Spatial and Temporal Changes in Stream Network Topology: Post-eruption Drainage, Mount St. Helens

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CHAPTER 1

Introduction

> It is stimulating to consider the grand changes of a landscape during the millions of years of its erosional evolution. Unfortunately, this overview provides little assistance to those concerned with the short term behavior of landforms.
>
> S.A. Schumm (1975)

1.1 Geomorphology and Geography

The study of landforms, the processes that enact upon them, which both create and destroy these forms, comprises the field of geomorphology. A geomorphologist is concerned with both space, as reflected in the pattern and distribution of forms that constitute a landscape, and time, through the desire to understand how these forms have evolved and their possible future status. When a geomorphologist studies form, the main theoretical problem is the interpretation of spatial relationships in terms of a developmental sequence. Early geomorphic theory, and especially the work of W.M. Davis, employed this approach. Landscape evolution theory was deduced using the *a priori* model developed from the spatial distribution of forms. Uniformitarianism was the axiom from which the model was inferred.

That Davis' model was found to be an insufficient descriptor resulted from an incomplete appraisal of space-for-time substitution. In general, landforms evolve over timescales on the order of millions of years, and the assumption that external influences have remained constant over time was over-ambitious. Form changes as a result of the complex interplay between the initial form, external influences of geology and climate, denudational processes, and time.

Geography is concerned with distributions of phenomena in space, and the manner in which natural and human distributions interact to produce a landscape of activity. For many human activities, placement in space is partially constrained by the landform, and landforms are modified by the occurrence of various human activities. In order to study evolution of landform the geomorphologist must consider both human and natural agents of change. Climatic and geologic agents of change have been forefront in the geomorphologist's mind since the first emergence of the study. Biotic agents, consisting of human, animal and vegetative aspects, are factors of much more recent research concern.

Tobler's (1970) first law of geography states that everything in space is related to everything else, but near things are more strongly related than distant things. Hutton (Playfair 1806) and Gilbert (1889) both recognized this law in the behavior and configuration of landforms.

By studying the spatial distribution of landforms we can gain knowledge of the result of landscape processes. Such knowledge may be used in the formulation of generalized theories of geomorphic evolution.

Similarly, such knowledge may be used to aid in the planning of human activity on that landscape. In the case of stream channel networks, Abrahams (1972) has shown that certain difficulties arise in the substitution of space for time; the best method of eliminating such problems is to perform analyses on networks of the same order the complex interplay between the initial form, external influences of geology and climate, denudational processes, and time.

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Geographic research may encompass such theoretical geomorphic studies because the product of these studies can be utilized by other geographic specialities. To this end the study of drainage network development is both geomorphic and geographic in context.

1.2 Mount St. Helens Devastated Zone

Description of the May 18, 1980 volcanic eruption of Mount St. Helens may be found elsewhere (Lipman and Mullineaux 1982). Of interest here are the landscape changes brought about by those events. These are both geomorphic and geographic in nature. Man's environment was severely disrupted, and the threat of further disruption continues.

Landforms were extensively modified, particularly in the North Fork Toutle River basin, where the debris avalanche, mud flows, and pyroclastic flows rapidly formed a new set of surfaces on which geomorphic process could take place. In geomorphic theory, such rapid creation of new topography corresponds with the Davisian concept of initial rapid uplift as the precursor to geomorphic evolution (Davis 1899). Simplification of the initial conditions was both a strength and weakness of Davis' idea. Even when much of Davis' approach has been shown to be inappropriate, the virgin landscape formed by rapid diastrophism allows well defined reference points for research in landscape evolution.

The debris avalanche dam of Spirit Lake (hereafter called the "Debris Dam") provides such initial conditions. On its surface evolve "new" features. Destruction of living matter in the Debris Dam area has limited vegetative influence in early landform evolution. The total number of variables involved in any geomorphic study is thus reduced by two. That the Debris Dam also presents a relatively simplified geology contributes a third variable subtraction. With three less variables involved, geomorphic evolution may be more efficiently studied. Finally, the Debris Dam provides excellent opportunity to study rapidly evolving landforms, because lack of vegetation decreases resistance to erosion, and enhances rates of denudational processes. We make the assumption that the equilibrium form of a rapidly evolving landform will have similitude to slowly evolving landforms.

1.3 Channel Networks

The channel network is a two-dimensional representation of a three-dimensional form, the drainage basin channel system. Channel networks are dynamic forms, evolving in response to changes in the energy flux through the system, a manifestation of the hydrologic character of the area. Under most circumstances these changes are very slow, which creates observational difficulties.

Semi-arid environments (or where vegetation is sparse) provide the opportunity to study network evolution. Schumm (1956) studied landform evolution on industrial badlands in New Jersey but worked with prior developed networks so that he substituted space for time on the basis of evolutionary stage. Several authors have studied geomorphic changes in gully systems (e.g. Schumm and Hadley 1957, Blong 1970, Heede 1974). Yet in all these reports, the network characteristics have been of secondary import. Faulkner's (1974) study also used gully systems and Hortonian analysis to study network growth, but not topological properties.

Network analysis, starting with Horton (1945), continuing with Strahler and his students (Strahler 1952), and later with Shreve (1966) and Smart (1978), has been of static single-time-period systems. Evolving networks were not considered, except in experimental scale models and computer models. Only under conditions typified by the Mount St. Helens deposits does network development occur rapidly. A well documented record of these developments is available because of the profound influence of the eruption on human activity.

Stream networks have been studied using topographic maps as the data base (e.g. Morisawa 1957, Krumbein and Shreve 1970, and Werner and Smart 1976), and the map-derived networks have been compared with field surveyed networks (e.g. Mark 1983). Remote sensing techniques have been used in areas of sparse vegetation cover for studies of gully systems (Heede 1974, Faulkner 1974). None of the above methods have been applied to network change.

Channel permanence has been examined by Ovenden and Gregory (1980), but without reference to network topology or to growth models.

Theoretical network growth models were discussed by Dacey and Krumbein (1976) but were not tested on an evolving natural network. Parker (1977) used a dynamic scale model to simulate network growth, but did not discuss topologic properties, nor naturally occurring systems. Parker noted two modes of network growth which were dependent on the system slope.

Field observation of network growth by Abrahams (1975) was primarily concerned with headward growth and limited to a single time period. His results suggested the need for further analysis of the nature of network growth with respect to topologic randomness. Abrahams is also a leading proponent of further research into the effect of morphometric variables such as divide angles on the nature of the channel network (Abrahams 1984a) but most research is focused on understanding the distribution of channel lengths (Abrahams 1984b).

Further research into the nature of the channel network is needed, specifically with regard to field observation of network growth, and the correspondence between growth and topologic properties. Partial fulfillment of this need is presented in this dissertation. Opportunity to study evolving channel networks on newly created landforms has resulted from the Mount St. Helens eruptions.

1.4 Research Objectives

The overall objective of this study is the geomorphic analysis of channel networks in the Spirit Lake Debris Avalanche Dam area, Mount St. Helens, Washington, using data gathered by field and remote sensing techniques.

Specific objectives are:

a) To describe the topologic nature of the networks.

b) To evaluate the mode of network growth over time.

c) To discuss the relationship between topology and network growth.

Several working hypotheses are formulated as questions to which enquiry is directed.

a) Are the channel networks studied consistent with the random network model of Shreve (1966)?

b) Is network growth random or structured in space?

c) Does the mode of network growth remain constant over time?

If the answer to a, b or c above is negative, what mechanisms contribute to the rejection of the hypotheses?

1.5 Dissertation Organization

Each chapter of this dissertation contributes toward the achievement of the stated objectives. Chapter 1 introduces the research topic, its context and scope, its contribution to geomorphic knowledge in the light of previous research, and its place in geographic studies. Pertinent research which led to the development of present concepts and techniques is reviewed in Chapter 2, where also, definitions of terminology are presented. In Chapter 3 the field study site is placed in its geographic and geologic setting.

Methods for collection and analysis of field and laboratory data constitute Chapter 4. Channel networks, interpreted from aerial photography are compared with field observation. Probability statistics are used to evaluate the topologic properties and network growth.

The results of analysis, and a discussion thereof, are the concern of Chapters 5-7. Network growth is evaluated in space and time, and tested against the working hypotheses using statistical methods. In Chapter 5 a geomorphic overview of the study area channels and basins is presented, while Chapter 6 assesses the topologic properties in space and time. Network growth is discussed in Chapter 7 within the context of previous research and geomorphic theory.

Conclusions, recommendations, and the applicability of this research constitute Chapter 8.

CHAPTER 2

Channel Networks: A Review of Knowledge

> Every river appears to consist of a main trunk,
> fed from a variety of branches...communicating
> with one another...having a nice adjustment...
> John Playfair, "Illustrations of the Huttonian
> Theory of the Earth § 99. 1806

This chapter introduces many terms, denoted by an underline, and defined in Table 2.1.

2.1 Traditional Network Analysis

As with much scientific enquiry, a single research paper provided the locus from which current analytical methodology emerged. The work of R.E. Horton, culminating in his 1945 paper is acknowledged for pioneering quantitative analysis of channel networks. Previous work had qualitatively assessed drainage pattern. Glock (1931) and Zernitz (1932) were noted for this approach. During the qualitative era, channel networks had been likened to trees; the terms arborescent and dendritic were frequently employed, and many of the classic descriptive geomorphic terms were coined, such as, trellised, parallel, and rectangular.

Horton (1945) introduced the notion of "order" to the channel network system as a quantitative hydrophysical expression of drainage basin organization. Previous attempts at classification of streams (e.g. Gravelius 1914) had enumerated streams with the fingertip streams attaining the highest value (or "order"). Woldenberg (1983) has argued that this approach is derived from medical terminology of the 18th century. These classifications contributed little to an understanding of geomorphic processes. In the Hortonian approach, fingertip tributaries were assigned the lowest values (order = 1) except in the case of the "main stream" of the network. (Main stream was defined in a complex manner, which included the use of the greatest stream length as well as order.) The main stream was given the same order in all reaches from outlet to source.

Horton used his stream ordering scheme to explain changes in stream segment length with changes in stream order; this was called the stream length ratio. This relationship was believed to be log-normal. The bifurcation ratio related the number of stream segments of a given order to the number of stream segments of each order.

Channel network analysis was considered by Horton to be of hydrologic significance, but, apart from his analysis of the length of overland flow, he did not pursue this aspect in any detail. It is this aspect of Horton's work that has led geomorphologists to enquire more deeply into the nature of channel network organization.

2.2 Evolution of Horton's Laws of Network Composition

In his pioneering work, Horton examined two aspects of drainage basins that have distinct mathematical bases. First, he considered lengths of channels and slopes. This is a geometric approach (Jarvis 1975). Second he related these lengths to a classification scheme, called stream order, which is a study of continuity. This is the topologic approach (Shreve 1966, 1967, Scheidegger 1967).

Much of the regularity noted in the behavior of the Horton parameters is a consequence of the rules of ordering (Bowden and Wallis 1964, Scheidegger 1965, 1968, Ranalli and Scheidegger 1968a, Smart 1968, 1969b, Ghosh and Scheidegger 1970). Stream numbers per order and the distribution of network order were shown by Shreve (1966) to lie in a restricted region of the probability distribution plane, a result of mathematical derivation of Horton's laws and not any physical law.

Any search of the literature reveals two factors about the Hortonian method: 1) It quantified channel networks at a time when quantification was in its infancy and thus was widely accepted as a first approximation of reality; and, 2) it is certainly not clear that order has any geomorphic superiority to other morphologic parameters in the description of drainage basins, and order lacks sound theoretical basis other than Shreve's (1966) observation that the range of magnitudes for each order is just that in which the Strahler stream order is the most probable one. Hence the development of the random model.

2.2.1 Topological Analysis of Channel Networks

Most morphological analysis examines geometric properties of landforms. Geometric properties are those which remain invariant under the considerably restrictive constraints of rigid transformation through the actions of translation, rotation, and reflection. Projection is a non-rigid transformation that is still partly geometric in nature.

Topology arose from Euclidean geometry in the late 19th century. When a geometric figure is subjected to continuous non-rigid transformation without the fusion of points, those properties which remain invariant are topologic properties. Thus topology is well suited to the study of three-dimensional landforms using two-dimensional form analysis (Jarvis 1977).

Table 2.1 Glossary of terminology used in channel network analysis, indicated in text by an underline

Feature	Symbol	Source	Definition	Remark
outlet	--	Shreve 1966	Arbitrarily chosen end point of a network	Outlet link has path length = 1, system magnitude only one per network
sources	n	"	The furthest points upstream of a network	Source links always have magnitude = 1, also called exterior links
fork (junction)	f	"	Point of conduence of two channels	Forks with >2 incoming channels must be resolved to 2 channels per fork
link	l	"	Section of channel reach without intervening forks, outlets or sources	Fundamental unit of topological approach to network analysis
channel network		"	Collection of connected links coalescing from sources to the outlet	Also called drainage network, stream network or river network
topology	--	Guler 1741	Study of the properties of a form that remain invariant after continuous spatial distortion and non-fusion of points	Extension of geometry to a dimensionless medium
topologically distinct channel network	TDCN or N	Shreve 1966	Those networks whose schematic map projections cannot be continuously deformed and rotated in the plane of projection so as to become congruent	A major assumption is that all TDCN of the same magnitude occur with equal probability
topologically random channel network		"	Populations of channel networks within which all TDCN with a given number of links are equally likely	
exterior link	e	Shreve 1967	Reaches of the channel from the sources to the highest fork	Magnitude = 1
interior link	i	"	Reaches between forks	Magnitude >1
network magnitude	n	"	Sum of all sources of a network	Equivalent to magnitude of outlet link
link magnitude		"	Sum of all sources upstream from that link	Commutative property

Table 2.1 Glossary of terminology used in channel network analysis, indicated in text by an underline, cont'd.

topologic vector	--	Shreve 1967 Scheidegger 1967 Smart 1969	A binary string recording the status (interior or exterior) of each link of a network in a set order; each fork being traversed to the left until a source is reached, returning to last fork after each source and going right	Contains all the topologic information needed for network analysis and is highly suited for computer processing
ambilateral class	Λ	Smart 1969	The group of TDCN that have the same set of link magnitudes	When written, $\mu = 1$ links 1 of $\mu = 2$ and $\mu = n$ links are not included. Thus 11111122346 is written 234
path number	fj	Werner and Smart 1973	Set of paths of all links for a TDCN of a given n, written as number of links of given path, in ascending order	A path is defined as the number of connected links from outlet to the link in question. Path is a measure of topologic distance. Minimum path = 1, maximum path = n, but not all TDCN of magnitude n will have the maximum path. All fj are even for $n > 1$.
diameter	d	Jarvis 1972	The greatest path in a particular TDCN	$1 \leqslant d \leqslant n$. A network may contain more than 1 path which is also the diameter
path length	L	"	The number of links in a direct line between source and outlet	See path number
total path length	P	Werner and Smart 1973	Sum of all paths in a network	Same value for all TDCN within an ambilateral class or a path number class
exterior path length	Pe	" "	Sum of all paths to exterior links in a network	Same value for all TDCN within an ambilateral class or a path number class
interior path length	Pi	" "	Sum of all paths to interior links in a network	Same value for all TDCN within an ambilateral class or a path number class
mean exterior path lengths	Pe/n	" "	The exterior path length divided by the magnitude	Same value for all TDCN within a measure of the elongation distribution of a network
chain	--	James and Krumbein 1969	A continuous sequence of links which is not a complete subnetwork	Generally refers to the main stem of a network or subnetwork where main steam has the greater magnitude in a bifurcation

Table 2.1 Glossary of terminology used in channel network analysis, indicated in text by an underline, cont'd.

Cis chain	—	James and Krumbein 1969	A chain bounded of its upper and lower forks by tributaries entering from the same side	Theoretical maximum length is diameter
trans chain	—	" "	A chain bounded at its upper and lower forks by tributaries entering from opposite sides	Theoretical maximum length is the diameter
CH chain	—	Abrahams, 1980c	A cis or trans chain which includes equal magnitude bifurcation by including the upfork which is closest in angle to the down fork in the chain	No longer a purely topologic measure, again maximum size is the diameter
LCHO chain	—	" "	A chain of a single external link, bounded at its downstream end by a main stream	
LCHA chain	—	Abrahams, 1980b	An interior chain, bounded upstream by LCHO, downstream by CH chain	
CT link	—	Mock 1971	Upstream unequal magnitude links, downstream joined link less than classified link	Interior link, used for length distribution studies
B link	—	"	Upstream equal magnitude link downstream as CT	Must have 2 S links upstream
T link	—	"	Upstream unequal, downstream equal or greater joining link	T and TB links tend to be longer than CT and B links
TB link	—	"	Upstream equal, downstream equal or greater	
S link	—	"	Exterior link, downstream joins another exterior	
TS link	—	"	Exterior link, downstream joins interior link	S, TS tend to have same length in headwaters, TS increase downstream
semi-divide angles	SDA	Abrahams 1980a,c	Angles between divide and network link around a junction	Must be six SDA's at each junction formulated to explain differences in T, TB and CT, B links

Channel networks, when viewed as topological entities, are among the most elementary topological configurations because:

a) they are simply connected

b) only one or three channels can meet at a junction

c) information flows converge on the outlet

Horton's (1945) stream orders were not truly topologic, a result of the geometric subjectivity involved in classifying the main channel. In 1952 Strahler designated all fingertip tributaries of order 1, and did not single out a main stream from the remainder of the network. This was a truly topologic approach (Melton 1959).

Unfortunately, Strahler retained the Hortonian idea of non-combinatorial order for the meeting of two streams of different order. Only streams of equal order at a junction could increase the order value by 1. Thus, a considerable proportion of a network was not included in the final basin order designation, and severe information loss was a possibility (Jarvis and Werrity 1976).

2.2.2 Topologically Random Channel Networks

Shreve (1966) proposed a new model of channel network organization based on the probability of occurrence of individual stream segments. In order to do this, a new classification scheme was devised based on the ideas of Melton (1959). The terms link, fork, source, topologically identical, topologically distinct, and topologically random (Table 2.1) were introduced by Shreve (1966) in a discussion of Horton's Law of Stream Numbers. Shreve showed that stream numbers are essentially topologically random, and that

> ...in the overall infinite network, which will be termed an infinite topologically random channel network [ITRCN sic] all topologically distinct subnetworks with the

> same number of sources occur with equal frequency (Shreve 1967, p. 178).

An alternative statistical distribution of stream numbers was proposed by Liao and Scheidegger (1968), in which a Monte Carlo method was used to estimate bifurcation ratios. As Smart (1968) commented, the reason for this approach is unclear, because it uses a more complex statistical technique than Shreve's (1966) probability approach, and does not improve the results. That mean bifurcation ratios are about 3.5 in Liao and Scheidegger's study is not evidence of topologic randomness, but an artifact of the deviations of Horton's law discussed by Smart (1967) regarding increasing consistency with increasing sample order--another indication of the statistical properties of the system.

Order as a stream link classification was replaced by Shreve (1967) with magnitude, a property which is commutative at all forks (i.e. links of equal and unequal magnitude are added together to confer magnitude to the next link downstream). This is a much clearer designation than an alternative scheme proposed by Scheidegger (1965) in which fingertip tributaries are given a value of 2, and arbitrary non-real zero order streams are conceived. This scheme is related to the magnitude approach. Ranalli and Scheidegger (1968) also proposed a complicated coding system which is not in use at this time.

Each link has a magnitude (in the Shreve (1967) system), while the system (network) magnitude n, is obtained from the number of exterior links (Tables 2.1, 2.2).

Both Shreve (1967) and Scheidegger (1967) examined the topologic channel network in terms of graph theory and random walks. They found that the probability of a link drawn at random from an ITRCN will have magnitude μ, defining a subnetwork with $2\mu-1$ links, is exactly the

Table 2.2 Mathematical relationships of topologic properties

1/ Number of links in a network of magnitude n

$$\ell = 2n-1$$ Shreve 1966

2/ Number of forks in a network of magnitude n

$$f = n-1$$ Shreve 1966

3/ Number of TDCN having n sources

$$N(n) = \frac{1}{\ell}\binom{\ell}{n}$$ Cayley 1859

4/ Number of ambilateral classes for all TDCN having n sources

$$N'(1) = N'(2) = N'(3) = 1$$

$$N'(2m+1) = \sum_{i=1}^{m} N'(2m+1-i)N'(i)$$

$$N'(2m) = 1/2\ N'(m)\ [N'(m)+1] + \sum_{i=1}^{m-1} N'(2m-i)N'(i)$$

where m is an integer >1

Werner and Smart 1973

5/ Path length properties

Smart and Werner (1973) note there is no simple mathematical expression to calculate path length properties. They suggest the use of a computer program to process the topologic vector to determine the path numbers, from which all other path properties may be determined.

6/ Path number relationships

a. $$\sum_{j=1}^{n} fj = 2n-1$$

the total number of TDCN of magnitude n having the same path numbers is

b. $$v(f1,f2,\ldots.fd;n) = \prod_{j=1}^{d-1}\binom{fj}{1/2\ fj+1}$$

c. total path length

$$p = \sum_{j=1}^{n} jfj$$

Table 2.2 Mathematical relationships of topologic properties (cont'd.)

then it follows that

$$p = pe+pi$$

d. The number of different path length classes for a given magnitude Np(n) is given by

$$Np(n) = 1/2(n^2+3n) - n(w+1) + 2^{w-1}$$

where w = minimum possible diameter

e. The number of network diameter classes Nd(n) is

$$Nd(n) = n-w+1$$

f. Number of TDCN of diameter d and magnitude n, v(d,n) is

$$v'(k,n) = \sum_{j=1}^{n-1} v'(k-1,j)v'(k-1,n-j)$$

where

k is a maximum source height $\geqslant$ d

$$v'(o,j) = 0 \qquad j > o$$

$$v'(1,j) = 1 \qquad j = 1$$

$$v'(1,j) = 0 \qquad j > 1$$

$$v'(k,j) = N(j) \qquad k \geqslant j$$

and $v\ (d,n) = v'(d,n) - v'(d-1,n)$

(all "6" from Werner and Smart 1973)

same as the probability that in a symmetric random walk the first passage of the origin will occur at step 2 μ-1.

In using a binary probability approach, Shreve (1967) and Scheidegger (1967) assumed that all natural stream channel forks were a binary split. This tenet has yet to be challenged. However, in a recent publication, Mark and Goodchild (1982) have explored a non-binary coding for systems which include lakes fed by multiple inlets.

A symbolic representation of any channel network for use with binary probabilities was proposed by Shreve (1967), in which a binary string was produced by starting at the outlet and assigning each link the value I or E, depending on whether it is an <u>Interior</u> or <u>Exterior</u> link. Ranalli and Scheidegger (1968b) followed this idea, using the Lukasiewicz graph, in which the values 0 = interior, 1 = exterior were used. This method is convenient for computers. Unlike Shreve who used a left-hand rule at forks, Ranalli and Scheidegger used a right-hand rule. The "handedness" of the topologic vector results from the decision made at each node to consistently follow left upstream branch until a source is encountered, at which a return is made to the last bifurcation, and the right fork is taken, left, as before. When the node has been explored in both hands, then a return is continued until a free right hand is available. Smart (1970) adopted Ranalli and Scheidegger's numerical code and Shreve's left-hand rule, and termed the binary string a <u>topologic vector</u>. The advantage of using the topologic vector is the completeness of retained information (Jarvis and Werrity 1975). Smart (1969a) points out that the topologic vector has two major disadvantages. First, its size increases rapidly with increasing n, and second, the number of topologically distinct channel networks (TDCN) increases very rapidly with increasing n, making processing tedious (Smart 1970).

2.2.3 Grouped Topologic Information - Magnitude

A number of methods have been proposed by which to group topologic information obtained at the TDCN level. The ambilateral classification of Smart (1969a) groups networks by magnitude similarities of the link set. The link set is the set of link properties, which may include magnitude, path or any other topologic property, that defines a given subnetwork. Thus for two TDCN of magnitude n to be of the same ambilateral class, they must have identical numbers of links of equivalent magnitude (Figure 2.1). As Werner and Smart (1973) point out, the number of ambilateral classes (N') for given n is calculated by complex recursion, but the number of ambilateral classes increases at a slower rate than does that of TDCN for an increasing value of n. In terms of information content, Jarvis and Werrity (1975) consider the ambilateral class the next best description to the topologic vector, with a minimum information loss of 44% when n = 1 or 2, converging on 50% when n approaches infinity.

Analysis of natural networks by Werrity (1973) and Smart (1978) has shown that Smart's (1969) basic assumption that the ambilateral classes of a given n would occur with equal probability is not upheld by observation, a result which remains unexplained. However, this does not detriment the use of the ambilateral classification as method for grouping topologic data.

2.2.4 Grouped Topologic Information - Topologic Distance

Other topologic classifications are based on topologic distance rather than magnitude. Jarvis (1972) suggested the use of path length properties, particularly the diameter (defined by Jarvis in 1972 as the maximum source height, and later termed the diameter by Werner and Smart 1973) and the mean exterior path length. Smart (1978) considers the diameter to be the next most important property to magnitude because it measures the longitudinal extent of a network (Jarvis 1972) and provides a topologic measure for its geometric analog, the mainstream length.

The value of the mean exterior path length is that it relates path and magnitude and hence provides a measure of source distribution (Smart 1973). Werner and Smart (1973) discussed the theoretical basis for diameter and mean exterior path length, both of which may be calculated from the topologic vector. Greater information loss is incurred with these two properties than with the ambilateral classification, converging on 80% for the diameter, and 70% for the mean exterior path length (Jarvis and Werrity 1975).

Pathnumber (Figure 2.1), a classification of link path lengths proposed by Werner and Smart (1973), has received little attention in subsequent analyses (Smart and Werner 1976), but shows promise as a parameter for use in hydrograph analysis (Kirkby 1976, Smart 1978, Gupta and Waymire 1981). In terms of information content, path number is less valuable than ambilateral class, but more valuable than diameter and mean exterior path lengths (Jarvis and Werrity 1976).

Comprehensive mathematical treatments of the topologic properties of stream networks are provided by Werner and Smart (1973), and Dacey (1976). Summaries of the mathematical nature of specific topologic

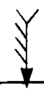
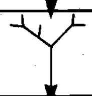
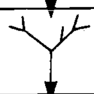
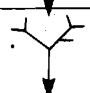
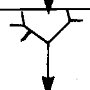
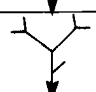
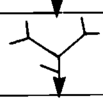
TDCN	Topologic Vector	Ambilateral Class	Path Number Class	Diameter
	010101011			
	001010111			
	000101111			
	010010111	(2)34(5)	12222	5
	001001111			
	010100111			
	010001111			
	000011111			
	000111011			
	001101011	(2)23(5)	1242	4
	001100111			
	001011011			
	000110111	(2)24(5)	1224	4
	010011011			

Figure 2.1 Relationship between TDCN, topologic vector, ambilateral class, pathnumber class and diameter for networks of magnitude 5

properties are found in Jarvis and Werrity (1975) and Smart (1978). Table 2.2 provides a summary of these relationships.

2.2.5 Tributary Organization Along Main Streams

A network may be examined using the main stream as a corridor into which flows assemblages of subnetworks, each of which possess such a corridor.

A chain is a sequence of links that comprise a part of a network or subnetwork (Table 2.1). In this respect chains differ from the topologic properties previously described because they isolate portions within the network. The term chain was first used by James and Krumbein (1969) in a study on geometric link lengths. James and Krumbein wished to examine sequences of links between junctions of subnetworks of differing magnitudes, and thus redefined the Hortonian main stem in terms of the sequence of channels formed by successive links of the greater magnitude at each junction. A cis chain is defined as "...the string of links terminated by lesser magnitude networks on the same side of the main stem...", while a trans chain comprises the link string terminated by opposite-sided subnetworks (James and Krumbein 1969, p. 547-548). That cis and trans chains should occur with equal frequency is predicted by the random model, but shown by James and Krumbein to be inevident (Smart 1972), especially in large networks. This aspect has been pursued by Abrahams (1981, 1984) and may be related to main-stem curvature.

Bifurcation where equal magnitude networks converge was considered unclassifiable by James and Krumbein (1969), but Abrahams (1980b) suggested that at such forks "...the incoming stream which is most closely aligned with the outgoing stream be designated the main stem."

Abrahams termed these chains CH chains. Unfortunately such chains are not purely topologic. This is a return to the Hortonian method of drainage network analysis. Flint (1980) used higher diameter as a differentiating criterion at equal magnitude bifurcation, but this approach does not work at ambilaterally symmetric junctions.

Mock's (1971) six-type classification of channel links eliminates the problem of equal magnitude bifurcation and introduces the chain as the set of links of less than or equal to 2n-3 links, between a tributary link and a bifurcating link (Table 2.1). It uses magnitude at forks as a basis of classification, incorporates the equal magnitude bifurcation and is purely topologic. Smart (1978) notes that Mock's scheme provides another means of hydrograph analysis, and when n = 6, it is of greater information content than the ambilateral class. Above n = 6 the "Mock-class" is a subset of the ambilateral class.

