/

      data         dat(1)/'1'/,dat(2)/'2'/,dat(3)/'3'/,dat(4)/'4'/,
     + dat(5)/'5'/,dat(6)/'6'/,dat(7)/'7'/,dat(8)/'8'/,dat(9)/'9'/

      data i1,i2,i3,i4,i5,i6,i7,i8,i9,i10,i11,i12/12*0/
      data j1,j2,j3,j4,j5,j6,j7,j8,j9,j10,j11,j12/12*0/
      data k1,k2,k3,k4,k5,k6,k7,k8,k9,k10,k11,k12/12*0/
      data l1,l2,l3,l4,l5,l6,l7,l8,l9,l10,l11,l12/12*0/

      data p1,p2,p3,p4,p5,p6,p7,p8,p9,p10,p11,p12/12*0.0/
      data p1,q2,q3,q4,q5,q6,q7,q8,q9,q10,q11,q12/12*0.0/
      data r1,r2,r3,r4,r5,r6,r7,r8,r9,r10,r11,r12/12*0.0/
      data s1,s2,s3,s4,s5,s6,s7,s8,s9,s10,s11,s12/12*0.0/
      data a1,a2,a3,a4,a5,a6,a7,a8,a9,a10,a11,a12/12*0.0/

      data ug1,ug2,ug,pugtld/4*0.0/

      if(kfile.eq.1) then
       fildat='prmt'//dat(klop)//'.dat'
       filtab='prmt'//tab(klop)//'.tab'
       filstc='prmt'//tab(klop)//'.stc'
       goto 5
      endif

      if(kfile.eq.2.and.klop.eq.1) then
       fildat='prmt'//dat(klop)//'.dat'
       filtab='prmt'//tab(klop)//'.tab'
       filstc='prmt'//tab(klop)//'.stc'
       goto 5
      endif

      if(kfile.eq.2.or.kfile.eq.3) then
```

```
         fildat='prmt-.dat'
         filtab='prmt-.tab'
         filstc='prmt-.stc'
        endif

5       open (32, file=fildat, status='unknown')
        open (33, file=filtab, status='unknown')
        open (34, file=filstc, status='unknown')

C---------------------------------------------------------------------

        mrk=0
        km1=0
        km2=0
        pct=0

        knb=knmb

        do 28 n=1, knb

10      read(32,100) knmb, irh, ich, asslp, depth, chlgd, mxgd,
     +              mxcr, mxcc, mark
100     format(1x, 3i4, 30x, f7.3, 14x, 3f7.3, 2i4, 8x, i4)

        if(mark.eq.0) then
         ug1=0
         ug2=0
         ug=0
         ugtld=maxupa
         km1=km1+1
         mrk=0
         goto 68
        endif

C---------------------------------------------------------------------

        if(asslp.le.minslp.or.chlgd.ge.(hc*asslp)) then
         ug1=0
         goto 15
        endif

        if(asslp.ge.maxslp.or.chlgd.le.(lc*asslp)) then
         ug1=1
         goto 15
        endif

        if(chlgd.gt.(lc*asslp).and.chlgd.lt.(hc*asslp)) then
         ug1=hc/(hc-lc)-chlgd/((hc-lc)*asslp)
         goto 15
        endif

C---------------------------------------------------------------------

15      if(depth.le.mindp) then
         ug2=0
         goto 18
        endif

        if(depth.ge.maxdp) then
         ug2=1
         goto 18
        endif

        if(depth.gt.mindp.and.depth.lt.maxdp) then
         ug2=(depth-mindp)/(maxdp-mindp)
         goto 18
        endif

C---------------------------------------------------------------------

18      ug=slpwt*ug1+dpwt*ug2

        if(mxgd.ge.30.or.mxgd.ge.(2*asslp).and.mxgd.ge.20) then
         ugtld=nupa(mxcr, mxcc)
         mrk=2
         km2=km2+1
        else
         ugtld=maxupa-ug*(maxupa-minupa)
         mrk=1
         km1=km1+1
```

```
      endif

68    write(33,110)knmb,irh-1,ich-1, asslp,depth,chlgd,mxgd,
     +              ug1,ug2,ug,ugtld, mrk,km1,km2

110   format(1x, 3i4, 7f7.3, f9.3, i3, i5, i4)