In a study of the distribution of chain types, Flint (1980) concluded that the tributary arrangement near network outlets and in headwater areas primarily reflects the limiting basin size. In a previous work Abrahams (1975) had found a predominance of cis chains in the headwater region. This tendency toward samehandedness in network pattern is attributed to competition between adjacent subnetworks (Flint 1980). These space-filling requirements of networks are probably a function of sub-basin area. Although topologic properties are used to describe the link types involved, and some tributary arrangements are ascribable to purely topologic distributions (Mock 1971), the main use of these grouped data is in the analysis of link length distributions.

2.3 Geometric Analysis of Channel Networks

Although the geometric aspects of channel network organization are not the concern of this dissertation, research conducted into geometric properties has led to further developments in the field which have relevance to this study. For instance, many of the tributary arrangement classifications have been proposed as a result of stream length studies.

2.3.1 Horton's Stream Length Laws

Horton (1945) considered that mean stream length within a stream order was statistically related to changes in stream order. Horton believed that "genetically similar" stream systems--where geologic and climatic factors were similar--should have nearly identical compositions. Chorley (1957) showed that stream length ratios were independent of setting.

Deviations from the straight line plot envisaged by Horton were found by Broscoe (1959) and Maxwell (1960). Bowden and Wallis (1964) showed that these deviations were asystematic, but that some deviations could be attributed to the Hortonian ordering system.

Correlation between the bifurcation ratio (topologic measure) and the stream length ratio was observed by Melton (1957) and deduced by Morisawa (1962), suggesting to Smart (1968) that many networks' geometric properties might be explained in a topologic manner.

2.3.2 Topologic Analysis of Stream Lengths

The first topologic analysis of link lengths was performed by Strahler (1954) working with magnitude 1 links. A lognormal distribution was found by Strahler and later confirmed by Schumm (1956).

Shreve's (1966, 1967) indication that links were distributed with equal probability in a TDCN renewed interest in the study of link lengths. Statistical theory was used by Smart (1969c) to provide a theoretical basis for further study, and showed that the mean stream length of a particular order is related to the stream number for that order, and does not require other parameters for a solution. In a more detailed study, however, Smart (1969b) found that there was no consistent relationship between magnitude and link length for different drainage networks, but the previously noted relationship only existed within a single network. A similar inconsistency between basins was also noted by Krumbein and Shreve (1970), Abrahams (1972), and Smart (1978).

Using an approach similar to Smart's analysis, Scheidegger (1968) (also Liao and Scheidegger 1969, Ghosh and Scheidegger, 1970) arrived at an interpretation that there is a definite increase in link lengths with Strahler order, contrary to Smart's (1968) findings. Scheidegger used a Monte Carlo procedure which, as Smart (1969b) noted, used a small sample size that probably accounts for the different results. Both Smart's (1968) and Scheidegger's (1968) assumption that interior link length does not change with magnitude was found by Smart (1969b) to be invalid, and has been substantiated by Mock (1971).

Schumm (1956) had shown that a lognormal distribution approximated the relationship between link length and magnitude, Smart (1969b) found an expotential relationship, and James and Krumbein (1969) and Shreve (1969) concluded that a gamma distribution best approximated the stream length and magnitude relationship.

Such divergence of stream length models led scientists to use alternative topologic and chain properties to explain interior lengths. James and Krumbein (1969) used cis and trans chains and found that the gamma distribution produced statistically acceptable predictions of lengths for all cis and trans chains, but that the deviations were due to trans chains.

Interior link lengths were examined by Mock (1971) using a six-type classification. Although the data sample was small, Mock found that link length and link type were dependent at the 0.001 level of significance. Further examination of link lengths using the Mock classification by Abrahams and Campbell (1976) showed that when $\mu \geqslant 5$, TS (Table 2.1) links had the same length distribution, a result later confirmed by Flint (1980). TS links tended to become longer downstream, because valley sides lengthened (Abrahams and Campbell 1976, Marcus 1980, and Abrahams 1984b).

Jarvis (1976), Smart and Werner (1976), and Smart (1978, 1981) have used path properties to examine link lengths, finding that diameter gave a good indication of link length distributions and enabled regional contrasts to be made (Jarvis 1976). In an examination of main stream length Shreve (1974) found diameter to be a useful predictive measure. Smart (1978, 1981) used a four-fold classification which described the kind of upstream links at a fork, by interior or exterior nature. Smart's (1981) analysis confirmed Flint's (1980) results that exterior link length is a function both of magnitude and distance downstream, of which distance downstream is a function of the path length (Jarvis and Werrity 1976). Flint and Proctor (1979) also suggest that the downstream link lengths from an interior-interior fork may be a function of tributary diameter as well as relative positions on the main stem.

2.3.3 Stream Lengths and Basin Morphology

A large number of drainage basin parameters have been used to describe the arrangement of features in a drainage basin. Of interest here is the attempt to correlate network topology with basin morphology. Notable studies include those of Abrahams (1980a b, 1982) who examines the importance of divide angles and chain curvature, and those of Werner (1972), Flint (1974), and Smart (1976, 1978), who worked with subnetwork areas as controlling factors on network topology. Abraham's (1980a) work with semi-divide angles (Table 2.1) suggests that hillslope form may also be important in the topologic pattern. This research has led to the conclusion that tributaries do not form independently along opposite side valleys (Abrahams 1982) and that channel curvature influences link lengths (Abrahams 1982, 1984b).

Stream junction angles may also be important morphometric properties of channel networks (Abrahams 1980a, Flint 1980), constraining the available space for development and hence influencing stream lengths. As yet stream junction angles have not been studied for their effects on link lengths, the emphasis of research to date has concentrated on predictive models of tributary arrangement (Howard 1970c, Pieri 1980, Woldenberg and Horsfield 1983).

2.4 Channel Network Evolution

Evolution implies change over time. Channel network evolution involves changes in spatial configuration of the links of the network. Both the number of links and link lengths may change. All other changes in network characteristics may be derived from these changes. Network evolution is typically considered to be contemporaneous with drainage basin evolution.

The number of studies of network evolution have been few and have varied in approach. Models of network evolution have ranged from observational through theoretical to simulation types. A summary of the models employed by geomorphologists is presented in Table 2.3.

2.4.1 Observational Models

Development of drainage systems was first discussed by Glock (1931), who identified four stages: initiation, extension, maximum extension, and integration and reduction. Elongation or headward growth was considered to be the initial mechanism of channel network growth, followed by the addition of new tributaries (branching). Glock's interpretation was based on field observation.

The work of Schumm (1956) at Perth Amboy examined channel changes on badland topography, but emphasized the evolution of drainage basin morphology rather than network growth. Such emphasis is pertinent as studies of channel networks incorporate other, non-channel information (Abrahams 1984).

Schumm (1956) noted that changes in the number and lengths of links occurred simultaneously with abstraction, the integration and reduction stage of Glock (1931). Topologic analysis of such networks is complex and has yet to be carried out using natural channel networks surveyed in the field. Dacey (1976) and Werner (1972) have provided the mathematical background for such analyses.

Both Schumm and Glock observed the phenomenon of headward growth of channels. This method of network extension is the most favored

Table 2.3 Summary of network growth models utilized in previous research

type / source	observational	topologic	headward growth	simulation	convergent	field scale	experimental scale	deterministic
Glock 1931	X		X					
Horton 1945								X
Schumm 1956	X		X			X		
Leopold and Langbein 1962				X	X			
Howard 1971a		X	X	X				
Howard 1971b		X	X	X				
Smart and Moruzzi 1971a		X	X	X				
Smart and Moruzzi 1971b		X	X	X				
Smart and Wallis 1971		X						
Flint 1973			X				x	
Abrahams 1975		X	X					
Dacey and Krumbein 1975		X	X					X
DeVries 1976	X							X
Dunkerley 1977			X	X				
Parker 1977	X						X	
Abrahams 1980b	X	X						X
Dunne 1980	X							X
Faulkner 1974						X		X allometric

X = model used by a particular study

in geomorphic literature and is employed in several other studies which use different conceptual approaches.

2.4.2 Topologic Models

Initial bifurcation processes were considered as topologic phenomena by Abrahams (1975). An excess of cis links in the main stem suggests that branching is a controlled phenomenon, with sub-basin area playing a major role. This suggests a trial-and-error approach to branching patterns. In headwater regions Abrahams found that there was no topologic difference in the frequency of cis and trans links, suggesting that bifurcation was the major method of network growth. This result was in contrast to that of Smart and Wallis (1971), but concurred with their data on chain lengths, in which cis chains were considerably shorter than trans chains.

Three models of random network growth were developed by Dacey and Krumbein (1975). Unfortunately they tested their models on static systems, which assumes that growth was uniform across the basin. However, they concluded that in any model it is important to consider both bifurcation and branching growth modes. The importance of headward extension was minimized. A combination of two models gave high prediction of network arrangement, which led the authors to conclude that the relative importance of branching events at exterior and interior links is a function of link magnitude.

2.4.3 Scale Models

An example of network growth research using a scale model is that of Parker (1977). A 9x15 m container filled with a homogeneous sand, silt, and clay mixture was subjected to artificial rainfall. Initial slope conditions were important in determining network elongation; the greater the slope, the more elongate the network. This result substantiates Smart's (1969a) observation on the influence of basin relief on deviations from the random model. Parker (1977) observed two types of growth: 1) low slope, slow headward growth, 2) high slope, rapid elongation.

Network evolution on Parker's model exhibited characteristics similar to those observed by Schumm (1956), with larger streams dominating the abstraction process. Simultaneity of expansion and abstraction were shown to occur simultaneously, but to be spatially distinct phenomenon. As expansion continued in the headwaters, abstraction occurred near the outlet and spread headward. It is not clear if this headward spread was related to changes in the expansion rate.

Parker noted a tendency for exterior links to increase in length as abstraction proceeded, and for TS links to become longer than S links. TS links were found to drain internal areas of low relief; S links tended to concentrate in the high relief areas.

A study by Flint (1973) showed that the number of streams increased expotentially with time, until constrained by the container size. Drainage density at the expanding growth front remained constant through time.

2.4.4 Simulation Models

Parker (1977) notes that Horton's (1945) deterministic model represents an almost instantaneous development of rills over a surface. At the other extreme are the models of Howard (1971) and Smart and Moruzzi (1971a, b) where headward growth produces a wave of dissection (Howard 1971b, p. 30) moving toward the basin divide.

These two models are computer generated, and offer a significant improvement over the random walk model of Leopold and Langbein (1962), in which growth converged on the outlet--a growth mode which has only been observed in rills forming on new, loosely consolidated sands.

Some of Howard's (1971a) results are purely topologic in character, but produced tributary numbers that were abnormally low for natural networks. Random topology is shown to exist in networks generated from random walk methods (Howard 1971a), but the type of network generated is strongly influenced by the boundary conditions. Howard also suggested that the similarity between the simulation and natural networks may be superficial because of the lack of geomorphic information used in the model generation. Shreve (1975) argues that all physicial or deterministic theories can be recast into dimensionless forms, and that all deterministic models contain an uncertainty or statistical element.

The importance of Smart and Moruzzi's (1971a, b) work is that it successfully simulated real drainage networks. Similar success was achieved by Dunkerley (1977), who simulated controlled growth by evaluating drainage density after each growth event. Stream lengths simulated in this study were found to have a gamma-like distribution, a property deduced for real networks by James and Krumbein (1969).

2.4.5 Deterministic Models

In the rational model proposed by Horton (1945), the growth of channel networks is not headward, but rather by abstraction. An initial surface is quickly rilled by convergence of overland flow downslope of X_c, the critical distance to the divide. Micropiracy of these rills leads to dominance by major tributaries and the development of a branched channel network.

This emphasis on competition between rills and the need for "a certain minimum space or intercept between tributaries" (Horton 1945, p. 344) is currently receiving interest from Abrahams (1980a, 1983).

Criticism from Leopold et al. (1964) and Dunne (1980) has shown that it is difficult to translate Horton's microscale approach to full-scale landscapes. This scale-related problem has led to considerable difficulty in geomorphic interpretation, and the threshold between rill-hillslopes and channel-landscape networks is unknown.

A mechanism for headward growth has been proposed by Dunne (1980). Subsurface flow convergence is considered to be of prime importance. Where the upward drag force (a function of the hydraulic gradient) exceeds the surface material's cohesive resistance to erosion, sapping may occur, which stimulates headward growth. Cohesion is lessened by chemical weathering, which may be associated with the groundwater flow.

Dunne thought that a positive correlation would exist between relief and drainage density because of the hydraulic gradient of the groundwater. In contrast DeVries (1976) argued for a negative correlation because steeper slopes more efficiently removed groundwater-excess over storage capacity. Abrahams (1980b) showed that ground slope had poor correlation with network density in subsurface-fed systems.

Advances in deterministic models of network growth should next consider the case of saturation-excess overland flow, and the importance of soil piping (Abrahams 1984).

2.4.6 Allometric Models

A precise definition of an allometric model would place it either in a stochastic or a deterministic grouping, but the allometric approach is considered separately because of its history.

Allometry was first used by Snell (1891) to describe biological growth, and, following Huxley's exhaustive discussion (1932), received widespread attention. Gould (1972, quoted in Mosley and Parker 1972) defined allometry as "a general term for all relationships, dynamic or static, fit by power functions (and involving change of shape correlated with size increase)." In fluvial geomorphology the empirical relationship determined by Leopold and Maddock (1953) concerning discharge, channel width, depth and velocity are allometric. Growth models are not static models; they do not simply involve the measurement of some property at a single point in time (Gould 1966). Dynamic allometry concerns measurement over time (Mosley and Parker 1972, Bull 1975), but the power function approach is but one set of mathematical descriptors available, and research should be conducted not toward fitting data to these functions, but toward careful definition and observation of the factors responsible for growth or the morphologic features which undergo growth (Bull 1975).

Most of the research in fluvial geomorphology which has employed allometric models has not examined the dynamic case (Nordbeck 1965, Woldenberg 1966, Wilson 1969, Faulkner 1974 and Park 1978). Spatial allometry is a valuable descriptor and comparative technique, but it does little to enhance knowledge of evolutionary tendencies because, as Abrahams (1972) concluded, it is impossible to draw valid conclusions for space-for-time substitutions when the spatial forms are of different magnitudes.

Faulkner's (1974) approach is valuable because it provides a mathematical basis from which dynamic growth can be modeled, and it illustrates the importance of hydrologic competition as a controlling variable in the development of gully systems. Faulkner proposed, as a result of her observations but not of allometric model curve fitting, that two growth phases can be expected: a non-competitive phase prior to the channels reaching the divide, and a subsequent competitive phase.

Criticism by Mosley and Parker (1972) was not well founded because it focused solely on the static approach. However they did consider growth rates based on their observations of the scale model drainage evolution facility. Growth rates were not found to be linear in space or in time. Topologic factors were not considered in the analysis.

The findings of Dunkerley (1977), Flint (1973), Howard (1971a), Parker (1977) and Smart and Moruzzi (1971a, b) all have allometric components, although no attempt was made to quantify the processes recorded.

2.5 Channel Networks: A Summary

Quantitative assessment of channel networks is 40 years old. Order as perceived by Horton gave way to topologic structure with Strahler and later Shreve. Random topologic structure proposed by Shreve has been shown to successfully predict:

1) Horton's laws of drainage composition: bifurcation, length and area ratios (Shreve 1967, Smart 1968);

2) Observed correlations between bifurcation and length ratios (Smart 1968);

3) Observed correlations between stream numbers and stream lengths (Smart 1968);

4) Observed relations between stream frequency and drainage density (Melton 1958);

5) Observed relations between main stream length and basin area (Hack 1957, Shreve 1974, Jarvis and Sham 1981).

Topologic properties can be grouped by magnitude (ambilateral classification), by path (path length, diameter) or by tributary arrangement (chains). Geometric properties (link length) have yet to yield consistent results when related to topology, but the use of tributary arrangements have been promising in this respect.

Network evolution studies are still inconclusive. Headward growth models dominate the conceptual approaches. Simulation models have yielded little new information, while deterministic models have generated considerable controversy. Scale models have added significant information about modes of extension and abstraction. Topologic analysis has been limited to established networks. No single study has combined type of growth with changes over time and modifications in space.

The trend in geomorphic research is away from the simple postulate of random distribution of network topologies to a more complex analysis involving other drainage basin properties. As Abrahams (1984) points out, an increased knowledge of the factors controlling channel networks leads to a decreased reliance on stochastic elements in our models.

CHAPTER 3

The Physical Geography of the Debris Avalanche Dam of Spirit Lake

3.1 Description of Study Area

3.1.1 Location

Mount St. Helens is a Quaternary strato-volcano in the Cascade Range, located in northwest Skamania County, Washington, 33 km NNE of Portland, Oregon (Figure 3.1). Mount St. Helens is offset in a westerly direction with respect to the main NNW-SSE trend of Cascade stratovolcanoes, a factor which may contribute to its more explosive nature.

3.1.2 Geographic Setting of Spirit Lake Debris Dam

The Debris Dam occupies about 3 km^2 between the southwest tip of present-day Spirit Lake and the upper reaches of the North Fork Toutle River (Figures 3.2 and 3.3). Buried beneath its western portion lies Spirit Lake Lodge. To the north it is bounded by Harry's Ridge and Johnston Ridge, and to the south by the Pumice Plain. The ampitheatre of Mount St. Helens is 7 km to the south. The individual drainage basins of the study area are shown in Figure 3.4.

3.2 Character of the Debris Dam

3.2.1 Formation

By worldwide standards, the volcanic event at Mount St. Helens which occurred at 0832 hours on May 18, 1980 (hereafter referred to as the "May 18th eruption") was not amongst the largest known such events. Yet the destructiveness of the event, and its unpredicted occurrence contributed to its catastrophic nature.

Numerous studies have been reported the sequence of events that day (Lipman and Mullineaux 1982). Approximately 2.8 km^2 of rock-debris

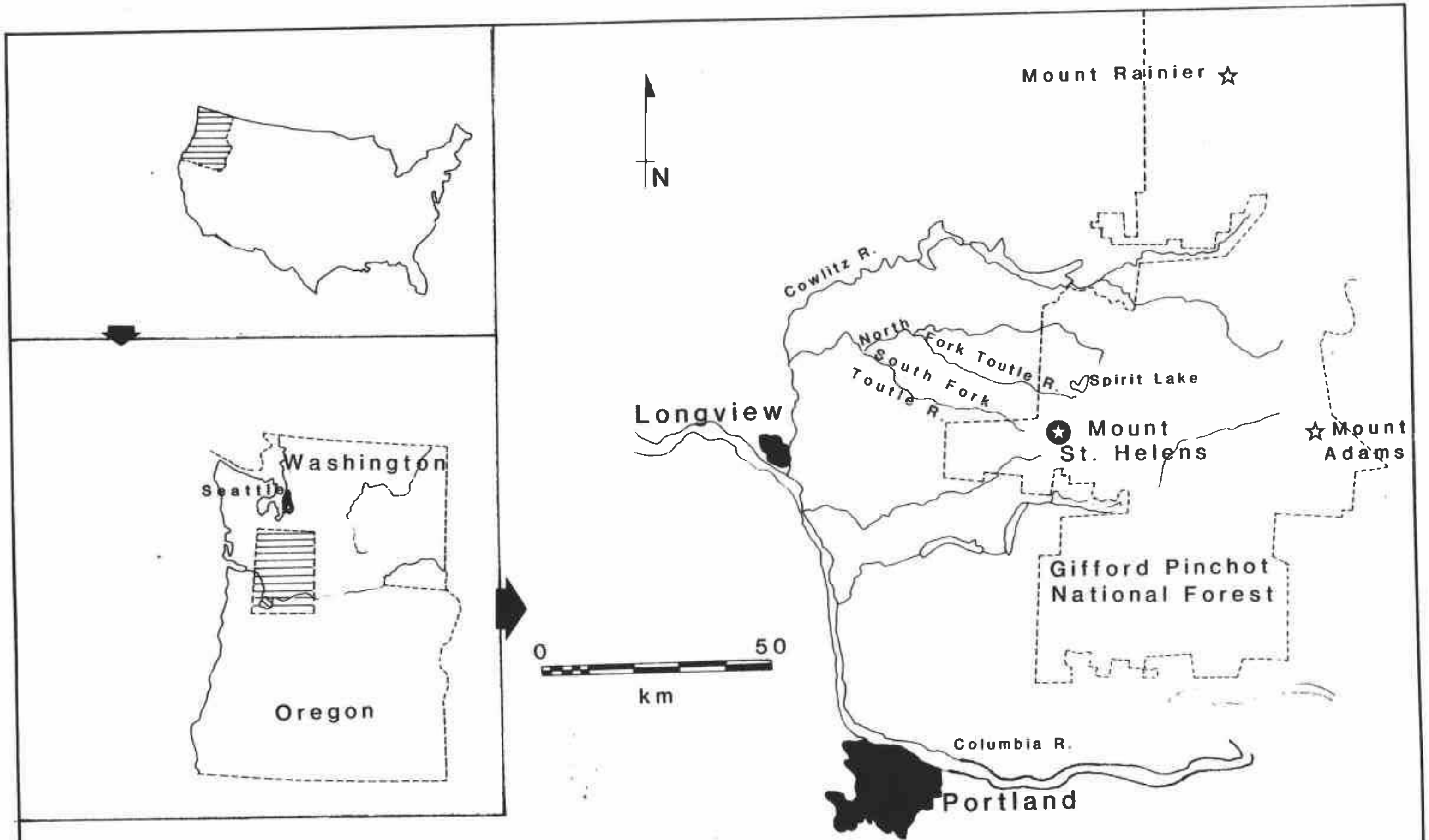


Figure 3.1 Location of Mount St. Helens and key drainage systems

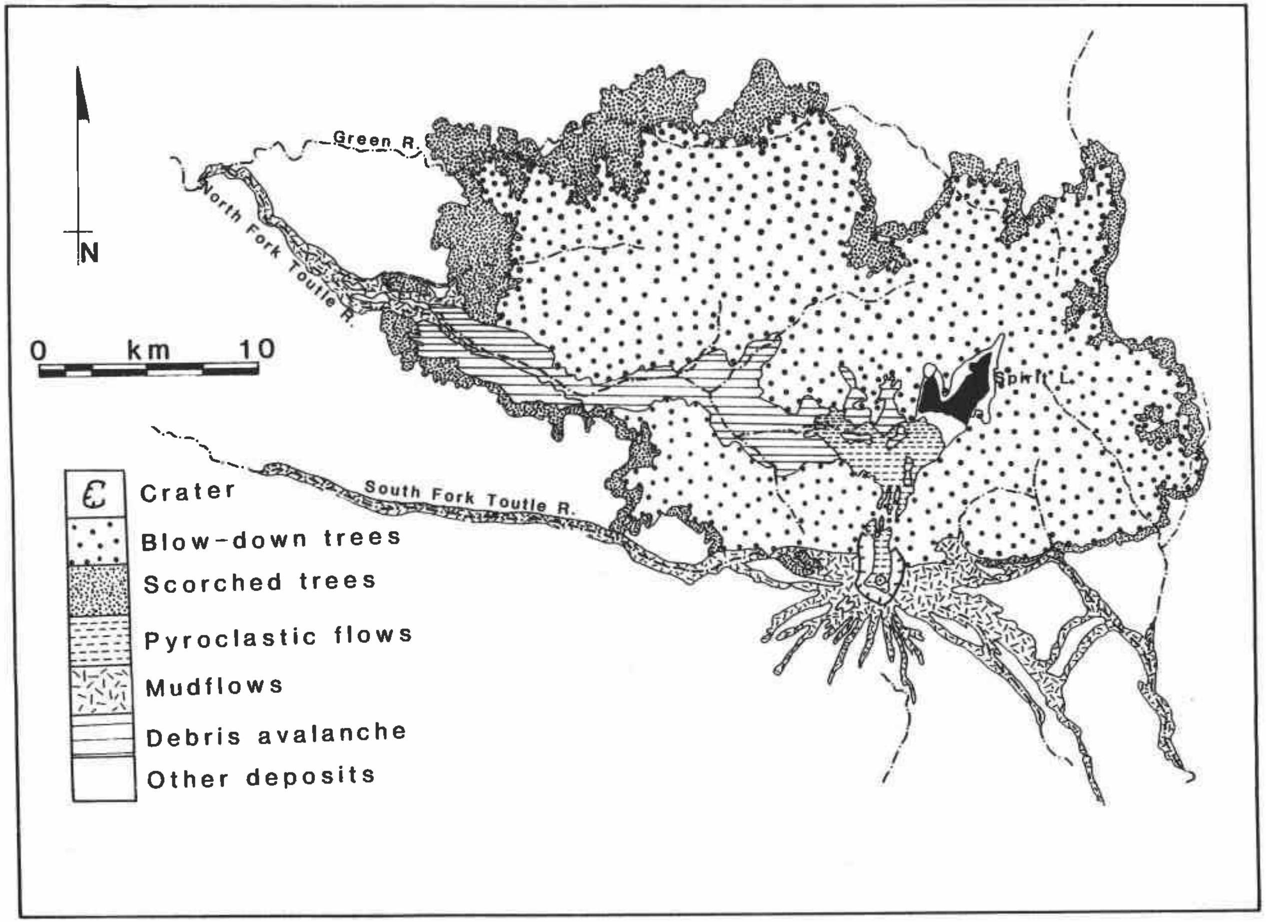


Figure 3.2 Sedimentary deposits and vegetation devastation which resulted from the May 18, 1980 eruption of Mount St. Helens

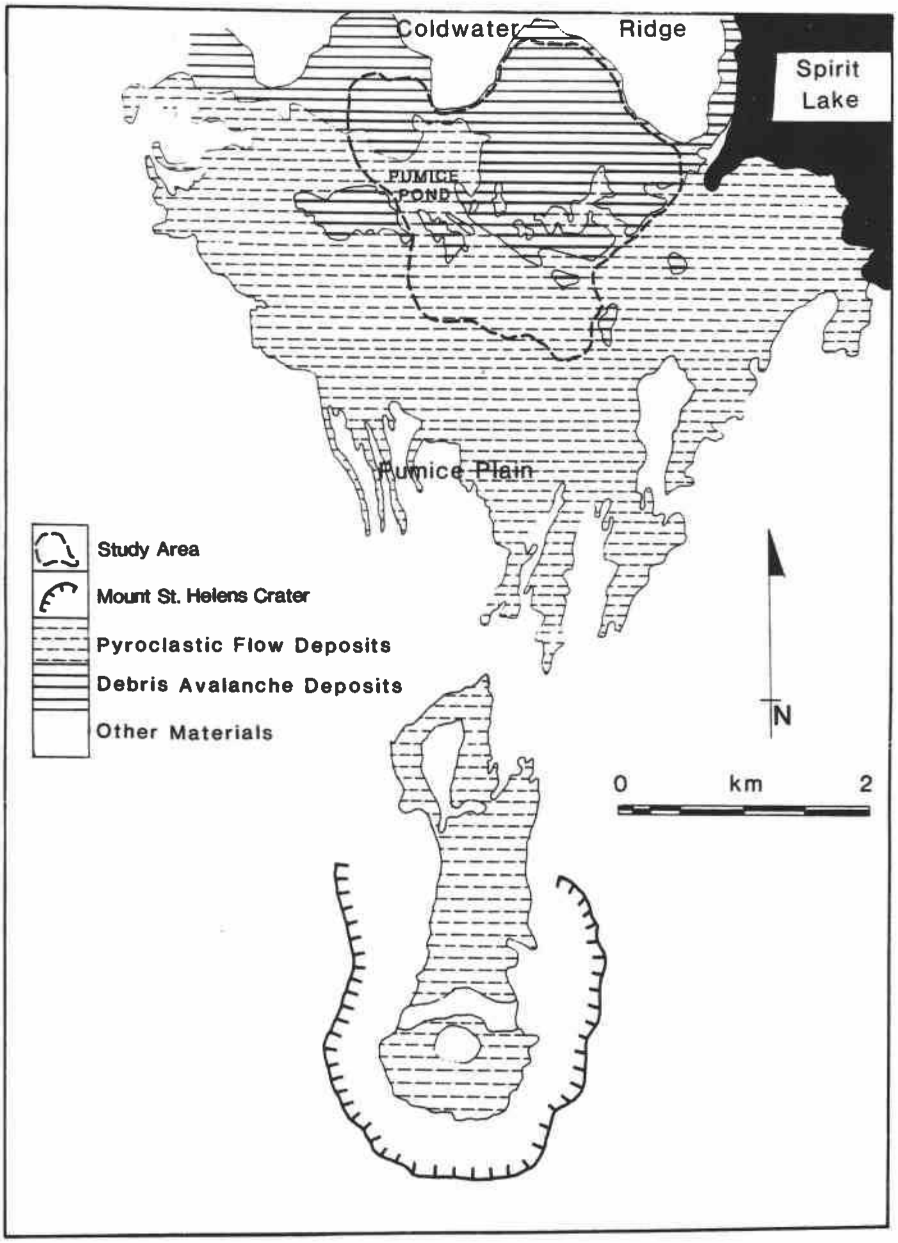


Figure 3.3 Study area location and associated sedimentary deposits

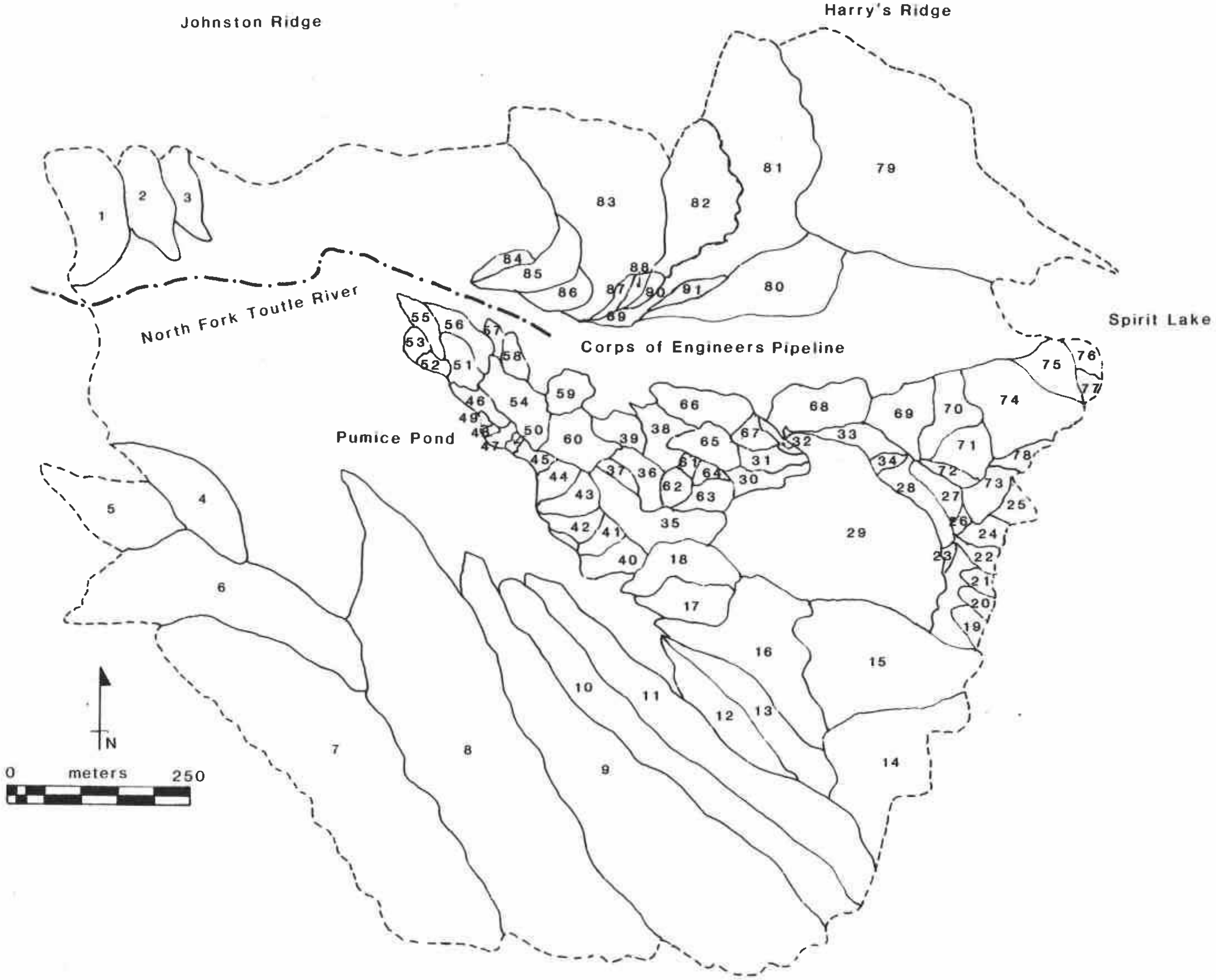


Figure 3.4 Location of the ninety-one study drainage basins

were displaced from Mount St. Helens, movement being initiated by a 5+ magnitude earthquake (Endo et al. 1982) which triggered a first-phase slide (Voight 1982). As a result of this and further slides (Moore and Albee 1982), magma chamber overburden was removed, creating an explosive decompression and enhancing slide movement (Voight et al. 1982) and further multiple slope failures.

The massive avalanche consisted of three lobes (Voight et al. 1982), a result of the pre-eruption terrain and the internal structure of the volcano. One lobe displaced Spirit Lake and raised the original level by 60m. A second lobe moved down the valley of the North Fork Toutle River, leaving a hummocky deposit. In between these, the third lobe ran northward, partly overtopped Johnston Ridge, and partly subsided back to create the Debris Dam of Spirit Lake (Figure 3.3). Concurrent and subsequent pyroclastic flow deposits added to the material of the blockage (Waitt 1982).

During emplacement of the Lahar materials and as a result of the May 18, 1980 pyroclastic flows into open ponds on the debris avalanche surface, mixing of hot volcanic material with cold water and ice brought about rapid gasification under partial confinement. Such rapid volume expansion was explosive, ejecting the overburden, and leaving the area packed with phreatic explosion pits.

3.2.2 Sedimentary Deposits

Initial geologic mapping of the eruption deposits by the U.S. Geological Survey indicates two major stratigraphic units comprise the Debris Dam (Voight et al. 1982): the Coldwater Ridge Unit and Pumiceous Pyroclastic Flows (Figure 3.3). Modifications to these preliminary interpretations have yet to be published.

3.2.2.1 The Coldwater Ridge Unit

With a maximum thickness of 195m, this unit contains segregated blocks of fresh and altered brecciated andesite, basalt and scorias (Voight et al. 1982). The volume of these materials was considered to be 90% of the total debris volume (Voight et al. 1982).

Brecciated dacite, colluvium and old tephra, everywhere veneered by blast deposits and thin pumice flows comprise the remainder. Mean particle size was 0-3.83 ϕ, with a standard deviation of 0.45 indicating a well sorted deposit (Voight et al. 1982).

3.2.2.2 The Pumiceous Pyroclastic Flows

Rowley et al. (1982) have described in detail these stratigraphic units. Two groups of pyroclastic flows, those of May 18, and another of June 12, 1980 are major contributors of material (Figure 3.3). Minor contributions come from the July 22, 1980 pyroclastic flow.

A large phreatic explosion pit--the "Pumice Pond"--was created in May 18 flows; subsequently, the June 12 flow added 8m of deposit to the floor. The May 18 material is at least 38m thick in the Pumice Pond. Within the hummocky portion of the Debris Dam, May 18 pyroclastic flow deposits may be found. Many basins with internal drainage basins examined in this study were formed with outlets of phreatic explosions. The resultant depressions are comprised of these deposits.

Fragmental material, mostly ash-sized shards, pumice and broken phenocrysts, forms the bulk of the pyroclastic flow deposits (Rowley et al. 1982). Some block-sized materials are present and these are generally pumice.

3.2.2.3 Tephra Deposits

The tephra deposition that followed emplacement of the Coldwater unit is known as blast deposit. Airfall tephra continued during and after emplacement of the pyroclastic flows. These tephra material were fine grained and blocked surface pores in the pyroclastic materials, which resulted in initially reduced infiltration. Removal of tephra under wind and surface wash action proceeded throughout the first year. As the tephra was removed, infiltration levels increased.

3.2.3 Topography

As a result of its complex origin and three-phase stratigraphy, the Debris Dam has a striking topography. The greater part of the study area displays a series of depressions, most of which are centered on phreatic explosion pits, up to 20m below the mean surface. Topographic highs, the most prominent 60m above the August 1980 Spirit Lake surface, have slopes up to 100+%, and most greater than 60%.

Slopes in the basins are partly a function of basin area: the smaller the basin, the steeper the slope. The two smallest basins (0.5 ha) have 60% slopes. The largest basins (5-8 ha) slopes range from 10-25%. The break in slope between hummocks and basins is sharp, and reflects a change in stratigraphy, from debris avalanche to pyroclastic flow deposits.

In the study area four types of basins are recognized, on the basis of topography and stratigraphy. The first type consists of gently sloping pyroclastic flows. Secondly there are basins with pyroclastic flow and debris avalanche, the latter on the exterior portions, close to the basin divide. Thirdly, there are a few basins developed in debris avalanche alone. Finally, there are basins with

Table 3.1 Geologic materials and drainage type associated with each study basin

basin #	basin type	basin #	basin type	basin #	basin type	basin #	basin type
1	Ta	24	Ic	47	Ic	70	Ic
2	Ta	25	Ic	48	Ic	71	Ic
3	Ta	26	Ic	49	Id	72	Ic
4	Tb	27	Ic	50	Id	73	Sc
5	Tb	28	Ic	51	TIc	74	Sc
6	Tb	29	Ic	52	TId	75	Sc
7	Tb	30	Id	53	TId	76	Sc
8	Tb	31	Id	54	Ic	77	Sc
9	Tb	32	Id	55	Tc	78	Sc
10	Tb	33	Id	56	Tc	79	Sa
11	Tb	34	Id	57	Tc	80	Ta
12	Tb	35	Id	58	Tc	81	Ta
13	Tb	36	Ic	59	Tc	82	Ta
14	Sc	37	Id	60	Ic	83	Ta
15	Sc	38	Id	61	Id	84	Ta
16	TIc	39	Id	62	Id	85	Ta
17	TIc	40	TId	63	Id	86	Ta
18	TIc	41	TId	64	Id	87	Ta
19	Sc	42	TId	65	Ic	88	Ta
20	Sc	43	TId	66	TIc	89	Ta
21	Sc	44	TId	67	Ic	90	Ta
22	Ic	45	TId	68	Ic	91	Ta
23	Ic	46	TIc	69	Ic		

Legend:

upper case = drainage type

T = North Fork Toutle River drainage
TI = capture by North Fork Toutle River after initial internal drainage
S = Spirit Lake drainage
I = Internal drainage throughout study

lower case = geologic type (1980 deposits)

a = slumped debris avalanche material with minor pyroclastic cover
b = deep pyroclastics >3m over debris avalanche
c = thin pyroclastics 1-3m deep over debris avalanche
d = debris avalanche monadnock, initially tephra covered

debris avalanche material which continues to slump off the pre-blast hillslopes, the lower part of which has a pyroclastic flow cover. The basin type is indicated in Table 3.1 along with an explanation of the letter code to be used for reference purposes in this dissertation.

That these different types of drainage basin may contribute to the channel network chracteristics, both topologic and geometric, is recognized. Analysis of the networks will include measures to elucidate these contributions.

CHAPTER 4

Methods of Study

> The greatest crime is not to do something because
> you fear only doing a little.
>
> Rene Descartes

4.1 Techniques of Data Collection

Two sources were used to obtain network data. One utilized aerial photography, the other field observation. Field observation was used to ground truth the aerial photography.

4.1.1 Aerial Photography

Monitoring of the area affected by the Mount St. Helens eruptions using remote sensing techniques has been extensive. Aerial photography, both color and panchromatic, has been most frequently used. Table 4.1 summarizes the aerial photography used for this study.

Channel networks were interpreted from the aerial photography using a variable magnification binocular stereoscope. A zoom transfer scope was used to produce maps at 1:4800 scale onto a base map prepared by Tallamy, Van Kuren, Gertis and Thielman Company for the U.S. Geological Survey in August 1980. Eleven maps were produced, one for each observation date, and then compiled into a single composite map for analysis. The observation date is referred to by "timeperiod" in the text. An "observation period" implies the length of time between two adjacent observation dates or timeperiods.

The maximum extent of channels interpreted from the photographs was determined by the sharp break in slope present at the head of each exterior link. These could easily be observed on the photography as characteristic shadows.

Photographic scale was different for each overflight, but was in the range 1:5000 to 1:10000. Scale was not determined for each flight.

4.1.2 Field Survey

Field survey was carried out in the summer of 1983. The ground-truthing obtained had two objectives. First, starting from a clearly identifiable point, 20 networks were traced upstream, each link being noted, and its position relative to other links. These networks were then identified on the September 1983 aerial photography, and the interpreted networks compared with the observed. The total interpreted links were compared with the total observed links using a t statistic on the hypothesis that the field and photographic networks are not significantly different. Table 4.2 shows that, at a 95% confidence level, there is no significant difference between field and photographic networks.

Second, actual link lengths were measured by tape for the same networks described above. Again observed and interpreted links were compared, using the t statistic (Table 4.2). Can't find

The two field survey techniques have provided sufficient information to overcome Coates' objections to discrepancies between photographic and field survey methods for channel network data (Coates 1958). In a recent paper, Mark (1983) has also argued that field survey is essential for any channel network studies and showed that statistical information helps limit the necessity for complete ground survey. The ground-truth and photo-interpretation method offers greater objectivity than the contour crenulation method of Strahler (1954).

Table 4.1 Summary of aerial photography employed to map network development

study time period	flight date	flight organization	photographic type
1	Oct 6 1980	OARNG	b/w
2	Dec 11 1980	OARNG	b/w
3	Mar 7 1981	USGS	b/w
4	Oct 31 1981	OARNG	b/w
5	Nov 24 1981	OARNG + USACofE	b/w - color
6	Feb 6 1982	OARNG	b/w
7	Mar 21 1982	OARNG	b/w
8	Oct 31 1982	OARNG	b/w
9	Dec 22 1982	USACofE	color
10	Mar 12 1983	USACofE/USGS	b/w - b/w
11	Sept 13 1983	OSU Dept. of Geography/USACofE	color

OARNG = Oregon Army National Guard
USGS = United States Geological Survey, Vancouver, Washington
USACofE = United States Army Corps of Engineers, Portland District, Oregon

b/w = black and white, panchromatic film
color = normal color film

Table 4.2 Statistical comparison of field and photograph networks

	# exterior links	
basin #	photo survey	field survey
2	29	30
18	40	45
28	67	70
36	23	25
43	10	10
53	11	11
59	35	36
61	10	10
65	33	34
73	61	66
76	28	28
80	37	38
84	41	43
89	12	12
15	147	145
21	48	46
30	11	10
44	11	10

$\chi^2 = 1.75$, 17df

$\chi^2_{tab,17df,0.01} = 33.41$

4.2 Secondary Data Extraction

On the October 1980 map a total of 105 independent basins were identified. As a result of subsequent channel growth, divide erosion and sedimentation from mudflows, only 91 of these basins remained independent by September 1983. These 91 basins and their channel networks are used in this study.

From each basin, topologic and geometric data were obtained. Smart (1978) has shown that from four geometric variables (link length, basin area, interior basin area, exterior basin area) and one topologic variable (topologic vector) a combined total of 31 properties can be calculated for each basin. To this we add the ambilateral classification and Mock's (1971) classification.

In this study, additional data are required regarding the type of growth that occurred between observation periods. For this purpose two new vector strings are created that encode geometric and topologic growth states for each link in each network.

The algorithm for calculation of these 31 properties was presented by Smart (1978, p. 136) and utilized in this study. A Pascal 6000 computer program was written by the author which employed Smart's algorithm plus modifications to assess ambilateral class.

4.2.1 Link Codes

For the purpose of this study two separate files were created which contained network information for different analyses.

1. Topologic Vector File

   This file contains the binary coding for each link in each network, as a vector string (Smart 1969).

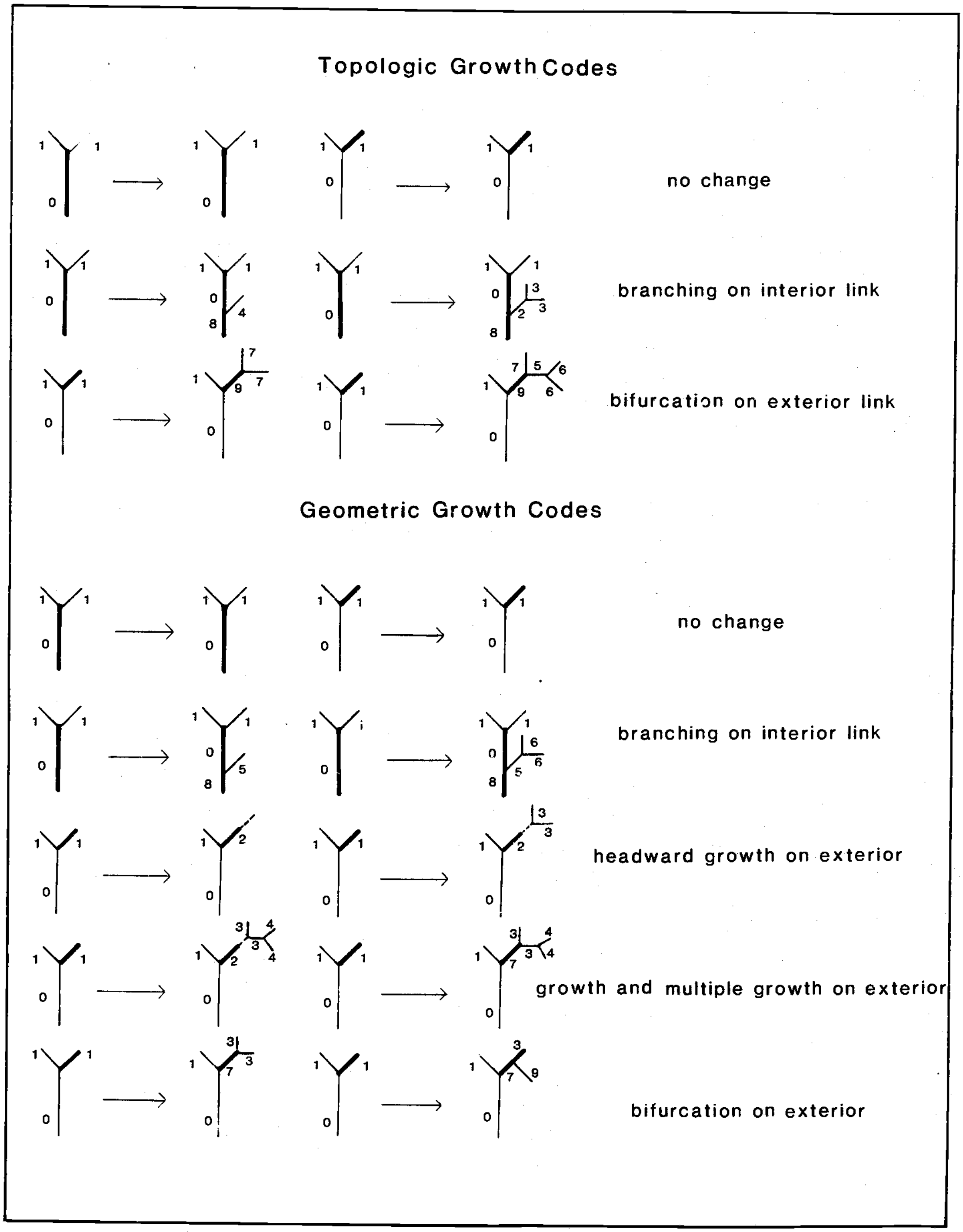


Figure 4.1 Schematic encodement of network growth types

2. Topologic Growth File

This file contains a single digit coding (range of values, 0-9) which describes the topologic changes that have occurred to a link within a single network since the last set of observations. A pictorial description for each code is given in Figure 4.1. Number codes used in the topologic growth file can be converted into topologic vector binaries, but the reverse is not true. (Conversion : growth values 0,2,5, 9 = binary 0, growth values 1,3,4,6,7,8 = binary 1)

The ideal situation in which growth events are recorded as individual events has been stated by James and Krumbein (1971). Figure 4.2 describes these ideal events in geometric, topologic, and morphologic terms.

Under ideal conditions the observer may record a single growth event in a network of magnitude n. The probability of this growth event occurring to a given link j is

$$(p;j) = 1/2n-1 \qquad 4.1$$

For topologic growth, the change in state following a growth event is governed by a link's designation as exterior or interior. An exterior link, with geometric growth type may experience one of four changes: no change, headward growth, bifurcation or branching. Similarly, an exterior link examined by topologic growth may only experience two possible states: no change or bifurcation with interior links; the states are two for both geometric and topologic approaches.

Therefore, in a random, single-growth event, the probability that a single link j in a network of size n will experience any one particular change in state is given in Table 4.3.

Geometric Growth Code	Topologic Growth Code
0	0
1	1
2	1
233	977
23443	95667
23344	97566
5	4
733 739 793	977
73443	95667
73344	97566
80	80
850	840
85660	82330

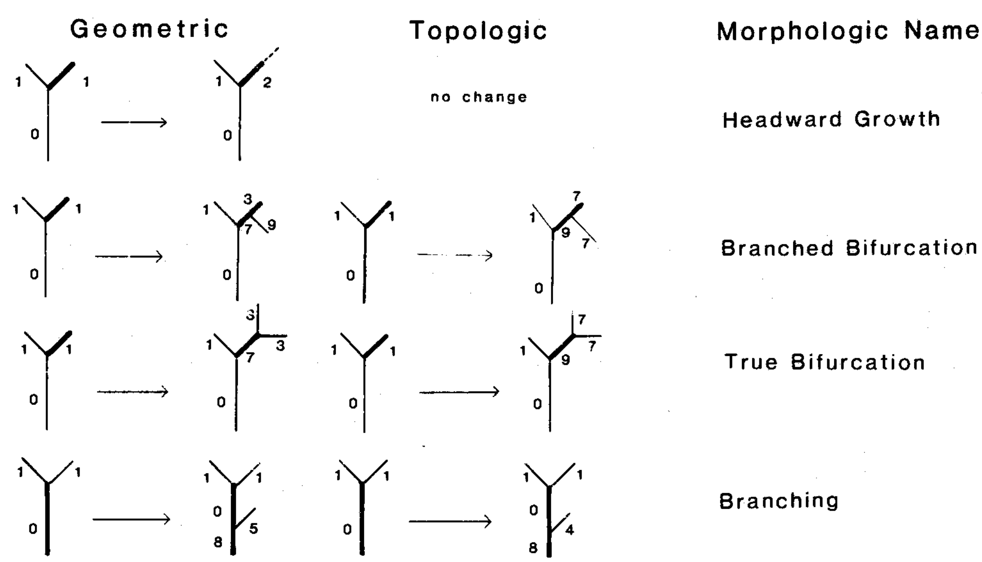


Figure 4.2 Translation of geometric to topologic growth codes and the encodement of ideal growth patterns

4.2.2 Link Lengths and Basin Areas

Link lengths and basin areas were obtained from the composite network map using a sonic digitizer. Each network was measured for each timeperiod. Three lengths were obtained for each link and the mean value used in the data base.

4.3 Analytical Techniques: Introduction

Analysis of the secondary data base is directed toward achievement of the study objectives, namely the recording and interpretation of geometric and topologic properties of networks and their development through time in the study area. Two distinct levels of primary data base analysis are recognized. First, a direct use of data, such as the actual link lengths and basin areas, which does not involve the generation of a second, or derived data set, such as in the creation of topologic properties from the topologic vector.

Three analytical phases were used.

1) Examination of link lengths and basin areas for each network, and calculation of link densities and drainage densities.
2) Generation and comparison of simple topologic properties for each basin at each time period. A comparison of simple topologic properties between basin types and among basins within a type.
3) Study of the nature of network growth, examining the amount of growth over a time interval, and the type of growth that occurs as a morphologic and topologic feature of geomorphic evolution.

4.3.1 Statistical Assumptions

The following assumptions were made with respect to the data base in order to comply with the requirements of statistical analysis.

Non-parametric tests

χ^2 - test requires

a. Independent samples

b. When degrees of freedom are greater than 1 the χ^2 test is applicable even when fewer than 20% of the cells have an expected frequency of less than five, if no single cell has an expected frequency of less than 1. This may be overcome by combining cells of appropriate types.

Analysis of Variance

a. Each of the distributions is normal.

b. Each of the distributions has the same variance.

c. The observations for each factor level are independent of observations for any other factor level.

These assumptions have been made in previously published materials (Shreve 1966, 1967, Smart 1967, 1968, 1976, 1978, etc.).

4.4 <u>Analytical Techniques: Geometric Properties</u>

Total stream length was calculated as the sum of the individual link lengths. Drainage density was calculated in two modes. First the drainage density for the entire basin was calculated as total network length divided by the entire basin area at the last date of observation. Second a drainage density was obtained for the basin area occupied by the current network at the time of sampling. Comparison of these two types of drainage density allows inferences to be drawn concerning changes in the hydrologic efficiency of the watershed through time.

Table 4.3 Probabilities of geometric and topologic growth at interior and exterior links

	calculated by	
link probability	geometric growth	topologic growth
(p ; je)	n / 4 (2n - 1)	n/2 (2n -1)
(p ; ji)	(n-1) / 2 (2n -1)	n-1 / 2 (2n -1)

4.5 Analytical Techniques: Simple Topologic Properties

A topologic vector was obtained for each network and at each time-period (Chapter 4.2.1). From the topologic vector it is a simple process to calculate all topologic properties, for each link, and for the entire network. A Pascal 6000 computer program was written to process the topologic vector for: link magnitude, link path length, total path length, exterior path length, diameter, mean exterior path length, ambilateral class, path number class and system magnitude. All topologic properties can be examined using non-parametric statistics (Shreve 1966).

4.5.1 Tests of Random Topology

Several tests of random topology were conducted on the networks using the probability approach initiated by Shreve (1966). The basic premise is that a link drawn at random from the network has a probability

$$P\ (\mu,n) = \frac{(n- \ +1)\ N(n-\mu+1)\ N(\mu)}{(2n-1)\ N(\mu)} \qquad 4.2$$

where

$$N(\mu) = \frac{1}{2\mu-1} \binom{2\mu-1}{\mu} \qquad 4.3$$

which is the number of topologically distinct channel networks of magnitude μ (Shreve 1966, p. 29).

For exact results one obtains an expression for m, the number of subnetworks of magnitude μ in a network of magnitude n. Hence Shreve (1966, p. 181) showed that

$$P(\mu;n) = \frac{1}{2\mu-1} \binom{2\mu}{\mu} \binom{2(n-\mu)}{n-\mu} \binom{2n}{n} \qquad 4.4$$

which is Cayley's expression. In turn this can be reduced to an expression relating the difference in magnitude between n and μ so that

$$P(\mu;n) = \frac{\prod_{j=1}^{n-1} n - (n-\mu-j)}{[2n - (n-\mu)] * [2n - (n-\mu+1)]} * \frac{1}{2\mu-1} \qquad 4.5$$

which is readily programmable and generates only small values at each iteration in order to increase computational efficiency.

The expected value of m for a given μ and n is then

$$E(m;\mu,n) = (2n-1)P(\mu;n) \qquad 4.6$$

Thus, in an infinitely large network, the probability of drawing an exterior link is 0.50, increasing (to 1.00 at n=1) as the network size decreases.

The theoretical probability (expected) and the observed frequency can be compared using a 2xn contingency table and χ^2-statistic of goodness of fit. This can be calculated for each timeperiod. In the case that observations in any timeperiod exhibit significant deviations from the expected values, that period may be examined with respect to all timeperiods using an Rxn contingency table and the statistic where R is the number of timeperiods. The null hypothesis in both cases is that the distribution of magnitudes in the network is topologically random.

The random model may also be tested for groups of networks within a basin type. In its complete form, this would require the three-dimensional Rxnxb contingency table, where b represents a basin type. However it is valid to test a single timeperiod only, so that the bxn contingency table may be used.

Network magnitude distributions can be tested using analysis of variance of population means once the data has been normalized. In this study data was normalized in both spatial and temporal dimensions. Spatial normalization was accomplished by reducing all basins to a common base. The resultant data had the dimensions of "links added per thousand links present at the previous observation." Temporal normalization then assessed the timeperiod between observations, giving a dimension of "links added per thousand links present per month."

4.5.2 Tests of the Ambilateral Classification

The ambilateral classification can be obtained in two separate manners. First by a "growth up" method described next in this section, and second by Smart's (1978, p. 136) "top down" method. As discussed later, these two methods produce different sets of ambilateral classes and have considerable implication in a discussion of the random model and network growth.

The ambilateral classification is unique for groups of networks when $n<9$. When $n\leq 9$, there is overlapping of classes (Smart 1978) of non-related TDCN. At $n=9$ there are two member sets to the 223445 class. It is therefore inadvisable to discuss random topology and the ambilateral classification for subnetworks of $n>8$.

In this study networks of a current magnitude greater than eight were subdivided into subnetworks of $n<8$ using the growth pattern through time as the basis for subdivision. This is the "growth up" method. The following procedure was used:

a) For each network start at timeperiod 1.

b) If n 8, classify into ambilateral class,

else reduce to required number of subnetworks where n 8 by

i. Successively creating subnetworks starting at the first upstream fork from the outlet link.

ii. If ith upstream fork (where i is an integer ≥ 1) does not provide necessary subdivision, proceed up link of greater magnitude, and subdivide, or if bifurcation is of equal magnitude, go to the left-hand fork and subdivide.

c) Go to next time period.

d) For each existing class check,

   i. If $n \geq 8$ then are number of new links going to make $n > 8$?
      If true, then start new subnetwork as in step b.
      If false, finish subnetwork as in step b.

   ii. If $n \geq 8$ then,
      start new subnetwork as in step b.

e) Repeat c, d until end of data.

This recursive procedure is readily programmed in Pascal 6000 using the magnitude string obtained from the topologic vector in Section 4.2.2.