C-----------------------------------------------------------------------

      if(ug1.eq.0.0) i1=i1+1
      if(ug1.gt.0.0.and.ug1.lt.0.1) i2=i2+1
      if(ug1.ge.0.1.and.ug1.lt.0.2) i3=i3+1
      if(ug1.ge.0.2.and.ug1.lt.0.3) i4=i4+1
      if(ug1.ge.0.3.and.ug1.lt.0.4) i5=i5+1
      if(ug1.ge.0.4.and.ug1.lt.0.5) i6=i6+1
      if(ug1.ge.0.5.and.ug1.lt.0.6) i7=i7+1
      if(ug1.ge.0.6.and.ug1.lt.0.7) i8=i8+1
      if(ug1.ge.0.7.and.ug1.lt.0.8) i9=i9+1
      if(ug1.ge.0.8.and.ug1.lt.0.9) i10=i10+1
      if(ug1.ge.0.9.and.ug1.lt.1.0) i11=i11+1
      if(ug1.eq.1.0) i12=i12+1
      if(ug2.eq.0.0) j1=j1+1

      if(ug2.gt.0.and.ug2.lt.0.1) j2=j2+1
      if(ug2.ge.0.1.and.ug2.lt.0.2) j3=j3+1
      if(ug2.ge.0.2.and.ug2.lt.0.3) j4=j4+1
      if(ug2.ge.0.3.and.ug2.lt.0.4) j5=j5+1
      if(ug2.ge.0.4.and.ug2.lt.0.5) j6=j6+1
      if(ug2.ge.0.5.and.ug2.lt.0.6) j7=j7+1
      if(ug2.ge.0.6.and.ug2.lt.0.7) j8=j8+1
      if(ug2.ge.0.7.and.ug2.lt.0.8) j9=j9+1
      if(ug2.ge.0.8.and.ug2.lt.0.9) j10=j10+1
      if(ug2.ge.0.9.and.ug2.lt.1.0) j11=j11+1
      if(ug2.eq.1.0) j12=j12+1

      if(ug.eq.0.0) k1=k1+1
      if(ug.gt.0.0.and.ug.lt.0.1) k2=k2+1
      if(ug.ge.0.1.and.ug.lt.0.2) k3=k3+1
      if(ug.ge.0.2.and.ug.lt.0.3) k4=k4+1
      if(ug.ge.0.3.and.ug.lt.0.4) k5=k5+1
      if(ug.ge.0.4.and.ug.lt.0.5) k6=k6+1
      if(ug.ge.0.5.and.ug.lt.0.6) k7=k7+1
      if(ug.ge.0.6.and.ug.lt.0.7) k8=k8+1
      if(ug.ge.0.7.and.ug.lt.0.8) k9=k9+1
      if(ug.ge.0.8.and.ug.lt.0.9) k10=k10+1
      if(ug.ge.0.9.and.ug.lt.1.0) k11=k11+1
      if(ug.eq.1.0) k12=k12+1

      pugtld=(ugtld-minupa)*100/(dfupa)

      if(pugtld.eq.0.0) l1=l1+1
      if(pugtld.gt.0.0.and.pugtld.lt.10.0)  l2=l2+1
      if(pugtld.gt.10.0.and.pugtld.lt.20.0) l3=l3+1
      if(pugtld.ge.20.0.and.pugtld.lt.30.0) l4=l4+1
      if(pugtld.ge.30.0.and.pugtld.lt.40.0) l5=l5+1
      if(pugtld.ge.40.0.and.pugtld.lt.50.0) l6=l6+1
      if(pugtld.ge.50.0.and.pugtld.lt.60.0) l7=l7+1
      if(pugtld.ge.60.0.and.pugtld.lt.70.0) l8=l8+1
      if(pugtld.ge.70.0.and.pugtld.lt.80.0) l9=l9+1
      if(pugtld.ge.80.0.and.pugtld.lt.90.0) l10=l10+1
      if(pugtld.ge.90.0.and.pugtld.lt.100.0) l11=l11+1
      if(pugtld.eq.100.0) l12=l12+1

      pct=pct+1

28    continue

      close(32)

C-----------------------------------------------------------------------

      p1=(i1*100)/pct
      p2=(i2*100)/pct
      p3=(i3*100)/pct
      p4=(i4*100)/pct
      p5=(i5*100)/pct
      p6=(i6*100)/pct
      p7=(i7*100)/pct
      p8=(i8*100)/pct
      p9=(i9*100)/pct
```