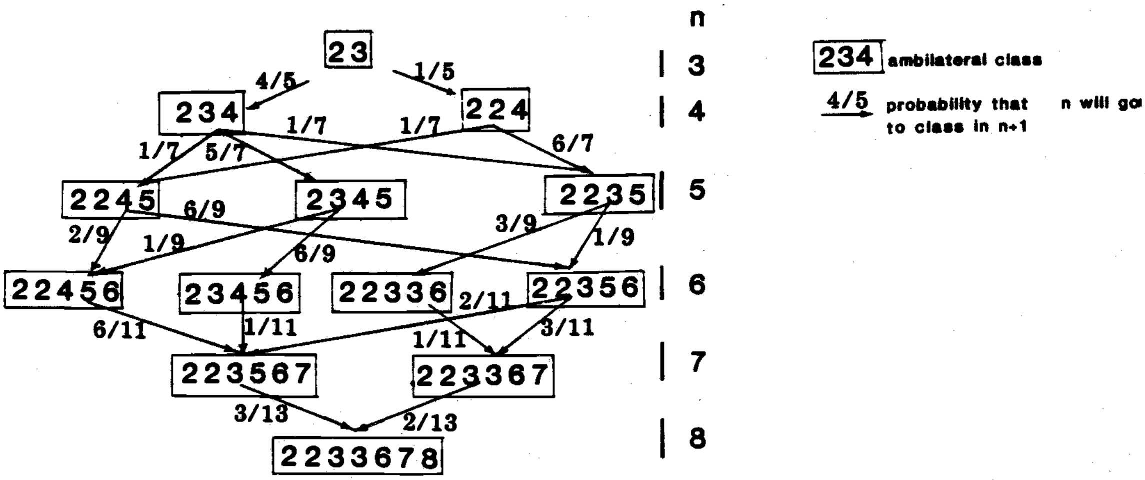
The random model assumes that the probability of occurrence of all TDCN in any ambilateral class of a given n are equal, the probability being a function of the number of TDCN per ambilateral class (Smart 1969). The "growth up" model is truly random because it assumes that all links are equally subject to new growth. Demonstrative probabilities for the growth-up model are given in Figure 4.3. Probabilities for the occurrence of any one ambilateral class of a given n reflect the distribution of TDCN to each class, hence

$$P(a;n) = \frac{N(a)}{N(n)} \qquad 4.7$$

Comparison of observed and expected frequencies is made using the χ^2 statistic. Between time-period and between basin comparisons are made using contingency tables as described in Section 4.5.1.

p(2233678) = 16/413 = 0.0387

which schematically is



if p(23 → 2245) = p(23 → 234 → 2245) + p(23 → 224 → 2245)

= (4/5 x 1/7) + (1/5 x 1/7)

= 2/14 = 1/7 = 0.1429

which may be calculated using the number of TDCN in 2245 with respect to all TDCN (n = 5)

it can be seen that the same applies for p(23 → 2233678)

but

p(22456) = 4/42 = 0.0952 (= p(23 → 22456))

yet p(234 → 22456) = p(234 → 2345 → 22456) + p(234 → 2245 → 22456)

= (5/7 x 1/9) + (1/7 x 2/9)

= 0.1111

which is termed a "partial probability" because it only considers part of the entire set of TDCN at any one magnitude.

Figure 4.3 Probabilities of network growth by the random addition, growth-up model: an example

Grouped data are used where required to bring expected frequencies above 1.00.

Smart's "top down" method was developed for analysis of mature networks. It works downstream from fingertip tributaries, examining the ambilateral class at each downstream link. Obviously this differs from the "growth up" method (which assumes random addition to existing links) by only adding at the link in the most downstream position. The net result is that the growth path of any single ambilateral class has only one route (Appendix 1), and this is not similar to the multiple growth paths associated with the random addition model. It is argued that the probabilities associated with Smart's method are not those calculated through the ratio of TDCN in any class to the total TDCN of that magnitude, but rather related to the probability of occurrence of subnetwork magnitudes derived from Cayley's expression (Section 4.5.1). Given a network of magnitude n and a subnetwork of magnitude p, then the probability of a new ambilateral class, with the addition of a new subnetwork of magnitude q, is

$$qi = \frac{\text{(Cayley probability of q in n) (2n-1)-(\# of subnetworks in p of q)}}{\text{(2n-1)}}$$

for each qi, q = 1 to p

then

$$\text{probability } qi = qi \quad \left(\sum_{i=1}^{p} qi\right)$$

Smart's method is employed here so that comparisons can be made between his results and those obtained herein. Probabilities of "top down" classes are derived from the random model method, not that just proposed.

4.5.3 <u>Path Properties</u>

Path properties are not tested for topologic randomness.

Comparisons are made of path properties for an alternative examination of organization in subnetworks of like magnitude, using the χ^2 statistic in an evaluation of similitude between subnetworks. The null hypothesis is: are the path properties of basin r similar to other basins?

Basins with similar path properties might be expected to have similar hydrologic responses. A positive test of similitude within a basin type would suggest that all basins of this type can be grouped together for hydrologic analysis.

4.6 Analytical Techniques: Network Growth

Network growth is examined from both topologic and growth-type approaches. In the topologic approach, the random network model is used. In the growth-type approach the basis for study is the mode of growth which occurs in the network.

4.6.1 Topologic Growth

It can be shown that the probability that any TDCN drawn at random from the population N of a network of size n occurring in a given ambilateral class is:

$$p(\mathrm{TDCN};N;n) = \frac{\#\mathrm{TDCN\ in\ ambilateral\ class}}{\mathrm{total}\ N\ \mathrm{for}\ n} \qquad \text{(Smart 1969)}$$

If a specific ambilateral class is observed, the probability that it will produce a specific ambilateral class of the next highest magnitude is related to the link number, 2n-1. This is demonstrated graphically in Figure 4.3. The growth of class (23) where n=3 has two options, to class 3 or class 2. There is no simple method for calculating this probability and it is best obtained by graphical means. This type of growth is termed the "random addition" model by this author.

In the random addition model, any link in a network of magnitude n is equally subject to growth by a single additional link to produce a network, n+1. Thus the probability of a class A being produced from class A is the number of links on which growth will lead to A divided by 2n-1.

By using the "growth up" method for obtaining ambilateral classes and the random addition model of growth, χ^2 statistics can be used to compare observed and expected values for each timeperiod and for each basin.

Where possible all growth paths are traced. The distribution of these paths should be random in Shreve's model. Once again χ^2 statistics compare observed and expected values.

4.6.2 Growth-type Approach

The analysis of the growth-type involves the use of the link code files for topologic growth. In a random model all growth types would be equally probable. Thus, in the observed growth, cases of multiple link addition would be treated as a different form of single-link addition, but would not be dependent on differences in the number of links added ($\mu>3$).

Hence, a probability contingency table is used based on Figures 4.1 and 4.1.

link probability		topologic growth
p(je;n)	=	n/3(2n-1)
p(ji;n)	=	n-1/3(2n-1)

This table should be compared with the single-link growth event probability (Table 4.3), because the probabilities of growth differ in each model.

Distributions of observed growth type versus expected growth type may be compared using the χ^2 statistic.

Growth-type examines:

a) The distribution of growth with respect to the magnitude of the affected link.

b) The distribution of growth with respect to time.

c) The distribution of growth by basin type.

d) The amount of growth as a function of time.

All multiple-growth of $\mu \leq 3$ is predictable and thus can be decomposed into ideal growth types.

4.7 Summary of Methodology

The methods used in this research fall into three groups: data collection, secondary data extraction, and analytical techniques. Data collection involved both field survey and air photo-interpretation. Secondary data extraction garnered the topologic and geometric base from which all other topologic variables and geometric parameters may be calculated.

Analytical techniques make use of the non-parametric statistics of the random model of Shreve (1966) in order to compare observed and expected distributions of topologic and geometric properties. Data are examined for both spatial and temporal similarities. Analysis of variance is utilized to compare the populations of system magnitudes. Network growth is assessed in terms of the amount of growth over time and space by analysis of variance, and in terms of location of new growth by link magnitude of affected links using the random addition model and χ^2 statistics.

CHAPTER 5

Characteristic Geomorphology of the Study Area

> Nunc naturalem causum quoerimus et assiduam, non rarum et fortuitum.
>
> Seneca

5.1 General Study Area Information

The 91 study networks contained a total of 8,121 links by the final observation period. Of these links 4,106 were exterior and 4,015 were interior. This sample is approximately 90% of the size of that used by Smart (1978). However, the range of magnitudes is greater than in Smart's study, being 10 to 292, and the number of basins studied, 91, is three times as many.

Network magnitudes for each timeperiod are listed in Table 5.1. The number of basins that experienced topologic change between each observation set is recorded in Table 5.2, as is the number of basins which exhibited any form of network at that time period.

Not all basins experienced growth at all times and many basins did not possess a surface network until some period after the start of observation. This late start may be attributable to the formation of channels via the collapse of pipes. Basins which exhibited piping phenomena during the field survey are indicated in Table 5.3. The importance of piping on the subsequent development of network topology is discussed in Section 6.

During the study period several of the drainage basins which existed as separate entities were captured by larger basins. Over the winter of 1980-1981 the four drainage basins which now comprise basin 29, merged, a result of capture by subsurface piping. Interpretation of thermal infrared imagery flown by the Oregon Army

Table 5.1 Network magnitudes through time for each network, and grouped by basin type

Basin Type Ta

basin \ period	1	2	3	4	5	6	7	8	9	10	11
1	2	8	8	13	17	28	29	29	29	29	29
2	-	-	-	-	-	-	-	-	1	10	30
3	-	-	-	-	-	-	-	-	4	12	34
80	7	13	16	16	16	22	22	26	32	38	59
81	6	9	9	21	24	48	54	81	140	192	277
82	2	12	14	28	28	42	42	65	80	88	143
83	12	26	30	37	37	50	50	62	80	101	110
84	1	6	6	14	14	27	27	32	34	34	42
85	-	2	4	8	8	14	14	22	22	22	23
86	-	-	-	-	-	-	-	2	8	8	24
87	-	1	1	4	4	6	6	6	6	6	13
88	-	-	-	-	-	1	2	4	4	8	12
89	-	1	2	2	2	4	4	6	6	6	11
90	-	1	1	1	1	4	4	8	8	8	12
91	-	2	8	8	8	12	12	15	22	26	26

Basin Type Tb

basin \ period	1	2	3	4	5	6	7	8	9	10	11
4	-	4	8	16	16	23	23	49	49	49	49
5	3	7	14	20	20	28	32	40	40	40	40
6	-	2	4	14	16	28	28	28	45	58	64
7	-	2	2	8	8	14	14	17	34	56	78
8	4	8	8	9	12	26	26	34	34	41	47
9	2	4	4	9	9	20	20	30	33	36	36
10	1	1	1	2	4	4	4	4	8	12	12
11	1	2	4	6	8	9	12	12	17	17	17
12	1	2	2	6	6	12	12	12	12	12	16
13	1	2	2	8	8	8	8	13	16	16	16

Basin Type Tc

basin \ period	1	2	3	4	5	6	7	8	9	10	11
55	-	-	-	-	-	-	1	4	10	19	59
56	-	4	8	13	13	18	18	18	18	36	82
57	-	-	-	-	-	2	2	2	4	9	10
58	1	6	12	14	14	17	17	20	22	22	24
59	-	8	10	10	10	10	10	12	15	26	37

Table 5.1 Network magnitudes, cont'd.

Basin Type Sa

period basin	1	2	3	4	5	6	7	8	9	10	11
14	-	-	-	5	5	12	12	14	18	21	23
15	2	6	14	25	25	40	40	46	67	112	184
19	1	4	4	4	4	4	4	4	6	8	22
20	1	1	1	1	1	5	5	5	5	5	16
21	1	1	1	4	4	6	6	6	6	6	7
73	2	12	12	25	25	34	34	40	46	56	86
74	1	4	8	27	32	44	44	60	71	92	145
75	-	2	8	14	14	14	14	14	18	18	44
76	1	1	1	6	8	9	9	9	14	14	29
77	6	10	18	18	18	18	18	18	18	27	28
78	1	9	14	14	14	14	14	14	14	14	14

Basin Type TIc

period basin	1	2	3	4	5	6	7	8	9	10	11
16	1	10	10	22	24	31	31	31	34	42	53
17	1	4	4	14	14	24	24	24	26	26	34
18	1	4	4	6	6	7	12	14	18	24	44
46	4	8	16	22	22	43	43	52	56	65	79
51	2	6	12	17	17	17	17	17	24	41	112
66	-	-	-	-	-	-	-	-	1	4	16

Basin Type TId

period basin	1	2	3	4	5	6	7	8	9	10	11
40	4	6	10	10	10	10	10	10	10	10	21
41	1	6	9	10	10	10	10	10	10	10	10
42	1	4	4	6	6	6	7	10	10	10	10
43	1	1	1	6	6	10	10	10	10	10	10
44	1	4	6	8	10	10	10	10	10	10	10
45	1	4	4	9	10	11	11	11	11	11	11
52	-	4	8	13	14	14	14	14	14	14	14
53	2	8	10	10	12	14	15	15	15	15	15

Basin Type Sc

period basin	1	2	3	4	5	6	7	8	9	10	11
79	17	38	44	63	68	108	115	130	163	198	230

Table 5.1 Network magnitudes, cont'd.

Basin Type Ic

period basin	1	2	3	4	5	6	7	8	9	10	11
22	2	4	4	4	4	9	9	9	9	14	22
23	1	1	1	4	4	8	8	8	8	8	10
24	1	5	5	8	8	13	13	13	13	13	16
25	2	4	4	4	4	4	4	10	10	10	12
26	3	6	6	6	6	6	6	6	6	6	10
27	1	1	1	1	1	2	4	6	6	13	22
28	1	1	1	1	2	6	11	14	14	28	71
29	1	4	7	16	19	28	31	52	85	149	292
38	-	4	10	21	21	21	21	22	24	26	26
47	-	1	1	4	6	6	6	6	6	6	20
48	1	4	4	4	4	6	6	6	6	9	11
54	-	4	12	15	15	52	52	52	74	128	278
60	1	1	1	8	13	28	28	28	28	44	101
65	1	1	2	6	6	6	6	14	14	34	34
67	1	4	4	8	8	12	12	12	12	12	14
68	1	1	2	6	6	12	12	16	16	18	26
69	1	4	6	9	12	14	14	16	18	33	61
70	1	1	1	3	8	8	8	10	10	19	42
71	1	1	1	8	14	14	14	18	21	24	45
72	1	4	4	7	7	7	7	8	8	10	12

Basin Type Id

period basin	1	2	3	4	5	6	7	8	9	10	11
30	1	3	8	10	10	10	10	10	10	10	10
31	1	1	2	2	2	4	4	6	12	16	20
32	1	4	8	10	10	10	10	10	10	10	10
33	2	6	9	9	10	10	10	10	10	11	11
34	-	4	4	6	6	6	6	6	6	6	10
35	8	14	19	32	34	36	36	42	50	51	51
37	-	1	1	6	6	6	6	6	6	8	10
38	-	1	2	5	6	6	6	6	6	8	10
39	-	4	4	4	4	4	4	4	5	5	11
49	-	1	1	1	8	12	12	12	12	12	13
50	1	1	1	1	1	1	1	1	2	5	10
61	1	1	1	1	1	1	1	1	3	4	10
62	1	1	1	1	1	1	1	1	1	4	14
63	1	1	1	1	3	4	4	4	4	4	11
64	1	1	1	1	1	4	4	11	15	24	31

Table 5.2 Number of basins participating in growth at any given time period, and the number of basins with networks in that time period

time period	basins with growth	extant networks
1	64	64
2	66	84
3	29	84
4	55	84
5	16	84
6	55	86
7	9	87
8	40	88
9	39	91
10	48	91
11	60	91

National Guard during the fall of 1980 indicated that there was a subsurface connection beneath the divides. The three captured basins were at a higher elevation than the fourth, and their accumulated runoff was not being stored on the surface. An obvious explanation is that this runoff was entering the fourth basin through subsurface flows. A similar situation occurred in what now is considered as basin 15, although only two initial basins existed in this case.

Fortunately for this study the four captured basins did not develop channel networks during their independence. However, the topological analyses which follow accommodate this change in status in order to examine any influence this may have had on the subnetwork development of these sub-basins.

Channel morphology was studied during the field research phase and data on link length, width, depth and bank slope were obtained, as well as estimates of channel roughness. Also alluvial fan deposits were examined for particle-size distributions. As would be expected, the alluvial deposits were generally finer than the source materials. For channels cut in type a or d materials (predominantly the debris avalanche units), alluvial deposits had a d_{50} of $+2.43\ \phi$. The U.S. Army Corps of Engineers (Jim Graham, pers. comm. 1984) indicated a d_{50} of $-0.99\ \phi$, with $\sigma = 0.07$, for the upper debris avalanche.

Lag deposits on the channel bed were much finer than those sampled in the main stem of the North Fork Toutle River below the Pumice Pond ($d_{50} = -2.76\ \phi$), but not significantly coarser than the source material; the lag deposits had a $d_{50} = -1.05\ \phi$, $\sigma = 0.11$.

In contrast, alluvium derived from the pyroclastic flow deposits is much coarser with a d_{50} of $+1.82\ \phi$, $\sigma = 0.12$, this distribution resulting from the lower densities of the pyroclastic materials enabling transport of material with larger diameter. Source materials for these pyroclastic deposits are generally much finer than those of the debris avalanche, with a $d_{50} = 2.55\ \phi\ \sigma = 0.18$.

Stream competence, in the downstream sections, was fairly high and able to transport considerable volumes of sediment. No data are available on sediment concentrations from these streams, but a single alluvial bed in a fan developed at the outlet of basin 29 was measured with a mean thickness of 0.21m ($\sigma = 0.53$) and an estimated volume of 1,750m^3, based on field survey. Given a channel length of 15 km (Table 5.3), this reduces to a channel erosion of 0.12m^3 per meter of channel length. This calculation assumes negligible hillslope contribution, and that the alluvial bed represented deposition from a single storm event.

Morphometric data gathered on channel shape indicated a major difference between those channels developed directly into debris avalanche material and those developed into pyroclastic flow material. Channels in the former had an ellipsoidal shape and a high width-to-depth ratio (10-15:1), and the banks were concave with low slopes. Depth was much greater in the pyroclastic flow channels, and increased more rapidly downstream than did width. Width-to-depth ratios for magnitude 2 links in pyroclastic flow deposits were in the range 1-1.4:1; for magnitude 20 links this ratio had the proportions 0.4-0.6:1. Undercutting of the near vertical banks constitutes a major sediment source for these streams. Banks at the outlets of basins 15, 29 and 74 were greater than 15m high, but the width did not exceed 3m.

Such obvious channel morphologic differences might be construed as an indication of geologic control on basin hydrology and hence the development of channel networks. Evaluation of this deduction is beyond the scope of this research, because insufficient data are available to perform critical analyses. The question should not be ignored, and forms a useful hypothesis for future research.

5.2 Properties of Individual Drainage Basins

From Table 5.3 it can be seen that drainage basin properties cover a wide range of values. This is a favorable condition for analytical work which purports to test general theories and to critically examine concepts, provided the sample size for the study is large enough. For parametric statistical analysis sample sizes should not be less than five, but for non-parametric statistics samples to a size of one are acceptable (Cochran 1954). The basin type Sa has only one member, and this has led to improvization in the analysis of variance; subnetworks within the basin are considered as individual samples because at timeperiod 1 a basic drainage network was established to which only new links were added, not additional length.

It is clear that not all the possible diameters or external path lengths have been included in the sample. To do so would require an unmanageable data base and would involve the pooling of data gathered from many study areas. It is considered that the precedent set by previous studies of channel topology (Shreve 1967, Smart 1978, etc.) is sufficient to warrant the use of these basins.

Geometric properties sampled offer considerable variation in the range of values obtained. Both drainage area and drainage density are markedly different from those presented by Smart (1978) and

Table 5.3 Some morphometric properties of the study basins

Legend

Basin Type

Geology

a - slumped Coldwater Ridge Unit with thin pyroclastic flow

b - Coldwater Ridge Unit plus overburden of deep pyroclastic flows (>3m)

c - Coldwater Ridge Unit, phreatic explosion pits and shallow pyroclastic flow (<3m) except in pits

d - Hummocky Coldwater Ridge Unit

Drainage

T - always linked to North Fork Toutle River System

TI - initially internal, especially to Pumice Pond, but since March 19, 1982 draining to North Fork Toutle River

I - internal drainage, mainly to phreatic explosion pits

S - drainage to Spirit Lake

Piping

Y - yes, piping strongly developed over 30% of system

P - present, but mainly manifested in headwater tributaries

N - no piping detected

n	= magnitude at observation time 11
d	= diameter
Pe	= exterior path length
TS	= number of TS links
A	= basin area (km^2)
L	= total geometric length (km)
$\bar{l}e$	= mean exterior geometric link length (m)
D	= drainage density (km^{-1})
LD	= link density (km^{-2})
slope	= mean slope of main stem
β_T	= topologic shape = $d^2/2n-1$
Ω	= Strahler order

Table 5.3 Some morphometric properties of study basins, cont'd.

Network No.	Basin Type	Piping	n	d	Pe	#TS links	A (km^2)	L (km)	$\bar{l}e$ (m)	D (km^{-1})	link density (km^{-2})	slope %	[illegible]	
1	Ta	N	29	16	147	10	0.11	6.79	2.58	61.73	263	11	4.49	3
2	Ta	N	30	16	208	18	0.09	3.84	2.75	42.67	333	13	4.34	3
3	Ta	N	34	17	283	11	0.07	3.46	1.41	49.43	485	11	8.50	3
4	Tb	N	49	11	588	16	0.20	8.29	3.85	41.45	245	8	1.25	4
5	Tb	N	40	15	463	19	0.07	5.45	2.53	77.86	571	7	2.85	3
6	Tb	N	64	18	943	31	0.21	12.33	3.71	58.71	304	10	2.55	5
7	Tb	N	78	28	1120	14	0.43	13.81	2.89	32.12	181	9	5.06	4
8	Tb	N	47	13	523	19	0.50	12.91	9.37	25.8	94	6	1.82	4
9	Tb	N	36	14	374	21	0.37	14.43	6.85	39.00	97	5	2.76	3
10	Tb	N	12	9	71	5	0.22	4.68	2.36	21.27	54	11	3.52	3
11	Tb	N	17	13	146	7	0.26	5.52	2.51	21.23	65	4	5.12	3
12	Tb	N	16	12	113	0	0.07	3.22	1.47	46.00	228	10	4.65	3
13	Tb	N	16	11	109	0	0.08	3.52	2.31	44.00	200	8	3.90	3
14	Sc	N	23	10	212	4	0.24	4.97	0.04	20.71	95	16	2.22	3
15	Sc	N	184	42	5537	65	0.16	12.41	0.33	77.56	1150	26	4.81	5
16	TIc	P	53	22	647	13	0.15	5.39	0.41	35.93	353	25	4.61	3
17	TIc	P	34	25	362	11	0.07	2.15	0.46	30.71	485	16	9.33	3
18	TIc	N	44	26	575	25	0.09	3.36	0.59	37.33	489	22	7.77	3
19	Sc	P	22	14	193	9	0.03	1.10	0.37	55.00	733	22	4.56	3
20	Sc	P	27	10	146	8	0.01	0.77	0.26	77.00	270	26	1.89	3
21	Sc	P	47	16	536	18	0.03	1.71	0.49	57.00	233	23	2.75	4
22	Ic	Y	22	17	105	6	0.06	1.61	0.28	26.83	387	17	6.72	3
23	Ic	P	10	9	71	9	0.01	0.47	0.71	47.00	1000	11	4.26	2
24	Ic	Y	16	11	87	2	0.02	0.85	0.53	42.50	800	13	3.90	3
25	Ic	Y	25	15	227	8	0.04	1.30	0.22	32.5	625	13	4.59	3
26	Ic	P	10	8	65	8	0.02	0.62	0.35	31.00	500	14	3.37	3
27	Ic	P	22	12	215	10	0.02	1.61	0.81	80.50	1100	6	3.35	3
28	Ic	P	71	32	1046	30	0.06	4.24	0.47	70.67	1183	8	7.26	4
29	Ic	Y	292	29	7165	92	0.27	18.04	0.38	66.81	1081	12	2.88	7
30	Id	N	10	9	73	9	0.02	0.27	0.21	13.5	500	16	4.26	3
31	Id	N	20	15	142	14	0.01	0.36	0.37	36.0	2000	18	5.77	3
32	Id	N	10	9	73	9	0.01	0.34	0.56	34.00	1000	15	4.26	2
33	Id	N	11	10	71	10	0.01	0.24	0.47	24.00	1100	16	4.76	2
34	Id	N	10	9	69	9	0.02	0.91	0.38	45.50	500	14	4.26	2
35	Id	N	51	28	764	19	0.12	4.62	0.51	38.5	425	11	7.76	3
36	Ic	P	26	12	136	14	0.06	2.55	0.72	42.5	433	17	2.82	3
37	Id	N	10	8	71	8	0.01	0.42	0.43	42.0	1000	12	3.37	3
38	Id	N	11	9	75	9	0.01	0.41	0.26	41.0	1100	14	3.86	3
39	Id	N	10	9	71	9	0.01	0.29	0.43	29.0	1000	13	4.26	2
40	TId	N	21	15	146	16	0.03	0.51	0.54	15.03	700	13	4.27	3
41	TId	N	10	9	72	9	0.01	0.19	0.37	19.00	1000	16	4.26	2
42	TId	N	12	10	73	10	0.02	0.64	0.49	32.00	600	9	4.35	3
43	TId	N	10	9	71	9	0.01	0.79	0.45	79.00	1000	11	4.26	2
44	TId	N	10	9	69	9	0.01	0.32	0.54	32.00	1000	13	4.26	2
45	TId	P	11	9	75	9	0.01	0.25	0.37	25.00	1100	17	3.86	3
46	TIc	P	79	34	1365	33	0.05	0.15	0.36	3.00	1580	5	7.36	4
47	Ic	P	20	11	122	11	0.01	0.25	0.28	25.00	2000	8	3.36	3
48	Ic	P	11	10	71	10	0.02	0.49	0.39	41.00	550	6	4.76	2
49	Id	N	13	10	79	10	0.01	0.62	0.45	62.00	1800	10	4.00	3
50	Id	N	10	8	71	8	0.04	0.61	0.46	15.25	250	11	3.37	3
51	TIc	N	112	49	2647	49	0.11	5.19	0.29	51.9	1018	14	10.77	5
52	TId	N	10	9	73	9	0.01	0.71	0.51	71.0	1000	17	4.26	2
53	TId	N	15	13	109	11	0.02	0.82	0.47	41.00	750	10	5.83	3
54	Ic	P	278	62	8699	121	0.18	10.9	0.63	60.56	1544	16	6.93	6
55	Tc	P	59	26	653	17	0.04	2.39	0.34	59.75	1475	8	5.78	3
56	Tc	P	82	25	1437	32	0.05	4.14	0.76	82.8	1640	5	3.88	4
57	Tc	Y	10	8	69	8	0.02	0.63	0.73	31.50	500	6	3.37	3
58	Tc	Y	24	14	264	5	0.03	2.18	0.81	72.67	800	11	4.00	3
59	Tc	P	37	18	421	16	0.06	2.67	0.59	44.5	617	10	4.44	3
60	Ic	N	101	23	2528	28	0.16	0.25	0.43	39.08	631	14	2.63	4
61	Id	N	10	8	70	8	0.01	0.34	0.35	34.00	1000	19	3.37	3
62	Id	N	14	11	96	10	0.01	0.27	0.26	27.00	1400	13	4.17	3
63	Id	N	11	9	69	11	0.01	0.20	0.36	20.00	1100	10	3.86	3
64	Id	N	21	17	137	15	0.01	0.19	0.29	19.00	2100	15	7.05	3
65	Ic	Y	34	18	191	7	0.11	2.19	0.21	19.91	309	9	4.84	3
66	TIc	P	16	12	126	9	0.04	0.84	0.35	21.00	400	8	4.65	3
67	Ic	Y	121	12	65	12	0.02	1.56	0.47	78.00	700	6	5.33	3
68	Ic	Y	26	16	156	8	0.03	1.75	0.44	58.33	867	5	5.02	3
69	Ic	Y	61	23	672	22	0.12	4.39	0.53	36.58	508	6	4.37	4
70	Ic	Y	42	16	511	19	0.07	3.69	0.48	52.71	600	6	3.16	
71	Ic	Y	45	21	546	10	0.08	3.33	0.59	41.63	563	8	4.96	[illegible]
72	Ic	Y	12	10	83	8	0.03	1.10	0.54	36.67	400	9	4.35	[illegible]
73	Sc	Y	86	29	1183	25	0.09	0.99	0.38	11.00	956	8	4.92	4
74	Sc	Y	145	57	3504	57	0.15	9.36	0.41	29.07	967	11	11.24	5
75	Sc	P	44	14	523	6	0.03	0.74	0.37	24.67	1467	13	2.25	[illegible]
76	Sc	P	29	16	157	12	0.06	2.29	0.36	37.33	483	14	4.49	[illegible]
77	Sc	N	28	14	193	10	0.04	1.55	0.42	38.75	700	14	3.56	[illegible]
78	Sc	N	14	10	74	10	0.05	2.42	0.41	48.40	280	17	[illegible]	
79	Sa	P	230	66	6528	106	0.55	32.52	0.31	59.13	418	10	9.49	5
80	Ta	N	59	20	647	6	0.31	4.83	0.86	15.58	190	9	[illegible]	[illegible]
81	Ta	Y	277	68	8743	153	0.26	24.01	0.85	92.35	1065	14	8.36	6
82	Ta	Y	143	64	3407	82	0.19	16.08	0.84	89.33	752	11	14.57	4
83	Ta	P	110	27	1989	31	0.23	14.59	1.27	63.43	478	5	3.33	4
84	Ta	Y	42	25	504	17	0.07	3.77	0.79	53.86	600	6	7.55	[illegible]
85	Ta	P	23	12	162	10	0.05	2.73	1.32	54.60	460	16	[illegible]	[illegible]
86	Ta	P	24	20	216	12	0.01	1.32	0.84	22.00	400	8	8.51	[illegible]
87	Ta	P	13	11	75	9	0.07	1.41	0.97	20.14	185	4	4.85	[illegible]
88	Ta	P	12	10	81	10	0.01	0.50	1.19	50.00	1200	[illegible]	4.35	
89	Ta	P	11	9	71	9	0.01	0.47	0.85	47.00	1100	6	3.86	[illegible]
90	Ta	P	12	10	75	10	0.02	1.34	1.43	67.00	600	9	4.35	[illegible]
91	Ta	P	26	14	150	13	0.08	3.00	0.87	37.50	325	7	3.84	[illegible]

Krumbein and Shreve (1970). It may be that the small drainage areas and the high drainage densities cannot be compared with other data sets. Such incompatibility would render the random model invalid. It is assumed for the sake of this study that geometric scale factors do not affect the premises of the random model. This assumption has not been tested elsewhere in terms of network topology and growth modes, but scale translation problems have been widely reported in other hydrologic literature (c.f. Jarvis 1976b, Kirshen and Bras 1983, Gupta and Waymire 1983).

In general the drainage densities reported here are a factor of ten greater than those studied by Smart (1978) but are similar to those reported by Schumm (1956) for industrial badlands. Exterior link lengths are one hundred times smaller than those of Smart, comparable with Schumm's data, and 5-10 times smaller than that of Mock (1971).

It may be that the differences between Smart's data and the present research result from the contrasting timescales involved in the evolution of the two study areas. For Smart's study area in Kentucky, hillslopes and channel networks co-evolved, with fluvial processes modifying both landforms. At Mount St. Helens, the topography of the basins has been pre-determined with respect to the development of a channel network.

Mean basin slope as measured along the main stem axis is also considerably steeper than found in larger and more "mature" drainage basins. This slope factor has already been reported by Parker (1977) to be of significance in the formation of scale-model drainage networks. In the initial stages of network growth, Parker reported that networks with a high basin slope (>3.2%) produced a more elongated network than those created using a 0.75% slope. As all the present study basins exceed the experimental slopes used by Parker, it may be that all the networks will be elongated. For Parker's study, the slope was uniform across the experimental plot: natural drainage basins, including the Mount St. Helens subset, display decreasing slope with increased proximity to the outlet. Direct comparison with Parker's data should be considered in this light.

Topologic and geometric shape factors offer further information which may help in the analysis of topologic and growth trends. With both parameters larger values indicate greater elongation of the network and the basin. The two factors cannot be compared directly, but should be considered through analysis of population statistics, which are presented in the following section.

Finally the basin order is given in Table 5.3. The maximum order ($\Omega = 7$) for basin 29 reflects the high degree of compactness of the network. Very rarely does one encounter networks of order equal to 7 and magnitude as low as 292. Note also the wide range of magnitudes, diameters and exterior path lengths associated with the subset of networks of order 3.

5.3 Data Comparisons of Drainage Basin Character

Although the individual basins exhibit considerable variety (Table 5.3), it may be possible to reduce that variety by using summarizing statistics and data grouping. The variety for the complete study area is assessed by the mean and standard deviation in Table 5.4.

Obviously it is not possible to draw any inferences about magnitude, diameter, and exterior path length from these values as these are dependent on basin area, and basin type. Drainage density

Table 5.4 Analysis of variance of fire basin characteristics by basin type

Te Exterior link length

	$\bar{x}$	σ	$\Sigma\bar{x}$	ANOVA of 5 basin characteristics by basin type			
Ta	1.19	.66	17.82	97.12	7	13.87	18.4
Tb	3.79	2.45	37.85	61.08	81	0.75	
Tc	0.75	0.1	3.73	158.2	88		
Sa	0.31	--	--				
Sc	0.4	0.1	4.44				
TIc	0.41	0.11	2.46				
TId	0.47	0.07	3.74				
Ic	0.49	0.15	9.30				
Id	0.39	0.10	5.79				

$F_{tab(0.05,7,81)} = 2.12$

LSD = 0.76 (0.05)

Tb ≢ all the rest
Ta ≢ Sa, Sc, TIc, Id
all the rest cannot be distinguished from each other

D Drainage density

Ta	51.1	22.4	766.58	5570.14	7	788.59	2.17
Tb	40.7	17.6	407.44	29411.58	81	363.11	
Tc	58.2	20.7	291.22	34931.72	88		
Sa	59.13	--	--				
Sc	43.32	22.05	477.09				
TIc	29.9	16.6	178.8				
TId	39.2	23.6	314.03				
Ic	47.6	17.3	904.78				
Id	32.09	12.9	481.35				

$F_{tab(0.05,7,81)} = 2.12$

LSD = 16.47 (0.05)

Sa ≢ Tb, TIc, TId, Id
Ta ≢ TIc, Id
Tc ≢ Tb. TIc, TId, Id
TIc ≢ Ic, Sa, Tc, Ta
Sc ≡ Sa, Tc, Tb, Ta, TIc, TId, Ic, Id

LD Link density

Ta	562	329	8436	5379596.66	7	768513.8	4.545
Tb	203.9	153.8	2039	13866745.8	81	169106.7	
Tc	1006	517.6	5032	19246342.46	88		
Sa	418	--	--				
Sc	659.8	445	7258				
TIc	720.8	484.6	4325.0				
TId	893.8	182.1	7150				
Ic	730	449.3	14612				
Id	1051	524	15775				

$F_{tab(0.05,7,81)} = 2.12$

LSD = 156.96 (0.05)

Id ≡ Tc, Ic ≡ TIc, Sc Sa ≡ Ta rest indistinguishable
Sc ≡ Ic, TIc Tc ≡ TId
Tb ≢ anything

NB. The equivalency sign is used here to denote that the two populations cannot be distinguished from one another on the basis of ANOVA procedures.

slope

	$\bar{x}$	σ	Σx	ANOVA of 5 basin characteristics by basin type			
Ta	8.6	3.9	129	863.78	7	123.4	6.97
Tb	8.6	2.7	86	1451.8	81	17.71	
Tc	8	2.55	40	2315.6	88		
Sa	10	--	--				
Sc	17.3	6.1	190				
TIc	15.0	7.75	90				
TId	13.25	3.15	106				
Ic	10.2	4.02	204				
Id	14.07	2.55	211				

$F_{tab(0.05,7,81)} = 2.12$

LSD = 1.51 (0.05)

Sc ≡ TIc, Id not rest
TIc ≡ Id ≡ TId not rest
TId ≡ Ic ≡ Sa not rest
Sc ≡ Sa ≡ Tc ≡ Tb ≡ Ta not rest

β_T Topologic shape

Ta	5.84	3.06	87.6	488.27	7	81.38	4.72
Tb	3.35	1.34	33.48	1207.61	81	17.25	
Tc	4.29	0.91	21.47	169588	88		
Sa	9.49	--	--				
Sc	4.22	2.58	46.4				
TIc	7.42	2.47	44.49				
TId	4.44	0.56	40				
Ic	4.56	0.32	51.76				
Id	5.01	0.41	38.7				

$F_{tab(0.05,7,81)} = 2.12$

LSD = 1.51 (0.05)

Sa ≢ rest
TIc ≢ rest
Tb ≢ Ta, TIc, Sa, Id
Id ≡ Ta ≢ Tc, Sc, TIc, Sa
Id ≢ Sc, Tc
TId ≡ Ic ≡ Sc ≡ Tc

NB. Each ANOVA table has the form

Source of Variation	Degrees of Freedom	Mean Squares	
sum of squares between classes	r - 1	mean squares between treatments	Fischer's F
error within classes	$n_T - r$	error mean square	
total sum of squares	$n_T - 1$		

This format applies for each subsequent ANOVA table in this dissertation.

and link density show considerable spread about the mean, indicating that the conditions encountered do not represent a highly biased subset of reality, but rather a continuum of basin conditions.

So that basin characteristics could be compared by basin type, an analysis of variance was performed on the data available from Table 5.3. Of particular interest were the mean length of the exterior link, the drainage density and the link density. Slope was also subjected to this analysis.

The resultant analysis is somewhat confusing. No single basin type is consistently significantly different for all properties. This suggests two things. Firstly geologic influence plays no role in determining those properties, and secondly drainage type does not influence those properties. That geologic factors play no role in these geomorphic characteristics is important. Shreve's (1966) random topology model is highly dependent on freedom from geologic determinism. Several authors have shown that geologic influence plays a major role in subsequent channel topology (Smart 1967, Mock, 1971, Krumbein and Shreve 1970, Abrahams 1980a), with the networks exhibiting characteristics that reflect structural influences. This observation is by no means new. Geomorphology pioneers such as Gilbert and Davis noted such tendencies, and Strahler's (1952) and Melton's (1958) work on stream order gave quantitative assessments for geologic control.

At this point it is important to acknowledge the role of geology because comparison with the Random Network Model is dependent on the exclusion of geologic control. Geologic influence will be tested again in both Chapters 6 and 7, but this time within the structure of the model itself.

From Table 5.4 the basin type Tb (Toutle drainage with deep pyroclastics over Coldwater Unit) is clearly differentiable from all others in terms of its exterior link length. Further examination reveals that the geometric shape factor indicates a high degree of basin elongation for basins in this type, but that the topologic shape factor is the smallest of all basin types, although not significantly different from four other basin types. Confirmation of the conclusions that for Tb-type basins link lengths are significantly longer than elsewhere comes through a comparison of the drainage densities with the link density. Drainage density for Tb basins is not readily distinguished from other basins, but the link density is the smallest in the study.

One may conclude that watersheds of type Tb have a local uniqueness that can be attributed to geologic control, and basin elongation is the surface expression. Deep percolation of precipitation occurs as a result of the high porosity of the pyroclastic flows and tends to inhibit channelized flow. Where separate flow strata meet along a bounding plane, subsurface flow may be concentrated. Marginal bounding planes between two adjacent pyroclastic flows form the most likely site for channel initiation. The small number of marginal bounding planes would account for low link densities.

Type Tb basins are elongated as a result of the nature of deposition of pyroclastic flow sediments, and this in turn produces a low link density. Yet drainage density is indistinguishable from other basin types. Magnitude, diameter, exterior path and the number of Ts links show no such distinctions. The case for geologic influence is inconclusive at this stage of the analysis.

Topologic shape can be used to distinguish basin types Sa and TIc from all other basins. That both these basin types should exhibit topologic elongation is curious. If topologic elongation were the result of changes in base level then Sc and TId basins would also be similarly affected. A sharp break in slope occurs at the outlet of both Sc and TId basins, but not at the outlets of Sa and TIc basins and it may be this factor which has contributed to the differentiation. In Chapter 6 topologic elongation will be examined over time for all basin types, and this theory tested.

Basin types Ic, Sc and Tc cannot be distinguished from each other in terms of topologic shape and hence comprise a statistically similar group. Had type TIc been a part of this group then geologic control of topologic shape might have been invoked. But basin type TId is also contained in this group, and because this geologic type is grossly dissimilar from type c, one cannot support a geologic control argument.

The subject of topologic shape will be pursued again in Chapter 6 because it is necessary to delimit the influence of the change in drainage status and base level which occurred during 1982. Emphasis on topologic shape should not outweigh other considerations of the topology: diameter is important for topologic analysis, but is but one single factor and one which fails to highlight tributary organization.

Basin slope was found to have considerable variety within basin types and no geomorphic groupings could be distinguished. As indicated earlier, such a lack of identity is probably the result of the relatively steep slopes involved.

Only basin type Tb did not exhibit subsurface piping, because of the deep percolation into the thick pyroclastic flow deposits. None of the other basin types was internally consistent as regards the presence of piping. Thus it is impossible to statistically test the influence of piping on channel network development. Basin-by-basin comparison is fallacious if geologic or drainage control exists.

Where the contact between underlying debris avalanche materials and the overlying pyroclastic flow deposits was close to the surface (<2m) piping was well developed. Such thin pyroclastic flow deposits were most widespread in areas close to divides. Drainage densities in the headwater zones of these basins are significantly higher than either the overall basin drainage density or the mean study area drainage density. (Headwater DD = 89.47 km^{-1}, σ = 5.21, mean drainage density of basins with pipes = 46.35 km^{-1}, σ = 19.44, study area mean drainage density = 42.45 km^{-1}, σ = 18.74). The mean drainage density of basins without pipes, 38.68 km^{-1}, σ = 16.95, cannot be distinguished (t_{crit} = 1.217, t_{tab} = 1.987, at 95% limit) as a separate population.

Data are available for stream lengths, drainage densities and link densities for other areas of the North Fork Toutle River system (Parsons et al. 1984). For the debris avalanche area west of Jackson Lake, exterior link lengths had a mean value of 3.95m, and total drainage density was 0.33 km^{-1} in 1983. At the other extreme, channels on the mountain slope of Mount St. Helens averaged 1.6m for exterior link lengths, but drainage densities exceeded 80 km^{-1}.

This comparison indicates that the present study area lies within the bounds of the extremes observed in the Mount St. Helens devastated zone. Data from the blast-affected hillslopes outside the deposition zone of the debris avalanche are not utilized because the influence of pre-existing topography in this area makes comparison fallacious.

5.4 Summary of Basin Characteristics

Three main points have been considered:

1) The influence of geologic control on basin morphology.

2) The role of topologic shape as a basin characteristic.

3) The influence of piping on basin drainage densities.

Geologic influence is not conclusively proven. Tenuous influence is exhibited in type Tb basins, especially in terms of exterior link, but this may simply be a reflection of geometric basin shape, because drainage density is not distinctive.

Topologic shape is elongated for two basin types: Sa and TIc. Basins Ic, Sc, Tc and TId were statistically similar in terms of topologic shape. This finding, combined with the lack of distinction of basin type Tb, suggests lack of geologic control.

Subsurface piping may have increased headwater drainage densities. No distinctions could be made between the overall drainage densities of the three categories of piping.

The conclusions draw from these analyses have important bearing on the subsequent research because they allow the Random Topology model to be tested under the conditions attached to its implementation. Attention should be drawn to the heterogeneous nature of the basin morphological properties, but the lack of definitive geologic, piping or drainage type influence must not be taken as conclusive evidence of the validity of the Shreve's Random Model. It is the purpose of the analytical framework of Chapter 6 to work within the constraints of the Random Model of Channel Topology and to examine trends and tendencies that may arise using geomorphic principles.

CHAPTER 6

Topologic Properties of Study Networks

> We have no measure of the scale at which a particular process has most to contribute to the formation of a spatial pattern, and our notions regarding the scale problem remain intuitively rather than empirically based.
>
> D. Harvey (1969)

6.1 Introduction

Geomorphic theory which encompasses a random model approach has been viewed by Chorley and Kennedy (1971) as a first-order approximation of a system for which little is known about its development. Spatial forms are a posteriori expressions of the collective history of process, and the channel network is the product of many millenia throughout which process has operated. Autocorrelation between form factors and within process factors may be at such a level of complexity that it is impossible to unravel the key components.

The etymological root of "random" means "to run about;" stochastic is derived from the Greek "stokhos," a target for archery practice. A stochastic model with random elements is then a model which seeks a predictive target without a single, manifest direction.

Topologically random channel networks were recognized by Shreve (1966) to be a reflection of our inability to elucidate the pertinent factors which control network patterns.

> Though intuitively attractive this [topologically random] hypothesis is by no means self-evident, for the possibility exists that certain of the possible topologically distinct networks might be statistically promoted or inhibited, not by gross geologic controls, but by the subtle interaction of links in the network or as Playfair (1806) put it the 'nice adjustment,' mediated by the interdependence of slope and channel processes.

In the strictest mathematical sense, the only complete test of the random model is that which uniquely specifies all TDCN, and that can provide sufficiently large sample sizes from which to draw statistical inferences. Jarvis and Werrity (1975) point out that for n>6 this specification is operationally not feasible and aggregation of data must occur. It is not valid, however, to compare results that mix grouping methods, not to compare results base grouping on stream orders of grossly different magnitudes.

The methods utilized in the study seeks to conform to these data set constraints while at the same time examining the temporal and spatial exhibition of topological structure and continually testing the influence of geologic control and drainage outlet status.

In Section 1.5 it was stated that one of the working hypotheses was to examine the appropriateness of the random model of channel topology to the observations obtained at Mount St. Helens. This hypothesis is scrutinized in this chapter.

6.2 Tests of Random Topology Using Link Magnitude Distributions

The tests of random topology conducted here examine:

a) the concurrence between the observed and expected distributions of link magnitudes (Section 6.2.1)

b) the distribution of link magnitudes within time periods (Section 6.2.2) and comparisons of the between-time-period distribution of link magnitudes

c) the distribution of link magnitudes within basin types (Section 6.2.3) and comparisons of the between basin type distribution of link magnitudes

Recall that the distribution of link magnitudes can be derived from the expression

$$P(\mu;n) = \frac{1}{2n-1} \quad \binom{2\mu}{\mu} \quad \binom{2\,(n-\mu)}{n-\mu} \qquad \binom{2n}{n} \qquad \text{eqn 4.4}$$

and that occurrence is dependent on individual network magnitude.

Valid statistical technique would require large sample sizes for any network where n>6. Sample sizes created from this study are too small as they stand, but, following the example of Werner and Smart (1974) and Smart (1978) it is possible to use subnetwork data, on the assumption that a subnetwork is just a representative subset of the entire network. Implicit in this methodology is the concept that "individual channel networks in nature do not ordinarily exist independently but are portions of far larger networks that for practical purposes are essentially infinite" (Shreve 1967, p. 178).

6.2.1 Overall Magnitude Distribution

Ideally every single magnitude should be individually tested against the theoretical value, but, because that would involve testing 136 magnitudes and generating a total of 21,642 expected values, and also because the numbers of larger magnitudes are too small for realistic evaluation, this was not done. Rather, data for the first eight magnitudes were tested individually, and three grouped sets were created for larger magnitudes based on arbitrary partition of the range of sample magnitudes. The data set used for this evaluation was composed of all magnitudes for all time periods and all basins (Table 6.1). Under the random model premise, time-dependent observations are but subsets of the infinite network.

Observed and expected distributions are presented in Table 6.1 and χ^2 values are given. The hypothesis tested asked whether the

Table 6.1 Distribution of link magnitudes, summed over all timeperiods and all study basins

mag	obs	exp	mag	obs	exp	mag	obs	exp	mag	obs	exp
1	16394	16394	35	4	2.1	69	4	0.75	105	1	0.10
2	3458	3624	36	2	2.1	70	2	0.70	106	1	0.10
3	1639	1857	37	2	2.0	71	1	0.67	107	1	0.10
4	1058	1252	38	2	1.9	72	3	0.65	108	3	0.10
5	733	888	39	4	1.9	73	2	0.63	109	2	0.09
6	526	561	40	3	1.8	74	1	0.63	110	1	0.09
7	441	452	41	1	1.7	75	3	0.60	113	2	0.09
8	284	319	42	1	1.6	76	2	0.58	114	1	0.09
9	162	159	43	3	1.6	77	1	0.55	115	2	0.09
10	109	98	44	1	1.6	78	4	0.50	116	3	0.09
11	47	44	45	2	1.5	79	3	0.45	117	1	0.08
12	31	30	46	2	1.5	80	2	0.41	118	2	0.08
13	20	17	47	1	1.5	81	1	0.36	119	1	0.08
14	16	14	48	1	1.4	82	1	0.31	121	2	0.07
15	13	12	49	2	1.4	83	1	0.28	124	1	0.06
16	19	10	50	2	1.3	84	1	0.25	126	1	0.06
17	15	8	51	2	1.3	85	3	0.23	129	1	0.06
18	6	6.5	52	1	1.25	86	1	0.21	134	1	0.06
19	10	5.3	53	1	1.2	87	3	0.21	139	1	0.06
20	7	4.8	54	3	1.2	88	2	0.18	140	1	0.06
21	8	4.1	55	2	1.2	89	1	0.18	141	1	0.06
22	5	3.6	56	1	1.1	90	2	0.16	142	2	0.05
23	6	3.1	57	1	1.1	91	1	0.16	144	1	0.05
24	9	3.0	58	5	1.1	92	1	0.14	149	2	0.05
25	8	2.9	59	1	1.05	93	1	0.14	150	1	0.05
26	6	2.8	60	1	1.05	94	2	0.14	156	1	0.05
27	3	2.7	61	4	1.05	95	1	0.14	157	1	0.05
28	7	2.6	62	2	1.00	96	1	0.12	158	1	0.04
29	4	2.6	63	1	0.95	97	2	0.12	159	2	0.04
30	5	2.5	64	1	0.95	98	1	0.12	160	1	0.04
31	3	2.4	65	3	0.90	99	3	0.11			
32	6	2.3	66	3	0.90	100	1	0.11	all others	28	4.42
33	4	2.3	67	2	0.85	101	1	0.11			
34	2	2.3	68	1	0.80	104	2	0.11	total	25291	

χ^2 critical = 147.93 $\quad$ χ^2 $tab_{12df,0.05}$ = 21.34

random model is a suitable descriptor of the distribution of link magnitudes in the study area.

The overall distribution of magnitude 1 links exactly matched the theory. Magnitude 2, 3 and 4 links were significantly less frequent than would be expected, while magnitude 5 and 6 links were only different (and only marginally so) at the 0.01 level of significance. No cause for rejection of the hypothesis was given by magnitudes 7 and 8, but a marginal case existed for the group 9-20. Above magnitude 20 there were excessive numbers of links. These statistics are sufficient to reject the null hypothesis.

Attention should then be drawn to reasons for non-compliance with the random model. The results for magnitudes 2-4 suggest an excess of magnitude 1 links elsewhere in the system. From Mock's (1971) classification, these links are designated as TS links. Mock showed that the probability of occurrence of TS links in the infinite topologically random network can be calculated using

$$P(\mu_{TS}, n) = \frac{n}{2n-1} \; \frac{n-2}{2n-3}$$

from which it follows that

$$\lim_{n \to \infty} P(\mu_{TS}\ n) = \lim_{n \to \infty} \frac{n}{2n-1} \; \frac{n-2}{2n-3}$$

and

$$P(\mu_{TS}) = \lim_{n \to \infty} P(\mu_{TS}; n) = 0.25$$

which is equivalent to the probability of occurrence of S-type links.

A total of 16,394 exterior links formed the large network, of which 8,820 were S-type, and 7,574 were TS-type. A χ^2 critical value of 8.25 overturns the hypothesis, indicating further consideration.

If subnetworks of up to magnitude 3 are considered for all bifurcations where the downstream link magnitude is greater than 8, the observed 1927 exterior links involved by far exceed the expected number of 1024.6. Of these 1927 exterior links, 995 were TS-type, with 338 magnitude 2 subnetworks, and the remainder in third magnitude systems. Thus a total of 1,090 TS-type links were associated with links of magnitude greater than 8, leaving 836 S-type links. Given the equal probability of occurrence presented by Mock for S and TS-type links, a critical χ^2 value of 32.2 indicates a significant departure from the random assumptions.

Without further analysis it would be imprudent at this stage to declare the study networks non-random. Some considerable statistical assumptions were made in order to achieve a sufficiently large data base for this analysis. However, the rejection of the hypothesis suggests that some aspects of the model would require further investigation.

Badland drainage networks frequently exhibit a tendency for an excess of small subnetworks in the downstream portions of the network, as Schumm's (1956) data reveals. Magnitude distributions are next considered within time periods, then within basin types in order to seek out integrity of network composition without the infinite network assumption.

6.2.2 Magnitude Distribution Over Time

Topologic analysis of channel networks typically examines channels that have "maturity"--that is, have had a long history of stability or establishment. The random model, has been verified for this type of network (e.g. Smart 1976, 1969, Krumbein and Shreve 1970, Jarvis

1977, Flint and Proctor 1979). Temporal analysis of the stream net development has not previously been accomplished for topologic properties, and this introduces an element of introspection regarding the formulation of the random model.

Shreve (1966, 1967) made no mention of the influence of sequential temporal observations on the validity of the random model, and contemporary research has not yet questioned this aspect of the model. When first this author began in-depth analysis of channel network, the immediate reaction was to assume that the random model held in time as well as space. As this research proceeded, a hypothesis was formulated that assigned random topology only to the fully developed network. All intermediate stages were unknown, but considered to be "ordered" in some non-random fashion, along the lines of the space-filling concept of Woldenburg (1969), Flint (1980) and Abrahams (1984a), but were masked by the final stage of development in which system equilibrium was achieved by "infilling" of network topology.

Examination of channel networks over time is directed toward testing the consistency of application of the random model. In order that this be accomplished the distribution of magnitudes 2-8 was considered. The results are presented in Table 6.2 for subnetworks up to magnitude 8 for all timeperiods.

No consistent deviations from the random model over time are detected. Timeperiod 1 shows a surfeit of TS links, but this tendency observed at other times. In fact the analysis suggests a trend quite the opposite to that previously discussed, with the random model upheld for all time periods except the first and the last, both these showing an excess of small magnitude junctions with the main stem.

Table 6.2 Distribution of link magnitudes (μ) with respect to time

	timeperiod																					
	1		2		3		4		5		6		7		8		9		10		11	
μ	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
2	30	33	129	126*	150	142	214	217	98	96	312	317	80	80	333	346	422	434	783	781	1005*	1023
3	16	14	55	53	33	39	102	104	48	45	161	158	56	51	162	165	188*	201	295*	346	520	526
4	2	4	29	31	30	27	70	79	44	39	91	94	28	34	105	95	114	117	216*	235	326	314
5	5	4	24	22	22	21	45	43	19	26	76	69	22	23	80	81	98*	85	128	129	214	226
6	4	3	8	11	18	18	36	31	18	18	51	58	17	17	58	59	71	74	102	87	139	147
7	2	2	7	7	14	13	40	27	11	14	41	44	20	14	53	47	80*	63	78	74	94*	83
8	0	2	0*	4	4	9	20	19	10	8	23	29	10	10	36	38	43*	51	67*	53	76*	64
total	59		252		271		527		248		755		233		827		1016		1669		2374	

$\chi^2 = 8.97$

* these observations have critical χ^2 values which suggest a significant difference from the expected value

Establishment of a well defined main stem during the early part of network development was an observation noted by Parker (1977) and suggested by Schumm (1956). Partitioning of a drainage basin by a main stem, whether it be controlled by subtle topographic guidance or by flow convergences obtaining sufficient magnitude for bed incision to become permanent, has topologic implications which should be carefully considered. The more complete the partition, the greater the dominance of this initial path on the pattern of all subsequent paths. Proof of this concept is not obtained through examination of lumped magnitude distributions, but rather through observations of the growth of subnetworks as individual networks, with respect to the initial main stem system. This is pursued in Chapter 7.

6.2.3 Magnitude Distributions Between and Within Basin Types

This section examines the influence of basin type on magnitude distribution using the 8 by 9 contingency table--8 magnitudes, 9 basin types.

From Table 6.3 it is clear that no one basin type exerts an influence which allows it to be statistically distinguished from the others in terms of magnitude. When basins are grouped by geologic type, distinction could not be made between them, though within types a,b and c the predominance of TS links was again manifest. Drainage type apparently had no significant influence on magnitude distribution.

6.2.4 Changes Induced by Drainage of Spirit Lake

The debris avalanche dam (the study area) between Spirit Lake and the North Fork Toutle River has been considered a potential hazard to downstream population centers. Four factors have combined to give cause for concern. First the debris dam is comprised of unconsolidated

Table 6.3 Distribution of link magnitudes (μ) with respect to basin type

	Ta		Tb		Tc		Sa		Sc		TIc		TId		Ic		Id	
μ	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp	obs	exp
2	689	679	361	318*	196	127*	826	824	43	36	25	24	17	22	1234	1256*	23	28
3	270	274	131	134	43	59	445	451	22	24	10	15	9	11	695	701	14	19
4	145	151	74	70	28	47*	278	263	15	18	7	9	6	7	469	453	14	15
5	107	106	49	81*	19	38*	162	175	11	13	5	7	4	6	362	344	14	13
6	87	82	38	67*	16	26*	108	106	8	10	4	6	4	5	249	238	12	10
7	72	65	40	49	16	21	96	87	7	7	5	5	8	4	195	176	10	7
8	38	49	39	41	16	17	45	49	7	5	7	4	10	4*	102	104	10	5
total	1408		732		334		1960		135		63		58		3306		97	

$\chi^2 = 9.35$

* these observations have critical χ^2 which suggest a significant difference from the expected value

sediments which have great erosion potential. Second runoff from the Spirit Lake Catchment raised lake levels by 20m in two years, thus amplifying the hydraulic gradient across the debris dam. Immediately after the eruption the level of Spirit Lake was 40m greater than the prior status, because of sediment deposition in the Spirit Lake Basin.

A third concern was the rate of development of drainage networks in the debris dam area, coupled with headward erosion of the North Fork Toutle River. Finally, peizometric survey and thermal infrared photography revealed defined pathways of shallow groundwater flow, with substantial flow rates, from Spirit Lake into the North Fork Toutle River.