```
      p10=(i10*100)/pct
      p11=(i11*100)/pct
      p12=(i12*100)/pct

      q1=j1*100/pct
      q2=j2*100/pct
      q3=j3*100/pct
      q4=j4*100/pct
      q5=j5*100/pct
      q6=j6*100/pct
      q7=j7*100/pct
      q8=j8*100/pct
      q9=j9*100/pct
      q10=j10*100/pct
      q11=j11*100/pct
      q12=j12*100/pct

      r1=k1*100/pct
      r2=k2*100/pct
      r3=k3*100/pct
      r4=k4*100/pct
      r5=k5*100/pct
      r6=k6*100/pct
      r7=k7*100/pct
      r8=k8*100/pct
      r9=k9*100/pct
      r10=k10*100/pct
      r11=k11*100/pct
      r12=k12*100/pct

      s1=l1*100/pct
      s2=l2*100/pct
      s3=l3*100/pct
      s4=l4*100/pct
      s5=l5*100/pct
      s6=l6*100/pct
      s7=l7*100/pct
      s8=l8*100/pct
      s9=l9*100/pct
      s10=l10*100/pct
      s11=l11*100/pct
      s12=l12*100/pct

      uga=dfupa/10
      a1=minupa
      a2=minupa+1*uga
      a3=minupa+2*uga
      a4=minupa+3*uga
      a5=minupa+4*uga
      a6=minupa+5*uga
      a7=minupa+6*uga
      a8=minupa+7*uga
      a9=minupa+8*uga
      a10=minupa+9*uga
      a11=minupa+10*uga
      a12=maxupa
C--------------------------------------------------------------------

      write(33, *)' '
      write(33, 31)'===^===^===^=====^======^======^======^==',
     +'====^======^======^======^======^===^====^==='
      write(33, 31)'  No. row col  asslp  depth  chlgd  mxcgd',
     +'  ugslp  ugdep  ugtal  ugupa   mrk mk1  mk2 '
      write(33, 31)'=========================================',
     +'============================================='
31    format(a41, a45)
      close(33)


      write(34, *)'================================================',
     +            '==================='
      write(34,45)'  High coeffieint : ',hc,     '  Low coeffieint : ',
     +             lc
      write(34,45)'   Min side slope : ',minslp,'  Max side slope : ',
     +             maxslp
      write(34,45)'    Minimum depth : ',mindp, '   Maximum depth : ',
     +             maxdp
      write(34,45)'   Minimum uparea : ',minupa,'  Maximum uparea : ',
     +             maxupa
```

```
      write(34,45)'     Slope weight : ',slpwt, '    Depth weight : ',
     +            dpwt
      write(34,46)'Thrsld using mxgd : ',km2,   'Thresld using ug : ',
     +            km1
      write(34, *)'==================================================',
     +            '=================='
      write(34,25)'==========                    ', filstc,
     +            '                    =========='
45    format(5x, a20,f6.3, 4x, a19,f7.3)
46    format(5x, a20,i6, 4x, a19, i7)
25    format(a29,a9,a29)

      write(34, *)'==================================================',
     +            '=================='
      write (34,*)'        ======================================',
     +            '=========='
      write (34,*)'        ==============    STATISTICS    =======',
     +            '=========='
      write (34,*)'        ======================================',
     +            '=========='
      write (34,*)'        ============== Ug1 - asslp/chlgd ======',
     +            '=========='
      write (34,*)'        ======================================',
     +            '=========='

130   format(12x, a17, i5, a13, f7.2, a2)

      write (34,130)'   Ug1 = 0.0    :',i1,' ( = zero % :',p1,' )'
      write (34,130)'0.0 < Ug1 < 0.1 :',i2,' ( < 0 -9 % :',p2,' )'
      write (34,130)'0.1 < Ug1 < 0.2 :',i3,' ( 10--19 % :',p3,' )'
      write (34,130)'0.2 < Ug1 < 0.3 :',i4,' ( 20--29 % :',p4,' )'
      write (34,130)'0.3 < Ug1 < 0.4 :',i5,' ( 30--39 % :',p5,' )'
      write (34,130)'0.4 < Ug1 < 0.5 :',i6,' ( 40--49 % :',p6,' )'
      write (34,130)'0.5 < Ug1 < 0.6 :',i7,' ( 50--59 % :',p7,' )'
      write (34,130)'0.6 < Ug1 < 0.7 :',i8,' ( 60--69 % :',p8,' )'
      write (34,130)'0.7 < Ug1 < 0.8 :',i9,' ( 70--79 % :',p9,' )'
      write (34,130)'0.8 < Ug1 < 0.9 :',i10,' ( 80--89 % :',p10,' )'
      write (34,130)'0.9 < Ug1 < 1.0 :',i11,' ( 90--99 % :',p11,' )'
      write (34,130)'   Ug1 = 1.0    :',i12,' (  = 100 % :',p12,' )'

      write (34,*)'        ======================================',
     +            '=========='
      write (34,*)'        =============== Ug2 - depth =========',
     +            '=========='
      write (34,*)'        ======================================',
     +            '=========='

      write (34,130)'   Ug2 = 0.0    :',j1,' ( = zero % :',q1,' )'
      write (34,130)'0.0 < Ug2 < 0.1 :',j2,' ( < 0 -9 % :',q2,' )'
      write (34,130)'0.1 < Ug2 < 0.2 :',j3,' ( 10--19 % :',q3,' )'
      write (34,130)'0.2 < Ug2 < 0.3 :',j4,' ( 20--29 % :',q4,' )'
      write (34,130)'0.3 < Ug2 < 0.4 :',j5,' ( 30--39 % :',q5,' )'
      write (34,130)'0.4 < Ug2 < 0.5 :',j6,' ( 40--49 % :',q6,' )'
      write (34,130)'0.5 < Ug2 < 0.6 :',j7,' ( 50--59 % :',q7,' )'
      write (34,130)'0.6 < Ug2 < 0.7 :',j8,' ( 60--69 % :',q8,' )'
      write (34,130)'0.7 < Ug2 < 0.8 :',j9,' ( 70--79 % :',q9,' )'
      write (34,130)'0.8 < Ug2 < 0.9 :',j10,' ( 80--89 % :',q10,' )'
      write (34,130)'0.9 < Ug2 < 1.0 :',j11,' ( 90--99 % :',q11,' )'
      write (34,130)'   Ug2 = 1.0    :',j12,' (  = 100 % :',q12,' )'

      write (34,*)'        ======================================',
     +            '=========='
      write (34,*)'        ========== Ug3 = Ug1+ Ug2 in weights ==',
     +            '=========='
      write (34,*)'        ======================================',
     +            '=========='

      write (34,130)'   Ug3 = 0.0    :',k1,' ( = zero % :',r1,' )'
      write (34,130)'0.0 < Ug3 < 0.1 :',k2,' ( < 0 -9 % :',r2,' )'
      write (34,130)'0.1 < Ug3 < 0.2 :',k3,' ( 10--19 % :',r3,' )'
      write (34,130)'0.2 < Ug3 < 0.3 :',k4,' ( 20--29 % :',r4,' )'
      write (34,130)'0.3 < Ug3 < 0.4 :',k5,' ( 30--39 % :',r5,' )'
      write (34,130)'0.4 < Ug3 < 0.5 :',k6,' ( 40--49 % :',r6,' )'
      write (34,130)'0.5 < Ug3 < 0.6 :',k7,' ( 50--59 % :',r7,' )'
      write (34,130)'0.6 < Ug3 < 0.7 :',k8,' ( 60--69 % :',r8,' )'
      write (34,130)'0.7 < Ug3 < 0.8 :',k9,' ( 70--79 % :',r9,' )'
      write (34,130)'0.8 < Ug3 < 0.9 :',k10,' ( 80--89 % :',r10,' )'
      write (34,130)'0.9 < Ug3 < 1.0 :',k11,' ( 90--99 % :',r11,' )'
      write (34,130)'   Ug3 = 1.0    :',k12,' (  = 100 % :',r12,' )'
```