As a result of these observations, U.S. Army Engineers considered the debris dam to be a temporary retaining structure with insufficiently stable foundation which may be compounded by a fluidized base, surface sapping of material, and an increasing build-up of head in the reservoir that would either overtop and breach the dam, or cause failure by slumping. Mitigation of the hazard achieved temporarily by the construction of a pumping station and pipeline to discharge lake water into the upper North Fork Toutle River, and lower lake levels by up to 12m.

Research conducted by Parsons <u>et al.</u> (1983) suggested that the rate of runoff to Spirit Lake would decline naturally as tributary capture of Mount St. Helens rampart streams gained momentum with the increased downcutting of the North Fork Toutle River, and the greater hydraulic potential this route offered. Extrapolation of historic rates of capture indicated that 40% of the rampart would drain directly to the North Fork Toutle River by 1986.

This prediction was not substantiated if only because the Spirit Lake pumping operations accelerated channel incision and "rejuvenated" of the North Fork Toutle River to such an extent (20m at Carbonate Springs, 3m at Castle-Coldwater confluence) that capture was decidedly more rapid than anticipated, and the target of 40% was achieved by the spring of 1983. Future capture rates will not be as spectacular as Pearson (1985) has demonstrated a return to a quasi-equilibrium state for the North Fork Toutle River, and 60% of this river has now re-established a channel bed which is superimposed on the pre-eruption bed (Keenan 1985), thus limiting further incision.

Network development, in some topologic identity, may have been influenced by this change in base level, which, for type Ta, Tb and TI streams amounted to 30m in some places. It is possible to test this hypothesis by comparing magnitude distributions for the pre-incision period with those of the post-incision period (time periods 1-8 versus 9-11).

The results (Table 6.4) are fairly unremarkable, offering no distinctions in terms of magnitude distributions, either overall, or in terms of the individual or collective basin types. Magnitude distributions, it would appear, are independent of changes in the hydraulic gradient or local base level.

Long-term network development, which is usually encountered in network studies, would not be, on the scant evidence accumulated here, liable to magnitude pre-disposition as a result of episodic tectonic events. Nothing can be said concerning climatic change using this data.

Table 6.4 Comparison of magnitude distribution before and after drainage of Spirit Lake

	before		after	
	obs	exp	obs	exp
2	1248	1217	2210	2184
3	633	654	1003	946
4	469	453	656	674
5	293	289	440	445
6	210	223	312	297
7	188	191	252	243
8	103	96	186	171

χ^2 critical = 14.75

$\chi^2_{tab,12df,0.05} = 21.34$

6.2.5 Recollection

In the overall-infinite network, magnitude distribution was shown to contend the status of the random model. Excess small-magnitude subnetworks were found in downstream locations. The establishment of an initial main stem was considered an inhibitor to further random growth, and this main stem possessed an excess of type TS links. Deviation from the random model was not exhibited at any other timeperiod except in the final period, number 11.

Geology and drainage type did not affect magnitude distributions, and North Fork Toutle River incision did not contribute a noticeable change. Magnitude, as a topologic entity, independent of pattern, is a feature produced by factors which remain undetermined.

6.3 Ambilateral Classes: Network Pattern

Smart's (1971a) introduction of the ambilateral class into network analysis was a valuable addition to the methodology and to the recognition of pattern. Of all the grouped topologic information approaches, the ambilateral classification contains the greatest information content when n 4. Pathnumber, Mock-class, and diameter are merely subsets of the ambilateral classification.

In two major papers, Smart and Werner (1976) and Smart (1978) have employed the ambilateral classification to examine network pattern. Both papers employed the "top-down" methodology. It is presently argued that this is somewhat analogous to the "top down" random-walk simulation model of Leopold and Langbein (1962), which Smart and Moruzzi (1971a, b) criticized because it was only relevant for rill systems.

"Growth-up" or "outlet-to-source" methodology was proposed in section 4.5.2 of this dissertation because it drew upon the conceptual-empirical approach of the headward growth model. This particular method is used in Chapter 7 to examine growth patterns. For tests of the topologic structure of study networks the approach of Smart and Werner is pursued.

Presentation of results in this section is divided in two. The first deals with the overall-infinite network, and examines all ambilateral classes, $A(n)<7$. Second basin type categories are formed and ambilateral classes compared to the random model for each time period. In this section the earliest time periods and some basin types had insufficient subnetworks of $n=7$ to warrant valid analysis, but the data can be grouped by diameter (Werner and Smart 1973) and examined in that manner.

6.3.1 Overall Ambilateral Class Distribution

Previous assay of magnitude distribution had instilled doubt as to the fit of the study data to the random model. When the pattern of magnitude distribution is considered, it is evident that there are, in the overall-infinite network, serious deviations from the model (Table 6.5) at all subnetwork magnitudes 4-7. Classes that by themselves are outside the 95% significance band are indicated with an asterisk.

Small magnitude classes ($n=4,5$) show marked deficiency of the smallest diameter networks. Magnitude 6 classes have a notable surfeit of class 233, diameter=4, a vivid contrast to the next two smaller magnitudes, but the earlier bias against small diameter is restored for magnitude 7.

A hydrologic argument for the apparent lack of small diameter networks may be presented in terms of a topologic property, the pathnumber, which is a measure of the topologic distance of each link to the subnetwork outlet. By proposing that unit travel time from any link to the outlet is simply some constant function of the individual link path, the pathnumber for a network represents the unit hydrograph (Calver, Kirkby and Weyman 1972). The number of links of a given path will all contribute their flows to the outlet at the same time, hydrograph peakedness will then be related to this number of similar paths (Surkan 1968). This approach is not without precedent and has been used successfully by Gupta et al. (1980) and Wang et al. (1981), and further theoretical argument is given by Kirkby (1976).

Networks with small diameter have greater hydrograph peakedness than other networks of the same magnitude. Maximum diameter networks (maximum diameter = network magnitude, and contains only one ambilateral class) have remarkably flat hydrographs. The pathnumber for class 34 is 12222, while class 24 is classified as 124. At large magnitudes this peakedness is most pronounced. For a minimum diameter network of magnitude 16, the pathnumber 1,2,4,8,16 is in marked contrast to the maximum diameter pathnumber 1222222222222222. Note also that for minimum diameter networks the peak response is displaced to the final paths, but for intermediate diameter networks, the peak is more centrally located (e.g., for n=16, class 222222234457,11,15 has pathnumber 122466442).

Synthetic hydrographs produced by intermediate diameter networks more closely approximate these generated by real networks (Kirkby

1976), and this would suggest a hydrologic and geomorphic preference for this type of network organization. In large basins, where link length varies in some manner, this approach breaks down. Kirkby (1976) has demonstrated that for small basins with areas (<1 km^2) topologic structure dominates geometric structure. This information is important for the present research.

The random model is not inflexible in these terms. For n=7, there are 16 TDCN of diameter 4, 44 of diameter 5, 56 of diameter 6, and 32 of diameter 7. In Table 6.6 the hydrologic response, as portrayed by the pathnumber, is divided into four "peakedness" classes and four timing classes. Calculation of probability is based on TDCN distributions as with all random model calculations.

Both class 3456 and 2234 are found to be less frequent in reality than predicted by the model, with $\chi^2_{crit} = 9.55$ $\chi^2_{tab,6df,0.05} = 12.59$. When class 2234 is compared to all others, then it is found to be outside the random model predictions at the 95% level ($\chi^2 = 6.95$, $\chi^2_{tab,1df,0.05} = 3.84$), but class 3456 is within the model bounds ($\chi^2_{crit} = 0.63$), as are classes 2334 and 2235 ($\chi^2_{crit} = 2.5$). Magnitude 6 pathnumbers are also contained in the model ($\chi^2 = 4.71$).

Outright rejection of the random model in terms of pathnumber distributions has not been proven; extreme diameter classes have been shown to be overpredicted. Smart's (1978, p. 144) data also fits the random model in this manner, but class 3456 is significantly underpredicted ($\chi^2_{crit} = 6.31$). Unfortunately no other data presented in the literature was in such a form that it could be used for further comparison.

Table 6.6 The distribution of pathnumber classes grouped by hydrograph shape (as deduced by the pathnumber

peakedness	none	single width mid-range	
time of peak	all	middle	late
pathnumber	1222222	124222	122224
ambilateral class	3456	2345 2356 2346	2456
N(TDCN)	32	48	8
study distribution %	20.8	33.3	6.8
p(TDCN)%	24.2	36.4	6.1

$\chi^2_{crit} = 9.55$ $\chi^2_{tab,6df,0.05} = 11.07$

∴ cannot reject hypothesis than pathnumber distribution is within the random model criteria.

Table 6.6 The distribution of pathnumber classes, cont'd.

double width mid-range			high
middle	late	mixed	late
12442	12244	12424	1246
2334 2235	2246 2336	2245	2234
24	12	4	16
24.3	7.3	3.8	3.5
18.2	9.1	3.0	12.1

but for the comparison of pathnumber 1246 against all others

$$\chi^2_{crit} = 6.95 \qquad \chi^2_{tab,1df,0.05} = 3.94$$

which suggests this group are significantly less observed than predicted.

These results, although discrepant at the extremes, suggest that the random model is applicable but allows the introduction of a deterministic element into the interpretation. Over-reliance on this particular result should be avoided, if only because it is accomplished using the hypothetical overall-infinite network. Furthermore, the information loss argument (Jarvis and Werrity 1975) also becomes significant because the pathnumber set for all magnitudes is always contained in the ambilateral class-set for the same magnitude. The chi-squared test is particularly sensitive to an increase in the number of degrees of freedom but pathnumber classes reduce the degrees of freedom. More exhaustive testing of this approach will be carried out in subsequent sections, especially in Section 4.3.2 and within Chapter 7.

Elongate networks, those with maximum diameter, have pathnumbers which have a flat hydrograph. With this information a explanation is proposed for the apparent contrasts of maximum and minimum diameter networks between Mount St. Helens and Smart's (1978) data.

The contour crenulation method formed the basis for derivation of Smart's data base, which allowed compatibility with data bases obtained during the "stream-order" era. A contour crenulation is a topographic manifestation of ephemeral drainage. Such zero-order or first-magnitude channels are created in response to an inability of alternative flow paths to cope with large volume inputs; they are products of storm magnitude-induced network expansion, a concept termed the variable source area concept (Hewlett and Hibbert, 1967), developed for hydrologic responses in forested terrain.

Jarvis (1976) has since shown that exterior link lengths are significantly longer if valley characteristics (a contour crenulation type approach) are used, for diameter in the range 4-12. This is partly a result of increased numbers of maximum diameter networks. In addition, Mark (1983) has shown that the contour crenulation method is insufficient to detect many headwater bifurcations detected through field survey.

Therefore, maximum diameter networks proliferate in contour crenulation based studies. This is through increased accuracy of field survey methods and, hypothetically, because variable-source area channels are response to precipitation extremes, events which can best be accommodated in terms of pathnumber-derived hydrographic response by maximum diameter networks. The response peak is then distributed over a greater period of time.

It would be elegant to examine the pathnumber distribution for entire networks, but two factors conspire to defeat the attempt. First, there are a very large number of pathnumbers in large magnitude networks, requiring sample sizes beyond the data base available. Second, there are other measures which then should be considered, such as geometric basin width (Kirkby, 1976) in order to ascertain the flow path characteristics in more detail.

6.3.2 Effect of Basin Type on Ambilateral Class

In Chapter 5 it was noted that basin type Tb was anomalous in terms of link density and exterior link length. No basin type controls were shown to exist for magnitude distributions (Section 6.2.3). Network pattern may be affected by basin type, and this section tests the distribution of ambilateral classes with respect to basin type.

For any basin type to be considered to influence topologic pattern a specific set of ambilateral classes must consistently exceed the bounds of the random model.

Chi-squared values from Table 6.7 show that the distribution of ambilateral classes when subdivided by basin type is inconsistent with the prediction of the random model. The results are somewhat discouraging to either camp in the random model dispute, as no clear trends are observed. However, the result must be considered in terms of the small numbers of observations available.

Although both type-d basin geologies have no correspondence with the random model at all four magnitudes, the classes involved in underprediction in magnitude 5 are not the same (class 23 in TId, class 24 in Id), while totally different class types are involved for magnitude 6 networks (class 233 in TId is underpredicted, class 234 is overpredicted for Id basins).

Once again exacting answers to the basin-type question are not provided by the analysis. Pathnumber, considered a caricature of hydrologic response, may well be more effectively examined in order to elucidate basin-type influences on topology (Table 6.8).

Only basin types Tc and Id exhibited conformity with the random model. Again no consistent trends were detected across geologic or drainage type. Class 2234 continued to be overpredicted in all basin types, but class 3456 was underpredicted for type-d basin geology. This result may indicate geologic control of topologic path, a result of the low infiltration rates of the debris avalanche producing more rapid flow concentration which helps determine initial channel pattern suited to more rapid concentration of flows. However if this were

Table 6.7 Effect of basin type on ambilateral class

Class	TIc			TId			Ic			Id			Ta			Tb		
2	10	25	11.25[1]	0	18	22.5[1]	90	83.6	.61[1]	0	20.8	26.00[1]	79	62.2	5.42[1]	56	44.8	3.5[1]
3	115	100	125[2]	90	72	90[2]	328	334.4	418[2]	104	83.2	104[2]	234	248.8	311[2]	168	179.2	224[2]
23	22	22.8	3.53[1]	0	15.7	34.92[1]	142	97.4	33.46[1]	5	11.1	15.09[1]	65	58.6	11.51[1]	65	41.4	20.99[1]
24	6	11.5		2	7.85		26	48.7		0	5.6		44	29.3		10	20.7	
34	52	45.7	80[2]	53	31.4	55[2]	173	194.9	341[2]	34	22.3	39[2]	96	117.1	205[2]	70	82.9	145[2]
224	2	3.33	6.94[1]	0	.23	X	22	12	10.85[1]	0	2.04	16.14[1]	8	2.19	39.4[1]	18	5.23	71.09[1]
233	8	6.67		5	.48		27	24		4	4.09		19	14.4		27	10.4	
234	12	13.3		0	.95		50	48		16	8.19		19	28.8		10	21.0	
235	21	13.3		0	.95		45	48		4	8.19		56	28.8		20	21.0	
245	4	6.67		0	.48		48	24		0	4.09		14	14.4		3	10.4	
345	23	26.6	70[2]	0	1.9	5	90	96	252[2]	19	16.4	43[2]	35	57.5	151[2]	32	41.9	110[2]
2234	3	8.72	25.99[1]	0		X	3	24	65.08[1]	0		X	11	15.75	28.45[1]	2	8.72	34.08[1]
2235	3	4.36		0			33	12		0			14	7.88		14	4.36	
2245	8	2.18		0			5	6		0			8	3.94		0	2.18	
2246	0	2.18		0			6	6		0			4	3.94		0	2.18	
2334	6	8.72		0			30	24		0			9	15.75		11	8.72	
2336	4	4.36		0			9	12		0			11	7.88		5	4.36	
2345	6	8.72		0			21	24		4			11	15.75		7	8.72	
2346	7	8.72		0			19	24		2			9	15.75		6	8.72	
2356	12	8.72		0			25	24		0			19	15.75		8	8.72	
2456	3	4.36		0			15	12		0			14	7.88		2	4.36	
3456	20	17.45	72[2]	10		10[2]	32	48	198[2]	6		12	20	31.5	130[2]	17	17.45	7.32[2]

X X not computed; too few data points

reject this set from random model hypothesis

1 $\chi^2_{critical}$

2 sample size

Class	Tc			Sa			Sc		
2	8	10	.5[1]	2	19	19.01[1]	42	48.2	1[1]
3	42	40	50[2]	93	76	95[2]	199	192.8	241[2]
23	31	15.14	23.29[1]	16	17.1	337[1]	33	37.4	.74[1]
24	4	7.57		4	8.6		20	18.7	
34	18	30.3	53[2]	40	34.3	60[2]	78	74.8	131[2]
224	4	2.05	28.55[1]	0	2.23	12.02[1]	9	5.09	18.34[1]
233	2	4.09		2	4.48		19	10.19	
234	7	8.18		8	8.45		27	20.4	
235	21	8.18		13	8.95		13	20.4	
245	2	4.09		0	4.42		7	10.19	
345	7	16.37	43[2]	24	17.9	47[2]	32	40.8	107[2]
2234	0		X	0	5.94	41.92[1]	2	8.6	25.89[1]
2235	3			2	2.96		4	4.3	
2245	0			0	1.48		2	2.15	
2246	0			0	1.48		0	2.15	
2334	1			0	5.94		16	8.6	
2336	1			0	2.96		4	4.3	
2345	0			8	5.94		8	8.6	
2346	0			0	5.94		9	8.6	
2356	1			15	5.94		3	8.6	
2356	0			0	2.96		7	4.3	
3456	[illegible]		6	14	11.9	49[2]	6	16.7	71[2]

Table 6.8 Distribution of pathnumber classes, grouped by "theoretical hydrograph response" for basin types

	3456		2345[a] 2356[b] 2346[c]					2456		2334[a] 2235[b]				2246[a] 2336[b]				2245		2234		total	χ^2_{crit}
	O	E	a	b	c	O	E	O	E	a	b	O	E	a	b	O	E	O	E	O	E		
Tc	0	1.45	0	1	0	1	2.18	0	0.36	1	3	4	1.09	0	1	1	0.54	0	0.18	0	0.72	6	11.51r
Sa	14	9.43	8	15	0	23	14.1	0	2.36	0	2	2	7.07	0	0	0	3.54	0	1.18	0	4.71	39	23.26r
Sc	6	14.8	8	3	9	20	22.1	7	3.69	16	4	20	11.09	0	4	4	5.54	2	1.84	2	7.39	61	19.93r
TIc	20	17.5	6	12	7	25	26.1	3	4.36	6	3	9	13.09	0	4	4	6.54	8	2.18	3	8.72	72	22.38r
TId	10	2.42	0	0	0	0	3.63	0	.6	0	0	0	1.8	0	0	0	.9	0	.3	0	1.2	10	32.17r
Ic	32	48	21	25	19	65	72	15	12	30	33	63	36	6	9	15	18	5	6	3	24	198	46.06r
Id	6	2.9	4	0	2	6	4.36	0	.72	0	0	0	2.18	20	0	0	1.09	0	.36	0	1.45	12	9.73
Ta	20	31.5	11	19	9	39	47.2	14	7.87	9	14	23	23.6	4	11	15	11.8	8	3.93	11	15.75	130	16.93r
Tb	17	17.5	7	8	6	21	26.1	2	4.36	11	14	25	15.09	0	5	5	6.54	0	2.18	2	3.72	72	20.85r
TDCN	32					48		8			24				12			4		16		132	

$\chi^2_{tab,6df,0.05} = 11.07$

r reject null hypothesis for this basin type a generally applicable postulate, one would expect minimum diameter networks to dominate materials on which subsurface concentration is inhibited, as in basin type Tb, but this was not observed. Yet type-c basins possess fewer maximum diameter subnetworks, than predicted, suggesting some geologic control for these networks.

Drainage type appears to have no effect on the pathnumber distribution. Returning to the hypothetical hydrograph response as generated by pathnumber gives further indication as to the suitability of this approach and the establishment of a tentative hierarchy. The class "double mid range, middle peak" (ambilateral classes 2334 and 2235) again is frequently underpredicted, while all other mid range classes show mixed prediction observance. This suggests the top-down hierarchy of "double-middle," other middle, maximum diameter, minimum diameter. Further examination of this proposal will occur in subsequent sections.

6.3.3 Temporal Distribution of Ambilateral Classes

In this section both the pattern over time and the influence of North Fork Toutle River incision are examined. Statistical analysis of the ambilateral class distribution for each timeperiod (2-11) is given in Table 6.9.

In all timeperiods n=7 classes also consistently fail to uphold the random model hypothesis. None of the other classes (n=4 through 6) maintain such consistency. For all but timeperiods 3, 4 and 5 this deviation can be attributed to class 2235 being observed more often than expected while the minimum diameter class 2234 is frequently under-observed. The diameter of class 2235 is 5, while that of 2234 is 4, and the pathnumbers are 12442 and 1246 respectively.

Table 6.9 Temporal distribution of ambilateral classes

timeperiod

class	1 o	1 e		3 o	3 e		4 o	4 e		5 o	5 e		6 o	6 e	
2	6	9.4	1.54[1]	14	10.2	1.77[1]	21	15.4	2.55[1]	27	20.4	2.61[1]	26	21.8	1.01[1]
3	41	37.6	47[2]	37	40.8	51[2]	56	61.6	77[2]	75	81.6	102[2]	83	87.2	109[2]
23	2	10	9.45[1]	7	16	9.84[1]	12	14.2	5.58[1]	16	15.4	4.80[1]	34	26.8	2.78[1]
24	8	5		14	8		13	7.14		13	7.7		11	13.4	
34	25	20	35[2]	35	32	56[2]	25	28.5	50[2]	25	30.9	54[2]	49	53.7	94[2]
224	0	.66	6.05[1]	4	1.38	10.02[1]	2	2.09	.98[1]	1	2.66	7.79[1]	4	3.33	14.98[1]
233	0	1.33		5	2.76		4	4.19		5	5.33		12	6.67	
234	3	2.66		2	5.52		9	8.38		16	10.67		5	13.3	
235	2	2.66		5	5.52		6	8.38		8	10.67		20	13.3	
245	0	1.33		4	2.76		5	4.19		9	5.33		3	6.67	
345	9	5.33	14[2]	9	11.04	29[2]	18	16.76	44[2]	17	21.33	56[2]	26	26.6	70[2]
2234	0	1.2	44.23[1]	0	2.78	34.66[1]	0	4.8	20.9[1]	0	4.12	18.23[1]	2	6.55	22.27[1]
2235	4	.61*		6	1.4		2	2.4		2	2.06		8	3.27	
2245	1	.3*		0	.7*		0	1.2		0	1.03		1	1.64	
2246	0	.3*		0	.7*		4	1.2		0	1.03		0	1.64	
2334	0	1.2**		0	2.78		4	4.8		6	4.12		10	6.55	
2336	0	.61**		4	1.4		0	2.4		0	2.06		2	3.27	
2345	0	1.2		0	2.78		7	4.8		4	4.12		2	6.55	
2346	2	1.2		0	2.78		6	4.8		8	4.12		4	6.55	
2356	0	1.2***		4	2.78		2	4.8		2	4.12		11	6.55	
2456	0	.61***		3	1.4		5	2.4		5	2.06		4	3.27	
3456	3	2.4	10[2]	6	5.58	23[2]	10	9.7	40[2]	7	8.24	34[2]	10	13.09	54[2]

class	7 o	7 e		8 o	8 e		9 o	9 e		10 o	10 e		11 o	11 e		χ^2 tab	d
2	21	22	.06[1]	33	30.4	.28[1]	29	39.4	3.43[1]	41	54.2	3.53[1]	56	106.4	29.84[1]		3
3	89	88	110[2]	119	121.6	152[2]	168	157.6	197[2]	230	321.6	271[2]	476	425.6	532[2]	3.84	4
23	38	28.9	4.23[1]	34	32.6	2.83[1]	56	39.1	13.54[1]	70	49.4	18.81[1]	115	79.1	44.84[1]	5.99	4
24	11	14.4		22	16.3		9	19.6		9	24.7		6	39.6			4
34	52	57.7	101[2]	58	65.1	114[2]	72	78.3	137[2]	94	98.9	173[2]	156	158.3	277[2]		5
224	4	3.52	13.34[1]	6	3.48	8.98[1]	6	5.28	7.23[1]	14	6.95	14.96[1]	22	9.28	62.39[1]	11.07	4
233	12	7.04		4	6.95		10	10.6		19	13.9		27	10.6			4
234	5	14.09		8	13.9		20	21.14		26	27.8		52	37.1			5
235	18	14.09		20	13.9		31	21.16		28	27.8		52	37.1			5
245	3	7.04		9	6.95		6	10.6		5	13.9		4	18.6			5
345	32	28.2	74[2]	26	73	73[2]	38	42.3	111[2]	52	55.6	146[2]	38	74.3	195[2]		6
2234	2	6.4	19.93[1]	2	7.03	25.86[1]	6	7.88	31.42[1]	4	7.88	27.78[1]	7	14.8	66.56[1]	18.31	4
2235	4	3.2		10	3.5		10	3.94		8	3.94		21	7.39			5
2245	1	1.6		2	1.75		1	1.96		6	1.96		6	3.7			5
2246	0	1.6		1	1.75		2	1.96		3	1.96		2	3.7			5
2334	10	6.4		6	7.03		6	7.88		10	7.88		20	14.8			5
2336	4	3.2		0	3.5		4	3.94		6	3.94		9	7.39			6
2345	5	6.4		10	7.03		12	7.88		10	7.88		13	14.8			6
2346	4	6.4		2	7.03		8	7.88		10	7.88		10	14.8			6
2356	8	6.4		10	7.03		18	7.88		11	7.88		26	14.8			6
2456	2	3.2		3	3.5		3	3.94		1	3.94		2	7.39			6
3456	13	12.8	53[2]	12	14.06	58[2]	25	15.8	95[2]	26	15.8	95[2]	6	29.6	122[2]		7

[1] critical χ^2 value for that magnitude group
[2] total observations for that magnitude group
*,**,*** observations grouped together (those with same superscript) for calculation

Although the pre-cursors of 2234 are not under-observed (classes 224 and 233) neither are the formative classes for 2235 consistently over-observed (classes 234, 235, 224). One conclusion that may be drawn from these data argues for "preference" of subnetwork growth toward the less extreme path number. As with previous examples, the n=7 subnetwork may be a critical magnitude for the hydrological response of these channel networks; a subnetwork organizational pattern that recurs throughout the time-dependent growth of the individual basin network.

Consistent failure of the null hypothesis occurs for all magnitude groups (4-8) of ambilateral classes for timeperiod 11. Although not as pronounced, time periods 9 and 10 also produce statistical deviations from the random model. Combining these three time periods allows a test of the incision question.

For the grouped pre- and post-incision data all magnitudes fail the null hypothesis test. This test does not allow trends to be considered using the probability distribution method. Therefore the 2xC contingency table allows comparison of each class within a magnitude set on a pre-incision-post-incision basis (Table 6.10). Two test statistics help interpretation. Chi-squared values again indicate a rejection of the hypothesis that pre- and post-incision patterns are similar.

Pearson's coefficient of contingency evaluates the similarity of the two states, with a value of 1.00 indicating exact similarity (Ostle 1972). Clearly the small values yielded in this situation further confirm dissimilarity between pre-incision patterns and their post-incision counterparts. An exception must be made for magnitude

Table 6.10 Effect of Toutle River incision on distribution of ambilateral classes

before incision of North Fork Toutle River

n=4

O	E
148	177.2
738	708.8
χ^2 =	6.01
886	

n=5

O	E
143	144
92	72
269	288
χ^2 =	6.82
504	

n=6

O	E
26	15.4
42	30.9
48	61.9
79	61.9
33	30.9
137	123.8
χ^2 =	20.68
325	

n=7

O	E
6	32.96
36	16.48
5	8.24
5	8.24
36	32.96
10	16.48
28	32.96
26	32.96
37	32.96
22	16.48
61	65.9
χ^2 =	55.47
272	

after incision of North Fork Toutle River

n=4

O	E
126	152.4
636	609.6
χ^2 =	5.72
762	

n=5

O	E
241	167.7
24	83.9
322	335.4
χ^2 =	75.34
587	

n=6

O	E
42	21.9
58	43.8
106	87.6
111	87.6
15	43.8
128	175.2
χ^2 =	64.82
460	

n=7

O	E
17	36.6
39	18.3
13	9.15
7	9.15
36	36.6
19	18.3
35	36.6
28	36.6
45	36.6
6	18.3
57	73.2
χ^2 =	51.94
302	

Contingency Table

		χ^2	CC	df	
mag =	4	0.01	0.002	1	3.84
	5	63.68	0.23	2	5.99
	6	30.07	0.19	5	11.07
	7	21.46	0.19	10	18.31

CC = Pearson's contingency coefficient
CC below .50
little association noted

4, where with one degree of freedom the contingency coefficient is very small, resulting from the large sample size, 1648.

Classes that make significant contributions to dissimilarity are: 23, 24, 234, 245, 2234, 2245, and 2456. From the methodology used to obtain ambilateral classes, a certain bias is inherent in the classes created at the next downstream link (Appendix 1). For a minimum diameter network of n=4 then classes 24, 224, 2234 are the only direct candidates possible of which 24 and 2234 are of interest here. In turn class 24 gives rise to class 245 and class 2245, and class 2456 is formed from class 245. Only classes 23 and 234 can originate from a magnitude 3 subnetwork: the classes, through their derivation from class 2, arise from a magnitude 2 subnetwork.

Both class 23 and 234 make sharp increases in proportion from the pre-incision to the post-incision state, while classes 24, 245, and 2456 all decline. Class 2234 can originate at the same level as class 24, class 2245 with class 245, but both class 2234 and 2245 show slight increases in proportion, suggesting a definitive change in pattern toward these two classes. In terms of the pathnumber hypothesis, this evidence shifts the emphasis toward late, large peaks--note also that there is a corresponding decline in class 3456 as well as 2456.