```
      write (34,*)'          =======================================',
     +           '=========='
      write (34,*)'          =============== Threshold in Uparea ===',
     +           '=========='
      write (34,*)'          =======================================',
     +           '=========='

      write(34,14)'ugtld=minupa(',a1,') : ',l1, '( = zero % :',s1,')'
      write(34,38) a1,' < ugtld < ',a2,' : ',l2,'( < 0 -9 % :',s2,')'
      write(34,38) a2,' < ugtld < ',a3,' : ',l3,'( 10--19 % :',s3,')'
      write(34,38) a3,' < ugtld < ',a4,' : ',l4,'( 20--29 % :',s4,')'
      write(34,38) a4,' < ugtld < ',a5,' : ',l5,'( 30--39 % :',s5,')'
      write(34,38) a5,' < ugtld < ',a6,' : ',l6,'( 40--49 % :',s6,')'
      write(34,38) a6,' < ugtld < ',a7,' : ',l7,'( 50--59 % :',s7,')'
      write(34,38) a7,' < ugtld < ',a8,' : ',l8,'( 60--69 % :',s8,')'
      write(34,38) a8,' < ugtld < ',a9,' : ',l9,'( 70--79 % :',s9,')'
      write(34,38) a9,' < ugtld < ',a10,' : ',l10,'( 80--89 % :',s10,
     +             ')'
      write(34,38) a10,' < ugtld < ',a11,' : ',l11,'( 90--99 % :',s11,
     +             ')'
      write(34,14)'uptld=maxupa(',a12,') : ',l12,'(  = 100 % :',s12,')'
      write (34,*)'          =======================================',
     +           '=========='
14    format(10x, a13, i3, a4, i4, 1x, a12, f7.2, 1x, a1)
38    format(10x, i3, a11, i3, a3, i4, 1x, a12, f7.2, 1x, a1)

      close(34)

      return
      end
C=====================================================================
C
C=====================================================================
C     This subroutine (4) is to elimite some source channels
C=====================================================================
C
      subroutine remvch
C
C---------------------------------------------------------------------

      parameter (mxr=400, mxc=500)

      character filtab*10, tab(9)

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      data         tab(1)/'1'/,tab(2)/'2'/,tab(3)/'3'/,tab(4)/'4'/,
     + tab(5)/'5'/,tab(6)/'6'/,tab(7)/'7'/,tab(8)/'8'/,tab(9)/'9'/

      if(kfile.eq.1) then
       filtab='prmt'//tab(klop)//'.tab'
       goto 5
      endif

      if(kfile.eq.2.and.klop.eq.1) then
       filtab='prmt'//tab(klop)//'.tab'
       goto 5
      endif

      if(kfile.eq.2.or.kfile.eq.3) then
       filtab='prmt-.tab'
      endif

 5    open (34, file=filtab, status='unknown')

      nmb=0
      killch=0

      do 10 ir=1, irow
      do 20 ic=1, icol

       if (ir.eq.1.or.ir.eq.irow) goto 20
       if (ic.eq.1.or.ic.eq.icol) goto 20
```

```
       if (ntw(ir, ic).eq.10) then

       nmb=nmb+1

       read (34, 105)  ugtld, mrk
105     format(62x, f9.3, i3)

C---------------------------------------------------------------------

       if(mrk.eq.0) then
       ntw(ir, ic)=14
       ir1=ir
       ic1=ic
11      kc=nfl(ir1, ic1)
       ir2=ir1+nfv(kc, 1)
       ic2=ic1+nfv(kc, 2)
       if(ntw(ir2, ic2).eq.9) then
        ntw(ir2, ic2)=14
           ir1=ir2
           ic1=ic2
           goto 11
        else
           killch=killch+1
           goto 20
        endif
        endif

C---------------------------------------------------------------------

       if(nupa(ir, ic).lt.ugtld) then

       ntw(ir, ic)=14

       ir1=ir
       ic1=ic

12      kc=nfl(ir1, ic1)
       ir2=ir1+nfv(kc, 1)
       ic2=ic1+nfv(kc, 2)

      if(ntw(ir2, ic2).eq.9) then
        ntw(ir2, ic2)=14

        if(nupa(ir2, ic2).lt.ugtld) then
           ir1=ir2
           ic1=ic2
           goto 12
        else
           killch=killch+1
           goto 20
        endif

      endif

      endif
      endif

20    continue
10    continue

      close(34)
      rt1=killch
      rt2=nmb
      rlop=rt1*100/rt2

C---------------------------------------------------------------------

      if(kfile.eq.1.or.kfile.eq.2) then
       kwt=3
       call wrtdoc
      endif

C---------------------------------------------------------------------

      do 30 i6=1, irow
      do 40 j6=1, icol

      if(ntw(i6,j6).eq.14) then
       ntw(i6,j6)=0
      endif
```

```
40    continue
30    continue

C-------------------------------------------------------------------

     if(kfile.eq.1.or.kfile.eq.2) then
       kwt=4
       call wrtdoc
      endif

      return
      end

C===================================================================
C
C===================================================================
C    The subroutine(5) is to refind heads and elimite some stubs
C===================================================================
C
      subroutine rwelm
C
C-------------------------------------------------------------------

      parameter (mxr=400, mxc=500)

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

C------- Writing all valley cells into one --------------------

      do 8 i8=1, irow
      do 8 j8=1, icol

       if (i8.eq.1.or.i8.eq.irow) goto 8
       if (j8.eq.1.or.j8.eq.icol) goto 8
       if (ntw(i8, j8).eq.0) goto 8

       ntw(i8, j8)=1

8     continue

C-------------------------------------------------------------------

      if(kfile.eq.1) then
       kwt=5
       call wrtdoc
      endif

C-------------------------------------------------------------------

      ksw=1
      call fhead
      ksw=0

C-------------------------------------------------------------------

      if(rlop.le.5) then
        minlg=mxflg
      else
        minlg=3
      endif

      khdtl=0
      kshort=0

      do 40 ir=1, irow
      do 40 ic=1, icol

      if (ir.eq.1.or.ir.eq.irow) goto 40
      if (ic.eq.1.or.ic.eq.icol) goto 40
      if (ntw(ir, ic).ne.10) goto 40

      khdtl=khdtl+1
```

```
      ntw(ir, ic)=1
      irhd=ir
      ichd=ic
      ir1=ir
      ic1=ic
      length=1

58    if(ntw(ir1, ic1).ge.1) then

      kc=nfl(ir1, ic1)
      ir2=ir1+nfv(kc, 1)
      ic2=ic1+nfv(kc, 2)

      if(ntw(ir2, ic2).ge.1) then

       kpp=9
       khead=0

       do 57 i7=-1,1
       do 57 j7=-1,1

         if(nfl(ir2+i7,ic2+j7).ne.kpp) goto 55

         if(ntw(ir2+i7,ic2+j7).ge.1) then
           khead=khead+1
         endif

55        kpp=kpp-1
57      continue

       if(khead.lt.2) then
         length=length+1
         ir1=ir2
         ic1=ic2
         goto 58
       else
         ntw(irhd, ichd)=10
         ired=ir2
         iced=ic2
         goto 90
       endif

      endif

C===================================================================

90    if(length.le.minlg) then
       kshort=kshort+1
95      if(ntw(irhd, ichd).ge.1) then
         ntw(irhd, ichd)=0
         kc=nfl(irhd, ichd)
         ir3=irhd+nfv(kc, 1)
         ic3=ichd+nfv(kc, 2)
         if(ir3.eq.ired.and.ic3.eq.iced) goto 40
         irhd=ir3
         ichd=ic3
         goto 95
       endif
      endif

      endif

40    continue

      write(*,*)
      write(*,45)'==== Shorter channels ( <=',minlg,
     +           ' cells ) eliminited :', kshort
45    format(1x, a26, i2, a21, i3)

C-------------------------------------------------------------------

      if(kfile.eq.1) then
       kwt=6
       call wrtdoc
      endif

      return
      end
```

```
C=================================================================
C
C=================================================================
C  The subroutine(6) is to re-order 1st & above 1st order channels
C=================================================================
C
      subroutine roder
C
C-----------------------------------------------------------------

      parameter (mxr=400, mxc=500)

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      khd=0
      korder=11

      do 10 ir=1, irow
      do 20 ic=1, icol

      if (ir.eq.1.or.ir.eq.irow) goto 20
      if (ic.eq.1.or.ic.eq.icol) goto 20
      if (ntw(ir, ic).ne.10) goto 20

      ir1=ir
      ic1=ic

18    kc=nfl(ir1, ic1)
      ir2=ir1+nfv(kc, 1)
      ic2=ic1+nfv(kc, 2)

      if(ntw(ir2, ic2).eq.1) then

        kp=9
        khead=0

        do 30 i=-1, 1
        do 40 j=-1, 1

          if(kp.ne.nfl(ir2+i,ic2+j)) goto 35
          if(ntw(ir2+i,ic2+j).eq.12) goto 20

            if(ntw(ir2+i,ic2+j).eq.1) then
              khead=khead+1
            endif

35         kp=kp-1

40       continue
30       continue

        if(khead.ge.1) then
          khd=khd+1
          ntw(ir2, ic2)=12
          goto 20
        else
          ntw(ir2, ic2)=korder
          ir1=ir2
          ic1=ic2
          if(ntw(ir1, ic1).eq.0) goto 20
          goto 18
        endif