As class 3456 must originate from class 3 via classes 34 and 345, another trend is also indicated, with a suggestion that in the growth from a magnitude 3 subnetwork, class 3 is less favored after incision than previously, hence the increases of class 23 and 234. Similarly in the post-incision phase class 224 and 2234 are preferred to class 24, and class 2245 to class 245. The end product of these observations can be related to one factor--an increase in the number of T,S,S subnetworks in the downstream direction, as indicated in the magnitude distribution studies (Section 6.2.2). Further assay of these ideas will occur in the chapter on Network Growth (Chapter 7), but with the emphasis on mode of growth as indicated by actual growth paths, not the "top-down" method used here.

6.3.4 Space and Time in Channel Network Patterns

Understanding the characteristic form of drainage basins, even through only examining the channel network, has been of limited research interest. That the channel network should be essentially a random structure denies a place for the interdependency of organized process. Random models are not without precedent in our interpretations of nature, with genetic mutation seemingly the most far reaching and commanding extensive research interest.

The development of the random model was based on our limited knowledge of "the grand changes of a landscape during the millions of years of its erosional evolution" (Schumm 1975). Unquestioning acceptance of the random model is admitting intellectual defeat in a geomorphic context. Natural channel networks range in spatial size from the small, rilled hillslope, with the obvious bias of link length elongation and the tendency towards creation of low magnitude subparallel networks, to regional networks that encompass both geologic and climatic variation and as a result display a multiplicity of network patterns.

Some of the aberations to the random model highlighted in this study (Table 6.11) are due to the scale of the basins involved. This conjecture has been discussed by Abrahams (1972) and Jarvis (1976)

Table 6.11 Summary of the effects of basin type and time on conformance of ambilateral class observations to the random topology model

observation period

basin	2		3		4		5		6		7		8		9		10		11	
Ta	✓	✓	✓	✓	X	X	X	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	X	✓
	✓	X	✓	X	X	X	X	X	X	✓	X	✓	X	✓	✓	✓	✓	X	✓	X
Tb	✓	✓	✓	✓	X	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	X	✓	✓	✓	X
	✓	X	✓	X	✓	✓	✓	✓	X	✓	X	✓	✓	✓	X	✓	X	✓	X	X
Tc	-	-	X	X	✓	X	✓	X	-	X	✓	X	✓	✓	✓	X	X	✓	X	✓
	-	-	✓	-	✓	-	X	-	X	-	X	-	X	-	✓	-	✓	-	✓	-
Sa	✓	X	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X	X
	-	-	-	-	✓	-	✓	-	✓	✓	✓	✓	✓	X	✓	X	✓	✓	X	X
Sc	✓	✓	✓	✓	✓	X	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	✓	-	✓	-	✓	-	X	-	X	-	✓	-	✓	-	✓	✓	X	X	X	X
TIc	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
	-	-	✓	-	X	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X
TId	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	✓	X	X
	-	-	-	-	✓	-	✓	-	✓	-	✓	-	✓	-	✓	-	✓	-	X	-
Ic	✓	-	✓	✓	✓	✓	✓	✓	✓	X	✓	✓	X	X	✓	X	X	X	✓	X
	-	-	✓	X	X	✓	✓	✓	✓	X	✓	X	✓	✓	✓	X	X	X	X	X
Id	✓	✓	✓	✓	✓	✓	✓	-	✓	-	✓	-	✓	-	✓	✓	X	✓	X	X
	✓	-	✓	-	✓	-	✓	-	X	-	X	-	✓	-	✓	-	✓	-	✓	-

✓ this observation set is acceptable within the random model
X " " " " unacceptable " " " "
\- " " " not computed due to small data sample size

not in terms of basin area, but in terms of comparative network magnitude. Clearly these two scale analogs are not directly translatable, one-to-another, especially when the geologic or climatic type differs between basins.

Several questions arise from the results presented herein, which, it had been hoped, may have been answered during the course of this study.

First, is the random model applicable to studies of network growth? Indications given here lead to speculation of the random model validity. Certainly, use of a ranked pathnumber hierarchy was sufficient to explain subnetwork variation, but additionally this alternative model did not deviate consistently from random model distributions. It should also be recalled that the information content of pathnumber is less than that in the ambilateral class.

Pathnumber models are only one type of hydrograph flow analog that can be used. In terms of real hydrographs, the topologic smoothing of geometric length hides many of the distributive factors of channelized flow convergence. Kirkby (1976) used a model of geometric basin width which incorporated mean link lengths at a given pathlength. The most pronounced effect of this approach was to separate the hydrograph response of basins by basin area; the greater the basin area, the less significant the pathnumber effect. However, this approach did nothing to aid in the discrimination of pattern preference for channel networks.

Second, is the use of the channel network alone sufficient to enable rigorous deduction of any type of geomorphic evolution? This question in part has been answered through the results of Flint (1980) and Abrahams (1983) in which other aspects of basin morphology have been employed. Satisfaction with these basin morphology approaches should be limited, because each employs a morphologic character which is dependent on the channel as a constraint on form. Hillslope analysts, and especially those of the model-building school of thought, have shown that hillslope form is highly dependent on the boundary conditions produced by the channel (Kirkby 1971). A search for valid morphological features that can be used to aid in channel network analysis should differentiate between forms produced as a result of channel process and those which contribute to creation of a channel in a particular location.

Third, how important is the creation of the initial channel pattern in the determination of subsequent network development? Both Parker (1977) and this study suggest that the early development of a low link-density but higher drainage density network influences subsequent pattern because the tendency of growth is not toward a "wave of dissection" (Howard 1971b) but rather to "space in-filling" (Abrahams 1976).

Given any simple bifurcation of a magnitude 1 link two questions are presented which, as yet, have to be answered. First, why did the bifurcation occur at that particular location? Ignoring the speculative theories proposed for this situation leads to the second problem, namely prediction of subsequent growth on each of the links. The creation of two sub-watersheds upon link bifurcation partitions the hillslope flow contributions which previously converged on a single link. In a geologically and topographically uniform basin, with similar soils, exact partition into two equal area basins will only result in similar subsequent network patterns if the basin shape is the same.

Despite the lack of evidence for the basin area partition theory from this, or any other study, the a posteriori network patterns observed do not point toward equal partition. Indeed the prevalence of the mid range-peak, middle-peaking pathnumbers are not patterns that occur under equal partition. Minimum diameter networks are those which have internal arrangements most likely to resemble equal partition growth modes. Maximum diameter networks comprise the other extreme; watershed partition being extremely unequal. Such subnetwork development is consistent with the observations of Flint (1980) and Howard (1971c) in which bifurcation in the upper watershed tended to produce one link with an orientation aligned with the shortest path to the major basin divide, with the other link proceeding up the longer axis toward the divide.

Consequently, this strong bias in growth direction also results in a predominance of Cis chains in headwater regions and valley asymmetry. For the study networks Cis chains were found to dominate headwater regions at timeperiod 11, in a ratio of 2:1 cis to trans chains. Not all headwater network development shows valley side preference; not all basins have a network pattern which is controlled by the watershed boundary conditions.

On a planar, uniformly dipping watershed channels will develop at the place of subsurface and surface flow convergence. The initial link growth should equally partition the basin on this basis. That such partition does not always occur indicates that flow convergence at the centroid axis of the basin is not a given state, and that in the initial production of a new channel, the inhomogeneity of the material over and through which flow occurs has as poignant an effect as the other factors involved. It may be that given micro-scale influence on the control of channel location, true determination of channel pattern will not be achieved.

Parker's (1976) experimental study needs to be expanded, with a strong experimental design that allows statistical analysis, and coupled with computer simulation of network growth. Ambilateral class and pathnumber class could be subject to rigorous scale-model production to examine both flow characteristics and the controls which produce particular patterns. Advocation of experimental geomorphology in the field of network development is long past due.

6.4 Summary of Topologic Observations

Magnitude distributions were found to deviate from the random model for magnitude 2, 3 and 4, and for magnitudes greater than 20. The former group were less prevalent than expected, while the latter were observed more frequently than predicted by the random model. An excess of TS-type links accounted for both anomalies. No consistent deviations from the random model were observed when the networks were studied over time, and the effect of North Fork Toutle River incision on magnitude distribution was not reflected by magnitude distributions. Basin types were not of an influence on magnitude distributions.

Pattern, as manifest through the ambilateral class, showed less tendency to comply with the random model, though this may in part result from the top-down methodology employed. Pathnumber was considered a more convenient descriptor of the pattern of small magnitude subnetworks than was ambilateral class, and the pathnumber was discussed as one factor contributing to hydrograph shape.

No clear tendency was observed when the distribution of ambilateral classes by basin type was examined, but there was a substantial number of deviations from the random model.

Over time the n=7 subnetworks consistently failed to fit the random model and pathnumber was considered a better descriptor when a weighting was added to explain the deficit of maximum and minimum diameter subnetworks. The North Fork Toutle River incision created two distinct pattern populations, with a shift away from maximum and minimum diameter networks at all subnetwork magnitudes in the post-incision period.

CHAPTER 7

Growth of Study Networks

7.1 The Nature of Network Growth

Most geomorphologists favor the headward growth concept for the description of network development across a landscape. For gully systems this phenomenon has been observed on numerous occasions. But headward growth alone will produce a single link channel. Branching and bifurcation must occur to produce the network tree.

Geometric and topologic growth differ because the former recognizes branching in exterior links while the latter only allows branching on interior links. Bifurcation growth is probably caused by different factors than branching growth. Topographic or geologic micro-structure may regulate bifurcation, although upstream basin area may be important. Branching results from the addition of a new link to an already established link. This would appear to be a hydrologic response, the probable result of increased subsurface flow rates.

Several hypotheses have been suggested (Section 1.5) as a framework from which to study network growth. Interest concerns rates of growth, location of growth and type of growth, and comparisons of growth between basin types. The influence of North Fork Toutle River channel incision is also considered.

7.2 Type of Growth

Table 7.1 shows the types of growth that occurred in each time-period and for each basin. At this level growth is first and foremost occurring as bifurcation, second as branching of exterior tributaries, and third as branching of interior tributaries.

Table 7.1 Growth type distributions for basin type and time

observation period	basin type	Actual values for growth type								
		Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id
	a	13	14	2	9	18	16	15	7	22
1→2	b	6	4	5	2	2	1	0	14	0
	c	9	0	0	4	0	0	0	0	2
	a	8	0	6	0	32	2	0	10	0
2→3	b	1	0	4	0	1	2	0	22	0
	c	4	0	2	1	0	4	1	4	1
	a	29	26	4	11	22	6	0	24	4
3→4	b	10	8	0	4	17	21	0	27	0
	c	6	9	2	0	2	10	0	6	2
	a	2	5	0	8	2	0	0	9	0
4→5	b	0	0	0	22	0	2	0	0	0
	c	0	0	0	0	4	4	2	2	0
	a	28	34	2	2	14	28	0	27	10
5→6	b	33	18	0	22	9	10	8	26	2
	c	10	2	1	0	12	2	0	20	0
	a	0	4	0	0	0	0	5	6	6
6→7	b	4	0	0	8	0	4	0	8	0
	c	0	0	0	0	0	0	0	1	4
	a	36	12	2	5	6	0	4	37	8
7→8	b	42	8	2	10	10	8	0	24	6
	c	27	4	0	2	13	0	0	16	2
	a	40	16	6	10	14	6	2	12	26
8→9	b	51	10	0	24	14	8	0	33	1
	c	30	7	4	2	14	3	0	30	0
	a	30	26	24	20	54	14	3	104	28
9→10	b	14	28	8	1	6	10	1	55	0
	c	5	2	1	8	12	9	0	34	0
	a	142	22	28	16	83	90	12	291	34
10→11	b	22	0	14	3	26	21	4	56	0
	c	24	4	4	4	20	18	0	60	0

a = bifurcation
b = branching on exterior
c = branching on interior

A statistical analysis of these results in comparison to the predictions made by the random model of Dacey and Krumbein (1975) (all types of growth are of a probability related to the number of interior or exterior links) reveals that exterior bifurcations were observed more frequently than expected. Interior branching occurred less frequently than expected.

Further interpretation of these distributions examined the between-time-period and within-time-period variability using analysis of variance of proportions (Table 7.1). The frequency of the growth type was divided by the magnitude of the network. Values of the error-sum-of-squares (within time-period variation) are smaller than those for the between-time-period sum of squares for timeperiods 2, 10, and 11, and the null hypothesis that the proportions are equal was rejected in all but timeperiods 5, 6, 7, and 9. Both timeperiods 5 and 7 experienced limited amounts of growth as can be seen in Table 7.2, a factor which contributes to the statistical result. During the growth period 8→9 North Fork Toutle River incision commenced, and it is possible to attribute the similarity between types to the considerable variation within types--that is, variation in proportion over individual basins.

That channel incision should create such a varied growth type response (but such a clear magnitude pattern response--Section 6.3.3) while initiation of channel growth (as exemplified by all basins for which the initial stream was a magnitude 1 system) has definite exterior bifurcation preference (about 62%) is a problem not readily addressed. It could be that super-position of a new energy gradient on an already existing network leads to multiple effects in order to

Table 7.2 Distribution of growth types over time: statistical evaluation

data by proportions of all growth

Observation Period 6 → 7

		$\bar{x}$	s	Σx	ANOVA Table			
	a	41.21	45.68	288.5	7202.07	2	3601.03	2.24
	b	51.01	50.07	357.1	28948.41	18	1608.25	
**	c	7.76	15.18	54.3	36150.48	20		

$F_{tab,0.05,2,18} = 3.55$
action: accept null hypothesis

Observation Period 7 → 8

		$\bar{x}$	s	Σx	ANOVA Table			
	a	41.8	27.81	376.4	4500.83	2	2250.41	3.88
	b	43.09	27.13	387.8	13934.17	24	580.59	
**	c	15.09	15.25	136.8	18435.0	26		

$F_{tab,0.05,2,24} = 3.4$
action: reject null hypothesis

Observation Period 8 → 9

		$\bar{x}$	s	Σx	ANOVA Table			
	a	44.24	26.2	353.9	976.66	2	488.33	0.98
	b	32.50	22.76	260.6	10413.25	21	495.87	
**	c	29.4	16.8	235.2	11389.91	23		

$F_{tab,0.05,2,21} = 3.47$
action: accept null hypothesis

Observation Period 9 → 10

		$\bar{x}$	s	Σx	ANOVA Table			
**	a	67.99	21.05	611.9	16500.02	2	8250.01	29.33
	b	19.33	16.73	174.0	6751.35	24	281.31	
	c	12.44	11.0	112.0	23251.37	26		

$F_{tab,0.05,2,24} = 3.4$
action: reject null hypothesis

Observation Period 10 → 11

		$\bar{x}$	s	Σx	ANOVA Table			
**	a	73.49	12.32	661.4	22454.54	2	11227.27	108.8
	b	15.9	9.64	143.2	2476.69	24	103.2	
	c	10.92	6.70	98.3	24931.24	26		

$F_{tab,0.05,2,24} = 3.4$
action: reject null hypothesis

Notes:
a = bifurcation, b = branching on exterior, c = branching on interior
** = this type is statistically separate from the others using LSD values at 0.05 level

data by proportions of all growth

Observation Period 1 → 2

		$\bar{x}$	s	Σx	ANOVA Table			
**	a	67.66	26.5	608.9	17205.4	2	8602.7	16.54
	b	7.67	13.41	69	12485.1	24	520.21	
	c	24.68	26.05	222.1	29690.5	26		

$F_{tab,0.05,2,24} = 3.4$
action: reject null hypothesis

Observation Period 2 → 3

		$\bar{x}$	s	Σx	ANOVA Table			
	a	33.69	36.39	269.5	9590.81	2	4795.41	4.67
	b	57.6	39.72	401.1	21567.34	21	1027.02	
**	c	8.68	13.39	69.4	31158.15	23		

$F_{tab,0.05,2,21} = 3.47$
action: reject null hypothesis

Observation Period 3 → 4

		$\bar{x}$	s	Σx	ANOVA Table			
**	a	55.24	17.9	441.9	6029.53	2	3014.76	10.04
	b	26.41	20.39	211.3	6303.97	21	300.19	
	c	18.3	12.82	146.4	12333.49	23		

$F_{tab,0.05,2,21} = 3.47$
action: reject null hypothesis

Observation Period 4 → 5

		$\bar{x}$	s	Σx	ANOVA Table			
	a	48.86	44.66	342.0	4405.75	2	2202.87	1.47
	b	14.04	27.74	98.3	26951.51	18	1497.31	
	c	37.37	42.2	261.6	31357.16	20		

$F_{tab,0.05,2,21} = 3.55$
action: accept null hypothesis

Observation Period 5 → 6

		$\bar{x}$	s	Σx	ANOVA Table			
	a	43.53	27.19	391.8	4497.16	2	2248.58	3.07
	b	41.33	33.52	372.0	17606.44	24	733.6	
	c	15.12	18.38	136.1	22103.6	26		

$F_{tab,0.05,2,24} = 3.4$
action: accept null hypothesis

Null hypothesis: the growth types observed conform to a distribution associated with the number of interior and exterior links produce a new type of network suited to the new gradient. The net result is then a composite network.

Discussion of changes in channel network pattern at the same time (Section 6.2.3) showed that after incision there was an increased tendency for subnetworks to merge with magnitude 2 or 3 subnetworks in the downstream direction. By using the geometric coding of growth types and the magnitude distribution and ambilateral class distribution files, it was possible to establish the type of growth which produced these new magnitude 2 or 3 subnetworks. The overall trend was toward bifurcation, but not significantly so, and the scale was tipped by a 75% preference for bifurcation on the geometric main stem.

When basin types were examined (Table 7.3), using the same technique, bifurcation once again proved to dominate, but no between-basin differentiation was detected, again, largely the result of considerable levels of within basin variation. It is convenient to assume that geology and drainage type play no role in the type of growth that occurs, except that for T and TI basins a difference may have been anticipated, the result of channel incision factors.

In basins in which subsurface piping has been shown to exist (Section 5.1), the collapse of these pipes will lead to the expression of a new channel. Collapse of the pipe is related to the material strength, the size of the pipe and the rate of excavation of the pipe, a surrogate of flow characteristics and material strength. Not all pipes collapse at the same moment in time.

Two considerations emerge from an understanding of pipe-into-channel evolution. First a pipe may be in existence long before the collapse to a channel occurs. This would lead to the occurrence of

Table 7.3 Distribution of growth types by basin type: statistical evaluation

Observation Period 1 → 2

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id		ANOVA Table		
$\bar{X}$	1.51	1.28	1.60	13	1.52	1.42	1.56	0.8	1.25	532.4	8	66.55	36.04
s	1.39	1.07	1.67	0.82	1.94	1.80	1.35	0.89	1.39	149.57	81	1.85	
ΣX	19.12	12.75	8	52	15.16	8.5	12.5	16.0	18.75	681.97	89		

$F_{tab,8,81,0.05} = 2.05$

LSD(0.05,81df) = 1.36

∴Sa basins are significantly different from all others in this observation period

Observation Period 2 → 3

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id		ANOVA Table		
$\bar{X}$	0.03	0.0001	0.45	0.1	0.4	0.4	0.42	0.26	0.06	2.51	8	0.31	1.99
s	0.06	0.0003	0.51	0.01	0.52	0.55	0.4	0.58	0.18	13.04	81	0.16	
ΣX	0.45	0.001	2.25	0.4	4.38	2	3.32	5.25	0.94	15.54	89		

$F_{tab,8,81,0.05} = 2.05$

no significant differences detected

Observation Period 3 → 4

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id		ANOVA Table		
$\bar{X}$	0.46	1.17	0.18	0.41	1.02	1.12	0.58	1.39	0.39	16.47	8	2.06	1.14
s	0.49	0.92	0.32	0.00013	1.07	0.85	0.73	2.46	0.73	151.4	81	1.80	
ΣX	6.97	11.68	0.92	1.64	11.27	5.58	4.66	27.79	5.78	167.87	89		

$F_{tab,8,81,0.05} = 2.05$

no significant differences detected

Observation Period 4 → 5

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id		ANOVA Table		
$\bar{X}$	0.02	0.07	0.002	0.1	0.04	0.02	0	0.2	0.2	0.66	7	0.09	0.63
s	0.07	0.12	0.0004	0.03	0.1	0.04	0	0.35	0.77	11.01	73	0.14	
ΣX	0.32	0.67	0.001	0.38	0.47	0.09	0	3.94	3.06	11.67	80		

$F_{tab,7,73,0.05} = 2.14$

no significant differences detected

Observation Period 5 → 6

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id		ANOVA Table		
$\bar{X}$	0.56	0.58	0.32	0.56	0.49	0.4	0.03	0.62	0.24	2.91	8	0.36	1.44
s	0.38	0.42	0.41	0.01	0.62	0.4	0.23	0.71	0.41	21.39	81	0.25	
ΣX	8.47	5.82	1.58	2.24	5.41	2.37	0.66	12.47	3.56	24.29	89		

$F_{tab,8,81,0.05} = 2.05$

no significant differences detected

Observation Period 6 → 7

data base too small for analysis

Table 7.3 Distribution of growth types by basin type: statistical evaluation, cont'd.

Observation Period 7 → 8

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id	
										1.92
$\bar{X}$	0.45	0.31	0.26	0.14	0.08	0.06	0.03	0.28	0.08	10.65
s	0.54	0.35	0.42	0.02	0.12	0.09	0.09	0.43	0.26	12.57
ΣX	6.69	3.10	1.31	0.56	0.86	0.35	0.25	5.62	1.17	

ANOVA Table

8	0.24	1.91
81	0.13	
89		

$F_{tab,8,89,0.05} = 2.05$

no significant differences detected

Observation Period 8 → 9

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id	
										2.42
$\bar{X}$	0.37	0.24	0.59	0.26	0.11	0.14	0.00001	0.07	0.01	7.73
s	0.55	0.32	0.64	0.02	0.17	0.14	0.00003	0.17	0.05	10.15
ΣX	5.61	2.41	2.93	1.04	1.26	0.84	0.0001	1.39	0.19	

ANOVA Table

8	0.30	3.33
81	0.09	
89		

$F_{tab,8,89,0.05} = 2.05$

LSD(0.05,81df) = 0.12
Tc differs from all others, Ta differs from all others
Sa ≡ Tb; but no others
Tb ≡ TIc; but no others. All others cannot be distinguished.

Observation Period 9 → 10

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id	
										2.6
$\bar{X}$	0.5	0.18	0.63	0.21	0.21	0.4	0	0.46	0.28	28.61
s	1.09	0.23	0.41	0.01	0.25	0.38	0	0.61	0.41	31.21
ΣX	7.47	1.76	3.13	0.84	2.34	2.42	0	9.23	4.16	

ANOVA Table

7	0.32	0.82
73	0.39	
80		

$F_{tab,7,73,0.05} = 2.14$

no significant differences detected

Observation Period 10 → 11

	Ta	Tb	Tc	Sa	Sc	TIc	TId	Ic	Id	
										34.72
$\bar{X}$	0.71	0.06	0.65	0.16	2.19	1.04	0	0.57	0.66	132.30
s	0.73	0.12	0.72	0.01	3.26	1.12	0	0.47	0.66	167.02
ΣX	10.54	0.58	3.25	0.64	24.09	6.25	0	11.32	9.93	

ANOVA Table

7	4.96	2.73
73	1.81	
80		

$F_{tab,7,73,0.05} = 2.14$

LSD(0.05,73df) = 0.97
Sc differs from all others
but the remainder are indistinguishable from each other.

Note: ≡ cannot be statistically distinguished from
≢ may be statistically distinguished from

interior branching should the network have already expanded well beyond the pipe location. Field studies of piping in 1983 showed this proposal to be true. Basin 54 contained 15 such pipes, varying from complete pipe to almost complete collapse. Several of the outlets were large enough to be explored.

Pipes of this size are, in hydrologic terms, enclosed channels. The discharge is similar to many of the open channels. As a result, the flow characteristics proposed under the pathnumber hypothesis is subject to some skepticism. Because it is unknown which newly formed channels in any timeperiod evolved from pipes, it is impossible to strictly interpret either the temporal distribution of the type of growth, or the temporal distributions of pattern.

Second pipes are the most likely factor contributing to bifurcation. Blong (1970), Heede (1974) and Dunne (1980) have all indicated that bifurcation occurs simply because headward channel growth has reached a point at which two pipes merge. The size of the pipe, and its contributory discharge are not important; preponderance is directed toward the role such pipes have on determining the future pattern of the network. Although pipe-induced bifurcation does not occur in all basins, it may be sufficient to help account for the preference of all growth types to bifurcation rather than branching.

7.3 Location of Growth

By adding the two types of exterior growth we can compare levels of interior and exterior growth over time and between basin types. Interior link magnitude, expressed as a percentage of the system magnitude, can be examined, and also the link path, as a ratio of the total interior path. Exterior links growths can also be examined using the path ratio.

In all cases the number of exterior links is far greater than the number of interior links and the distribution is non-random (Table 7.4). Tests of differences between and within basin type and time-period are presented in Tables 7.5 and 7.6 respectively. For exterior links geologic types a and b have no statistical differences, but neither type is considered statistically similar to types c or d. Why such a differentiation should occur is not apparent. One may have expected type d to be dissimilar or types a and c to be similar.

Interpretation of the results for drainage type is not much clearer, and it is considered that the statistical analysis was unsatisfactory for basin type comparison. Only one significant result was produced, that of differentiating type TId from all the other. Because the greatest magnitude of these basins did not exceed 22, and many were of magnitudes 10-12, the number of additions at any one time period is very small. This produced the unusual distribution of a growth being either 100% or 0% exterior at each time period, with only timeperiod 5 creating any growth at interior links.

Basins of this type were not known to support subsurface piping. Consequently, the argument concerning the timing of pipe collapse (Section 7.2) and its contribution to the location of growth is not applicable. Some error may have been introduced during the photo-interpretation phase because the steep slopes of these basins were frequently in shadow, which contributed to difficulty in detecting stream channels. Analysis of this type of data gathering error was not possible.

Table 7.4 Location of growth as a function of link magnitude

mag	# links added	random model expected	
1	3187	2489.6	*
2	326	521.3	*
3	201	247.5	
4	85	124.9	
5	40	58.2	
6	26	35.1	
7	21	24.2	
8	17	22.6	
9-20	26	31.2	*
21-60	21	52.7	*
> 60	19	47.6	*

* these magnitudes have observed distributions significantly different from the expected, at the 95% level of confidence

Table 7.5 Location of growth by basin type for exterior versus interior links

Comparison of exterior link distributions for geologic type

	$\bar{x}$	s	Σx	ANOVA Table			
a	9.25	4.91	92.5	11472.39	3	3824.13	21.24
b	32.05	15.91	320.5	6482.03	36	180.06	
c	49.69	18.69	496.9	17954.42	39		
d	9.51	9.69	95.1				

$F_{tab,0.05,3,36} = 2.86$

a significant difference exists between populations

LSD(0.05,20df) = $\pm$ 3.887

b $\equiv$ d but
b $\ddagger$ a $\ddagger$ c
d $\ddagger$ a $\ddagger$ c

Note: $\equiv$ cannot be statistically distinguished from
$\ddagger$ may be statistically distinguished from

Analysis of exterior growth by drainage type -- using proportions

	$\bar{x}$	s	Σx	ANOVA Table			
T	30.52	11.65	305.2	2705.54	3	901.85	6.52
S	25.6	15.8	256.1	4978.53	36	138.29	
TI	11.34	6.51	113.4	7684.07			
I	32.29	11.2	322.9				

$F_{tab,0.05,3,36} = 2.80$

the populations are significantly different at some place

LSD(0.05,20df) = $\pm$ 3.55

thus

T $\equiv$ I
and T $\ddagger$ S $\ddagger$ I
I $\ddagger$ S $\ddagger$ TI

Table 7.6 Location of growth by timeperiod for exterior links as a proportion of all links experiencing growth

	$\bar{x}$	s	Σx
1 → 2 (2)	11.01	10.05	99.1
2 → 3 (3)	3.42	3.36	30.8
3 → 4 (4)	2.95	2.01	26.58
4 → 5 (5)	5.28	10.94	47.5
5 → 6 (6)	10.27	5.92	92.4
6 → 7 (7)	6.11	6.04	55
7 → 8 (8)	2.97	1.53	26.7
8 → 9 (9)	13.6	8.19	122.4
9 → 10 (10)	15.34	9.02	138.1
10 → 11 (11)	28.97	14.82	260.7

ANOVA Table

5239.47	9	582.16	8.59
5422.31	80	67.78	
10661.78	89		

F = 1.99

$\therefore$ a significant difference between populations is present in the data

LSD (0.05,80df) = $\pm$ 2.75

thus
11 $\not\equiv$ any other time period
10 $\equiv$ 9, but 10 $\not\equiv$ any other time period
9 $\equiv$ 2 " 9 " " " " "
2 $\equiv$ 6 " 2 " " " " "
6 $\not\equiv$ 3,4,5,7 or 8
3 $\equiv$ 4 $\equiv$ 5 $\equiv$ 8
7 $\equiv$ 5 but not any other time period

Hence it is also clear that a difference lies between pre- and post-incision exterior growth

Note: $\equiv$ cannot be statistically distinguished from
$\not\equiv$ may be statistically distinguished from

Network growth at exterior links was found to be divided between S and TS type links. Figure 7.1 shows that the percentage of growth located on S links does not change significantly over time, when all networks are pooled. Growth on S-type links was observed by Parker (1977) and simulated by Howard (1971a) and Smart and Moruzzi (1971a, b), and it is this phenomenon that accounts for the descriptive observation of a "wave of dissection" sweeping toward the divide (Howard 1971b, p. 30).