      endif

20    continue
10    continue

C-----------------------------------------------------------------

        do 8 i8=1, irow
        do 8 j8=1, icol
```

```
          if(ntw(i8, j8).eq.12) then
          ntw(i8, j8)=ntw(i8, j8)-9
          goto 8
          endif

          if(ntw(i8, j8).eq.11) then
          ntw(i8, j8)=ntw(i8, j8)-10
          goto 8
          endif

          if(ntw(i8, j8).eq.1) then
          ntw(i8, j8)=ntw(i8, j8)+2
          goto 8
          endif

8       continue

C---------------------------------------------------------------------

      if(kfile.eq.1) then
       kwt=7
       call wrtdoc
      endif

      return
      end

C=====================================================================
C
C=====================================================================
C     The subroutine(7) is to re-order the final channel network
C=====================================================================
C
      subroutine fnlod
C
C---------------------------------------------------------------------
      parameter (mxr=400, mxc=500)

      integer cvl, hvl

      character fildat*9, filtab*9

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

C---------------------------------------------------------------------

      kk=0
      cvl=1
      hvl=10

      do 111 korder=11, 19

      kk=kk+1
      khd=0

        do 10 ir=1, irow
        do 20 ic=1, icol

        if (ir.eq.1.or.ir.eq.irow) goto 20
        if (ic.eq.1.or.ic.eq.icol) goto 20
        if (ntw(ir, ic).ne.hvl) goto 20

        khd=khd+1

        ntw(ir, ic)=korder
        ir1=ir
        ic1=ic

18       kc=nfl(ir1, ic1)
        ir2=ir1+nfv(kc, 1)
        ic2=ic1+nfv(kc, 2)

        if(ntw(ir2, ic2).eq.cvl) then
```

```
       kp=9
       khead=0

       do 30 i=-1, 1
       do 40 j=-1, 1

         if(kp.ne.nfl(ir2+i,ic2+j)) goto 35
         if(ntw(ir2+i,ic2+j).eq.(korder-1)) goto 35
         if(ntw(ir2+i,ic2+j).gt.(korder+1)) goto 20

           if(kk.eq.1) then
             if(ntw(ir2+i,ic2+j).ge.cvl) then
              khead=khead+1
              goto 35
             endif
           else
             if(ntw(ir2+i,ic2+j).eq.cvl) then
              khead=khead+1
             endif
           endif

35        kp=kp-1
40      continue
30      continue

       if(kk.eq.1) then
         if(khead.ge.2) then
            ntw(ir2, ic2)=hvl-1
            goto 20
         else
            ntw(ir2, ic2)=korder
            ir1=ir2
            ic1=ic2
            if(ntw(ir1, ic1).eq.0) goto 20
            goto 18
         endif
       else
         if(khead.ge.1) then
            ntw(ir2, ic2)=hvl-1
            goto 20
         else
            ntw(ir2, ic2)=korder
            ir1=ir2
            ic1=ic2
            if(ntw(ir1, ic1).eq.0) goto 20
            goto 18
         endif
       endif

      endif

20      continue
10      continue

c----------------------------------------------------------------------

       if(khd.eq.0) goto 222

       kkhd=0
       hvl=hvl-1

       do 50 irr=1, irow
       do 50 icc=1, icol

       if (irr.eq.1.or.irr.eq.irow) goto 50
       if (icc.eq.1.or.icc.eq.icol) goto 50
       if (ntw(irr, icc).ne.hvl) goto 50

       kkhd=kkhd+1

       kpp=9
       ked=0

       do 60 i9=-1, 1
       do 60 j9=-1, 1

         if(kpp.ne.nfl(irr+i9,icc+j9)) goto 65
            if(ntw(irr+i9,icc+j9).ge.korder) then
               ked=ked+1
```

```
            endif
            if(ntw(irr+i9,icc+j9).eq.cvl) then
              ntw(irr, icc)=cvl
              goto 50
            endif

65          kpp=kpp-1

60         continue

           if(ked.lt.2) ntw(irr, icc)=cvl

50         continue

           if(khd.lt.1) goto 222

111        continue

C------------------------------------------------------------------

222        do 15 i15=1, irow
           do 15 j15=1, icol
              if(ntw(i15, j15).lt.10) goto 15
              ntw(i15, j15)=ntw(i15, j15)-10
15         continue

C-----------------------------------------------------------------

         ksw=1
         call fhead
         ksw=0

C-----------------------------------------------------------------

           kwt=8
           call wrtdoc

           return
           end

C==================================================================
C
C==================================================================
C     The subroutine(8) is to write image file and document file
C==================================================================
C
      subroutine wrtdoc
C
C------------------------------------------------------------------

      parameter (mxr=400, mxc=500, degree=57.296)

      character filimg*9, fildoc*9, img(9), doc(9), tl(8)*39,
     +          title*48

      common /array/ ntw(mxr, mxc), nfl(mxr, mxc),
     +       relf(mxr, mxc), nupa(mxr, mxc), nfv(9,2)

      common /varib/ irow, icol, kwt, klop, knmb, kfile, killch, dfc,
     +       csize, dfdp, dfupa, minslp, maxslp, minlg, mxflg, hc,
     +       lc, mindp, maxdp, minupa, maxupa, slpwt, dpwt, rlop, ksw

      common /charc/ fildat, filtab

      data        img(1)/'1'/,img(2)/'2'/,img(3)/'3'/,img(4)/'4'/,
     + img(5)/'5'/,img(6)/'6'/,img(7)/'7'/,img(8)/'8'/,img(9)/'9'/

      data        doc(1)/'1'/,doc(2)/'2'/,doc(3)/'3'/,doc(4)/'4'/,
     + doc(5)/'5'/,doc(6)/'6'/,doc(7)/'7'/,doc(8)/'8'/,doc(9)/'9'/

      data tl(1)/' --- find all heads of source channels'/,
     +     tl(2)/' --- collect parameters around channels'/,
     +     tl(3)/' --- mark source channels for remove'/
      data tl(4)/' --- after remove some with lower Ug'/,
     +     tl(5)/' --- re-write new value for the network'/,
     +     tl(6)/' --- remove shorters and mark each head'/
      data tl(7)/' --- re-write network ordering system'/
     +     tl(8)/' --- final network treated by Ug thrsld'/

      if(kwt.eq.8) then
```

```
        filimg='fzntw.img'
        fildoc='fzntw.doc'
        goto 10
      endif

      filimg='out'//img(klop)//img(kwt)//'.img'
      fildoc='out'//doc(klop)//doc(kwt)//'.doc'
      title=fildoc//tl(kwt)

10    open (91, file=filimg, status='unknown')
      open (92, file=fildoc, status='unknown')

      write (6, *) ' '
      write (6, *) '==== Writing output file : ',filimg

      do 50 ii=1, irow
      do 50 jj=1, icol

50       write (91, 100) ntw(ii, jj)

100   format (i2)

      if(kwt.eq.8) then
      write(92,70)'file title  : Final Result ==> Minupa :',minupa,
     +            ' - Maxupa :',maxupa,' Used'
      goto 60
70    format(a39, i3, a11, i4, a5)
      endif

      write(92, *)'file title  : ',title
60    write(92, *)'data type   : integer'
      write(92, *)'file type   : ascii'
      write(92, 9)'columns     : ', icol
      write(92, 9)'rows        : ', irow
      write(92, *)'ref. system : plane'
      write(92, *)'ref. units  : m'
      write(92, *)'unit dist.  : 1.0000000'
      write(92, *)'min. X      : 0.0000000'
      write(92, 9)'max. X      : ', icol
      write(92, *)'min. Y      : 0.0000000'
      write(92, 9)'max. Y      : ', irow
      write(92, *)'pos"n error : unknown'
      write(92, 9)'resolution  : ', csize
      write(92, *)'min. value  : 0'
      write(92, *)'max. value  : 15'
      write(92, *)'value units : unspecified'
      write(92, *)'value error : unknown'
      write(92, *)'flag value  : none'
      write(92, *)'flag def"n  : none'
      write(92, *)'legend cats : 0'
9     format(a14, i3)

      close(91)
      close(92)

      return
      end
C
C======================================================================
C====================    END OF PROGRAM FICNM    ======================
C======================================================================
```