One would expect that as the wave approached the basin divide this dominance of S-type growth would diminish, especially in those networks in which the network expanded toward the divide faster than it created new links (that is geometric growth of drainage density outstripped topologic growth of link density--see Section 7.4.2 for further discussion). This was not observed in such networks for time-period 11. Observation may not have proceeded for a long enough time for this development to occur.

Preference for S-type link addition can be demonstrated by simple ratio methods and the assumption of equal probability amongst all exterior links. If there are six S-type links and three TS-type links in existence and three new links are formed on the exterior links, it would be expected that two new links would be formed on the S-type links. Chi-squared values given in Figure 7.1 demands rejection of the hypothesis that exterior growth is related to the distribution ratio of S-type to TS-type links.

Theoretical implications derived from the S-link preference have notable consequence on the emergent pattern. Consider Figure 7.2. That our observations do not give 50% of all n=6 networks as class

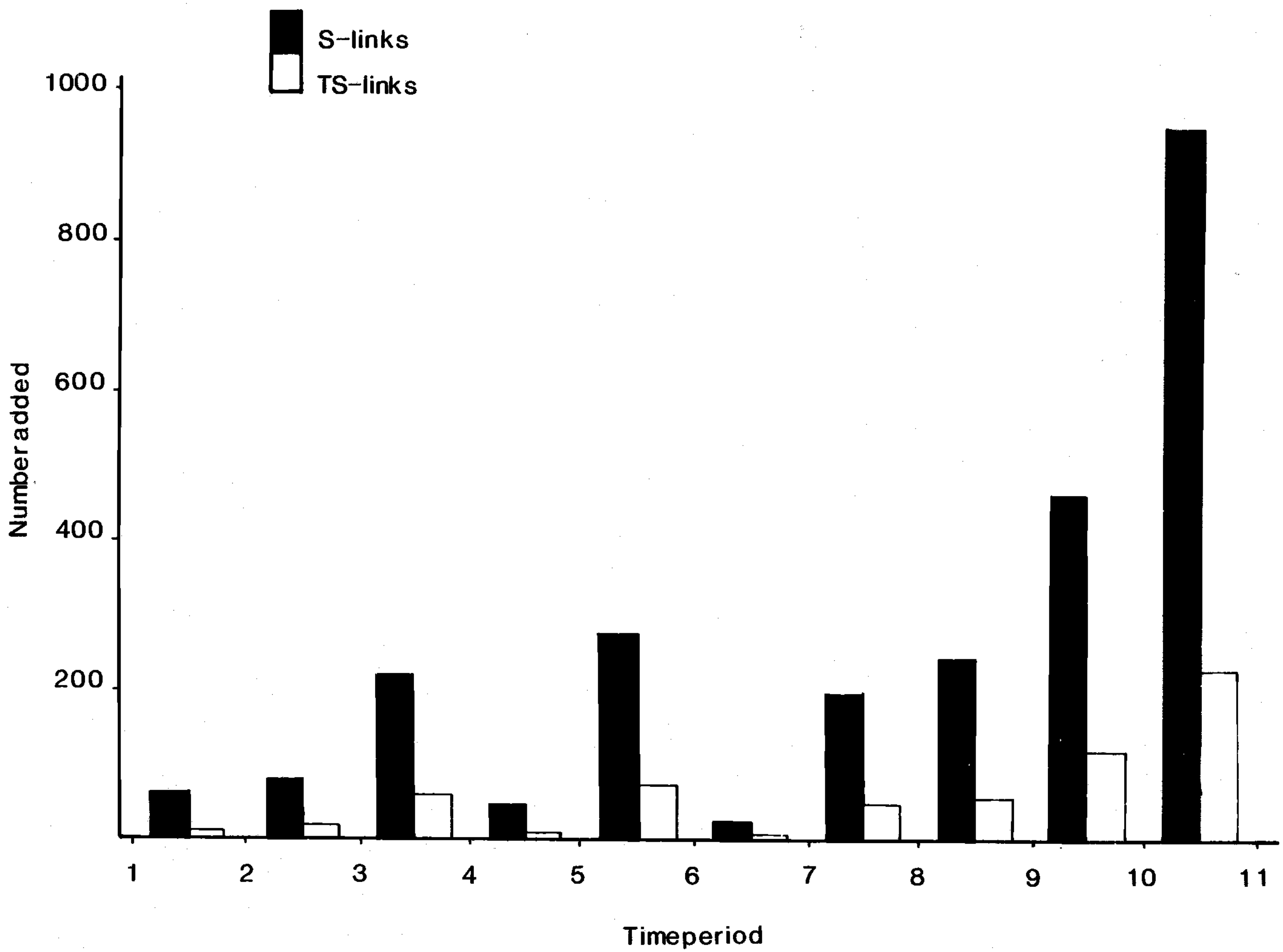
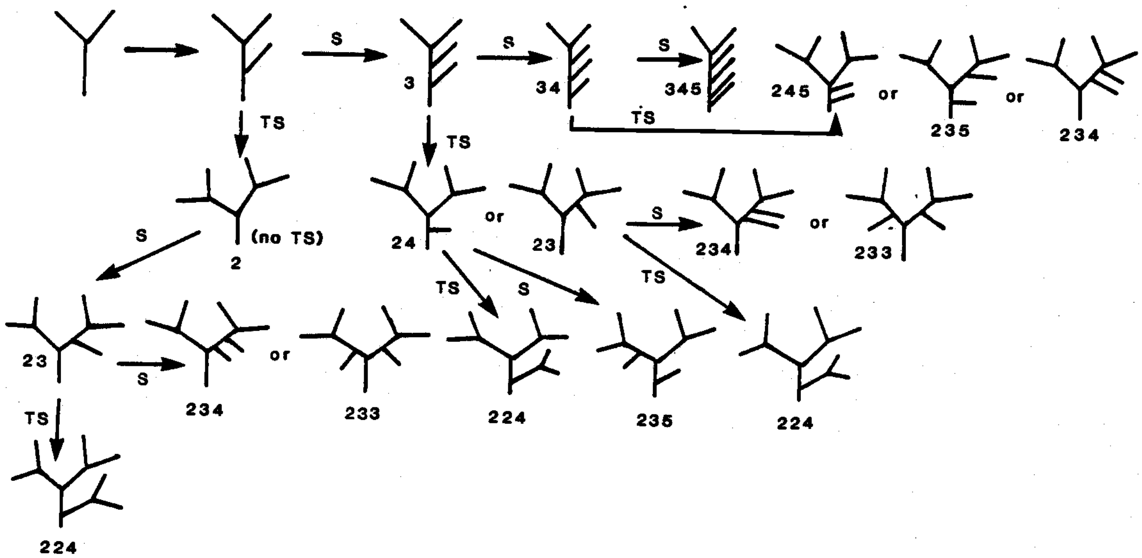


Figure 7.1 Growth at exterior links as classified by Mock's (1971) link-type

Schematically, a magnitude 2 network will evolve thus:



Given that exterior links are preferred 4:1 over interior links, and S-links 4:1 over TS links, the path

$(23) \rightarrow 3 \rightarrow 34 \rightarrow 345$

has, by the random addition model a probability of 0.381 but by the observed tendencies, a probability of 0.592 correspondingly, class 245 has

random addition model probability	0.142
observed tendency probability	0.026

class 224

random addition model probability	0.0347
observed tendency model probability	0.1416

Figure 7.2 Theoretical implications of S-link preference for the growth mode at exterior link

345 indicates that TS-link growth occurs frequently enough in small magnitude subnetworks to create a different structural distribution.

By examining the exterior link growth of only subnetworks n 8, the distribution of S or TS growth changed substantially, with TS links contributing in proportion to their numbers. Such a mode of contribution could help account for the rapidly diminishing frequency of maximum diameter networks as the network magnitude increased.

7.4 Growth Rates

Two types of network growth, the topologic and the geometric, are possible, and may be independent of each other. Geometric growth may be expressed in terms of drainage density, and the growth rate as a change in drainage density per unit time (Table 7.7). Topologic growth can be observed through changes in the link density over time or through changes in the rate of addition of magnitude over time. Link density changes are summarized in Table 7.8.

7.4.1 Changes in Drainage Density

The change in drainage density per unit time is partly a seasonal phenomenon, with the greatest changes occurring in the winter months. In general type TId and Id basins experienced their greatest drainage density changes during the early period of network growth, while Ic and Sc basins experienced most of their growth during the latter part of the study.

7.4.2 Changes in Link Density

Link densities were lowest in type Tb basins during the early part of the study, but by the end of the study period, type TId basins were also of low link density. Link density was highest for Ic basins in timeperiod 11.

Table 7.7 Changes in drainage density over time

basin	timeperiod 1	2	3	4	5	6	7	8	9	10	11
1	18	72	-	154	254	263	-	-	-	-	-
2	-	-	-	-	-	-	-	-	11	111	333
3	-	-	-	-	-	-	-	-	57	171	485
4	-	20	40	80	-	115	-	245	-	-	-
5	43	100	-	200	-	286	457	571	-	-	-
6	-	9	-	19	38	76	-	-	214	276	304
7	-	5	-	19	-	33	-	40	79	130	181
8	8	16	-	18	24	52	-	68	-	82	94
9	5	11	-	24	-	32	-	53	89	97	-
10	5	-	-	9	-	-	-	-	18	54	-
11	4	8	-	12	15	35	-	46	65	-	-
12	14	29	-	86	114	228	-	-	-	-	-
13	13	25	-	100	-	-	-	163	200	-	-
14	-	-	-	21	-	50	-	78	88	95	-
15	13	38	88	156	-	250	-	288	419	700	1150
16	7	66	-	146	160	206	-	-	226	280	353
17	14	51	-	200	-	342	-	-	371	-	485
18	11	44	-	67	-	78	133	156	200	267	489
19	33	133	-	-	-	-	-	-	200	267	733
20	100	-	-	-	-	200	-	-	-	-	1270
21	33	-	133	-	-	200	-	-	-	-	233
22	33	-	-	-	-	67	-	-	-	150	387
23	100	-	-	400	-	800	-	-	-	-	1000
24	50	250	-	400	-	650	-	-	-	-	800
25	50	100	-	-	-	-	-	250	-	-	625
26	150	-	-	-	-	-	-	-	-	-	500
27	50	-	-	-	100	200	-	300	-	650	1100
28	150	470	1081	-	-	-	-	-	-	-	-
29	17	26	34	40	47	53	67	100	249	467	1183
30	50	150	-	-	-	400	-	450	-	-	500
31	17	33	67	100	-	350	-	467	500	-	-
32	1000	2000	-	-	-	-	-	-	-	-	-
33	250	500	1000	-	-	-	-	-	-	-	-
34	-	200	300	-	900	-	-	-	-	-	1100
35	66	116	158	267	-	283	-	350	425	-	-
36	-	36	116	267	-	-	-	316	400	433	-
37	-	100	-	600	-	-	-	-	-	800	1000
38	-	100	200	500	600	-	-	-	-	800	1100
39	-	400	-	-	-	-	-	-	500	600	1000
40	130	200	333	-	-	-	-	-	-	-	700
41	100	600	1000	-	-	-	-	-	-	-	-
42	50	200	-	300	-	350	600	-	-	-	-
43	100	-	-	600	-	1000	-	-	-	-	-
44	100	400	600	800	1000	-	-	-	-	-	-
45	100	400	900	1000	1100	-	-	-	-	-	-
46	80	160	320	440	-	860	-	1040	1120	1300	1580

basin	timeperiod 1	2	3	4	5	6	7	8	9	10	11
47	-	100	-	400	600	-	-	-	-	-	2070
48	20	80	-	-	-	120	-	-	-	180	550
49	-	100	-	-	-	800	1200	-	-	-	1300
50	25	-	-	-	-	-	-	-	-	50	250
51	18	54	109	155	-	-	-	-	240	372	1018
52	100	500	1000	-	-	-	-	-	-	-	-
53	-	100	-	750	-	-	-	-	-	-	-
54	-	22	66	125	-	430	-	-	616	711	1544
55	-	-	-	-	-	-	25	100	250	475	1475
56	-	80	160	260	-	360	-	-	-	720	1640
57	-	-	-	-	-	100	-	-	200	450	500
58	33	200	400	470	-	570	-	600	630	-	800
59	-	133	167	-	-	-	-	200	250	433	617
60	6	-	-	50	81	175	-	-	-	275	681
61	100	-	-	-	-	-	-	-	-	400	1000
62	100	-	-	-	-	-	-	-	-	400	1400
63	100	-	-	-	-	300	-	-	-	-	1100
64	100	-	-	-	-	400	-	-	-	-	3100
65	9	-	-	18	-	-	-	55	-	127	309
66	-	-	-	-	-	-	-	-	100	200	400
67	50	200	-	400	-	700	-	-	-	-	-
68	33	-	-	66	-	200	-	400	-	5475	508
69	8	33	50	75	117	-	-	153	150	275	600
70	14	-	-	49	114	-	-	143	-	271	800
71	13	-	-	51	200	-	-	257	300	342	563
72	33	133	-	233	-	-	-	266	-	300	400
73	22	133	-	278	-	377	-	44	511	622	956
74	6	27	54	180	213	293	-	400	473	613	967
75	-	66	266	466	-	-	-	-	600	-	1467
76	17	-	-	100	133	150	-	-	233	-	483
77	150	250	450	-	-	-	-	-	-	700	-
78	20	180	260	-	-	-	-	-	-	-	280
79	12	71	80	112	124	194	207	236	298	343	418
80	23	42	52	-	-	71	84	103	122	190	-
81	23	35	-	81	92	185	208	312	538	738	1065
82	11	61	74	147	-	233	-	342	421	463	752
83	52	113	130	161	-	217	-	270	348	439	478
84	14	85	-	200	-	386	-	457	486	-	600
85	-	40	-	80	-	160	-	280	-	-	460
86	-	-	-	-	-	-	-	33	133	-	400
87	-	14	-	57	-	85	-	-	-	-	185
88	-	-	-	-	-	100	200	400	-	800	1200
89	-	100	200	-	-	400	-	600	-	-	1100
90	-	50	-	-	-	200	-	400	-	-	600
91	-	25	-	200	-	300	-	375	550	625	-

Table 7.8 Changes in link density over time

basin	timeperiod 1	2	3	4	5	6	7	8	9	10	11
1	19.0	44.6	-	14.4	3.4	18.6	-	-	-	-	-
2	-	-	-	-	-	-	-	-	18.8	34.6	46.6
3	-	-	-	-	-	-	-	-	33.6	25.8	41.6
4	-	24.7	15.75	27.8	-	27.53	-	4.5	-	-	-
5	29.7	15.2	-	19.06	-	12.25	13.04	10.75	-	-	-
6	-	11.99	-	18.26	10.48	13.46	-	5.61	9.57	20.23	10.40
7	-	13.64	-	14.39	-	9.63	-	6.64	18.27	17.52	19.91
8	3.64	6.81	-	6.47	8.29	23.58	-	11.65	-	19.84	19.76
9	4.15	40.44	-	3.30	-	24.64	-	13.27	8.3	5.55	6.39
10	15.98	-	-	44.16	-	-	-	-	10.14	25.42	4.83
11	12.78	12.96	-	13.39	4.95	9.14	-	20.08	8.44	12.27	6.00
12	23.84	19.97	-	8.95	13.12	11.77	-	-	9.09		3.58
13	9.38	15.38	-	14.69	-	-	-	19.73	9.87	34.96	3.81
14	-	-	-	30.72	-	43.19	-	12.95	4.15	8.99	-
15	2.66	9.17	8.47	14.23	-	8.74	-	1.66	11.75	27.45	15.86
16	12.73	30.63	-	14.70	2.14	7.29	-	5.87	8.19	1.42	17.09
17	2.20	7.59	-	21.65	-	24.47	-	-	12.5	-	12.27
18	9.35	12.21	-	4.76	-	5.21	4.71				
19	14.35	4.35	-	9.13	-	7.39	-	13.91	8.26	2.3	39.17
20	8.64	5.56	-	14.2	-	13.56	-	7.41	13.58	-	37.04
21	5.04	6.16	-	7.57	-	7.84	-	-	19.52	16.44	37.42
22	23.21	10.12	-	5.06	-	25.89	-	-	-	14.88	25.89
23	27.55	41.84	-	-	-	-	-	30.61	-	-	-
24	13.33	19.63	-	-	-	-	-	21.85	-	-	45.19
25	22.6	16.95	-	7.91	-	-	-	24.29	-	-	29.36
26	40.31	23.26	-	-	-	-	-	-	-	-	36.43
27	13.95	-	-	7.12	-	19.88	-	6.82	4.15	18.49	29.08
28	4.41	-	-	3.85	-	17.99	7.01	10.41	-	30.32	26.02
29	0.77	5.75	5.58	9.02	2.12	4.23	3.16	12.13	8.50	19.46	29.28
30	-	17.47	-	-	-	-	-	15.95	42.78	-	23.80
31	23.68	11.84	-	-	-	23.68	-	34.22	-	-	6.58
32	25.69	25.01	-	-	-	-	-	23.94	-	-	25.35
33	33.6	25.8	27.1	-	14.5	-	-	-	-	-	-
34	-	34.6	-	21.52	-	-	-	-	-	-	43.92
35	22.43	32.61	22.33	7.89	-	4.05	-	8.10	2.60	-	-
36	-	22.74	18.98	25.75	-	12.41	-	3.38	5.08	6.58	5.08
37	-	21.65	-	38.34	-	12.03	-	-	-	15.20	12.78
38	-	41.18	-	-	-	-	-	18.82	17.65	22.35	-
39	-	53.33	-	-	-	-	-	20.07	20.00	-	-
40	27.46	31.79	-	-	-	-	-	-	-	-	40.75
41	32.14	24.02	43.84	-	-	-	-	-	-	-	-
42	15.79	43.61	-	21.80	-	9.21	9.59	-	-	-	-
43	29.09	13.33	-	41.82	-	15.76	-	-	-	-	-
44	29.41	17.35	9.82	23.63	7.51	12.28	-	-	-	-	-
45	7.52	24.61	16.82	10.40	39.99	-	-	-	-	-	-
46	5.07	16.47	6.42	4.00	-	27.68	-	11.11	5.85	10.33	13.26
47	-	21.35	-	38.74	-	11.96	-	-	4.21	-	23.74
48	24.21	4.72	-	8.66	-	25.20	-	-	-	12.60	24.41
49	-	11.57	-	-	-	10.32	19.23	17.89	14.56	16.81	9.62
50	16.92	-	-	10.01	-	19.22	-	-	-	26.92	26.92
51	7.21	8.13	5.73	8.23	-	-	-	-	8.08	21.81	40.85
52	18.24	46.62	29.05	-	-	-	-	-	-	-	6.08
53	-	15.88	-	29.41	-	-	-	20.00	-	-	34.71
54	-	13.91	5.42	7.84	-	9.78	-	1.41	6.98	20.43	34.26
55	-	-	-	-	-	-	-	6.87	22.33	16.90	53.92
56	-	5.79	17.96	6.60	-	8.69	-	7.53	12.51	17.38	23.54
57	-	-	-	-	-	36.04	-	9.16	22.14	32.06	-
58	14.73	18.24	18.68	6.15	-	17.58	-	6.59	10.55	-	7.47
59	-	-	31.06	-	6.28	-	-	9.16	16.88	16.70	19.93
60	3.61	8.76	-	2.61	7.76	15.82	0.84	-	-	28.88	31.72
61	14.25	-	-	-	-	11.85	9.21	16.58	21.30	13.56	13.25
62	17.85	-	-	-	-	8.25	16.56	11.25	15.56	9.30	21.21
63	10.23	-	-	-	-	18.45	7.12	14.26	19.20	17.56	17.18
64	23.47	-	-	-	-	19.26	2.14	11.70	14.52	15.63	13.28
65	-	16.41	-	17.07	-	2.19	-	36.76	-	19.04	8.534
66	-	-	-	-	-	14.46	9.54	3.38	7.38	31.38	33.85
67	21.71	14.86	-	5.71	-	22.29	-	-	-	-	35.43
68	15.11	28.30	-	1.37	-	17.86	-	8.79	-	14.56	14.01
69	1.31	8.96	5.36	16.28	4.81	4.04	-	5.68	5.90	19.45	28.20
70	-	3.38	-	14.94	7.53	-	-	6.10	17.32	-	44.68
71	-	9.94	7.20	7.49	-	4.32	-	19.02	11.10	11.53	29.39
72	20.00	25.22	-	17.39	-	-	-	11.30	11.74	-	14.36
73	13.53	13.04	-	17.49	-	16.39	-	6.16	8.14	11.44	13.20
74	4.6	1.4	9.7	8.5	7.6	7.5	-	15.2	16.1	11.2	18.2
75	-	26.57	7.74	10.67	-	-	-	-	12.76	-	42.26
76	17.34	-	-	17.03	5.57	20.74	-	-	10.53	-	28.79
77	19.80	26.53	28.32	-	-	-	-	-	-	25.35	-
78	37.68	35.27	-	-	-	-	-	-	-	-	27.05
79	24.16	18.96	3.34	5.77	5.53	10.68	2.10	4.00	13.53	7.54	4.38
80	49.16	11.42	3.47	-	-	9.34	-	9.33	8.84	8.44	-
81	8.47	3.58	-	6.02	0.98	11.29	4.56	15.65	18.37	19.45	11.63
82	6.21	5.70	9.25	9.61	5.64	19.44	-	9.73	12.90	21.52	-
83	41.70	9.27	6.71	6.64	-	10.16	-	5.13	10.39	7.40	2.60
84	25.61	8.54	-	20.38	-	14.14	-	11.34	2.55	3.69	13.75
85	-	41.30	-	10.02	-	19.33	-	8.26	-	9.49	11.60
86	10.55	-	-	6.91	-	-	-	10.18	13.82	-	58.55
87	13.95	-	-	-	-	14.63	-	29.25	10.90	-	31.27
88	29.81	-	-	-	-	39.42	-	8.65	5.00	-	17.12
89	-	33.81	-	-	-	9.96	-	15.66	19.34	10.24	11.03
90	19.26	-	-	21.38	-	15.84	-	23.78	-	-	19.74
91	-	17.57	-	10.86	-	3.35	-	4.80	38.34	16.93	8.15

change expressed as $\frac{DDn}{DDN} - \frac{DDn-1}{DDN} \times 100$

where n = current timeperiod

n-1 = last timeperiod in which geometric growth occurred

N = time period of greatest drainage density (DD)

When the drainage density is higher than the link density in relative terms of basin-type comparisons, the inferred interpretation is toward a rapid establishment of a basic network structure, which, as time progresses, is filled in by secondary networks. Thus the mean link length, $\bar{\ell}$, is an important quality of network growth. The greater its value, the less developed the topological structure of the basin; the smaller the value, the more highly branched the network. Basins of type Tb do not significantly change the value of mean link length over time. In contrast, basin Sa with a very high initial value, has, by timeperiod 11, become a highly branched network.

7.4.3 Magnitude Growth Rates

By magnitude in this section reference is made to the system magnitude, denoted by n. Distributions of magnitude change over time are given in Table 5.1. Magnitude growth, in absolute terms, is portrayed in Figure 7.3.

Even with the limited number of data points available, two trends are immediately noticeable in Figure 7.3, with the transition from one to the other occurring between timeperiod 8 and timeperiod 9. The mean rate for the period TP 8 TP 11 is 232 links per month, or 2.54 links per month per basin. For the preceeding eight intervals the mean growth rate is only 76.7 links per month, although the variability about this mean is much greater (σ = 48.87 compared with 2.51 for the former group). With t = 5.32, the difference in populations is significant even at the 0.001 level.

Perhaps magnitude growth rate is the most definitive of the comparisons made in this study of the effect of incision of the North Fork Toutle River on network properties. Scale factors play an

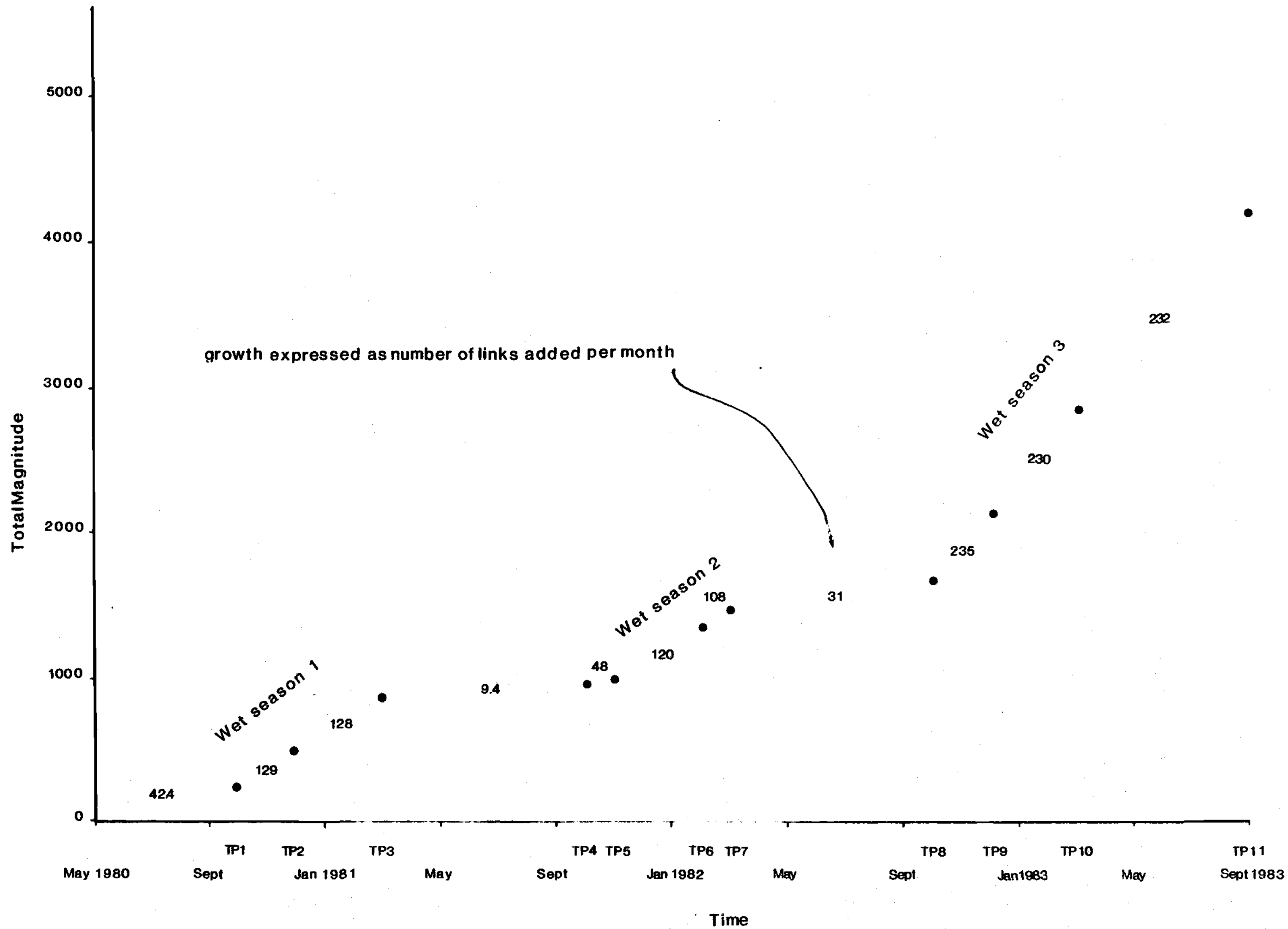


Figure 7.3 Absolute magnitude growth and the between-timeperiod growth rates

important role in comparisons of network properties such as growth rates, and the size of the network at the start of a growth session may play a role in determining between-basin comparisons. Data can be "normalized" by using the percentage of new additions to the starting magnitude. As seen from Figure 7.4 this method greatly exaggerates the growth rate between timeperiod 1 and 2; this tendency is observed for all basin types.

However, there are other factors highlighted using this technique. The graphs of Figure 7.5 show the by-basin type growth rate as a percent of starting magnitude. Emphasis on the post-incision rates is demoted, with the rate of period 5→6 becoming important for all basins except comprised of shallow pyroclastics overlying debris avalanche material (type c). In type-c basins the mean post-incision rate is still greater than pre-incision rates, but not significantly. Also apparent is the lack of differentiation of post-incision rates from the previous three pre-incision rates for geologic type d, where growth rates were at a maximum early during the course of the study.

Greatest growth rates per unit size were observed for Ic basins, and the slowest rates were recorded in basins with internal drainage and hummocky debris avalanche materials (type Id). Clearly the latter basins were limited by both small size and by internal drainage restraints, plus the nature of the geologic material, the relatively impermeable and slowly erodible debris avalanche deposits. Link density for Ic basins is also very high, suggesting that the growth rates were due solely to the material's properties.

What of drainage type influence on the rate of magnitude expansion? One hypothesis envisages an increase in the rate of

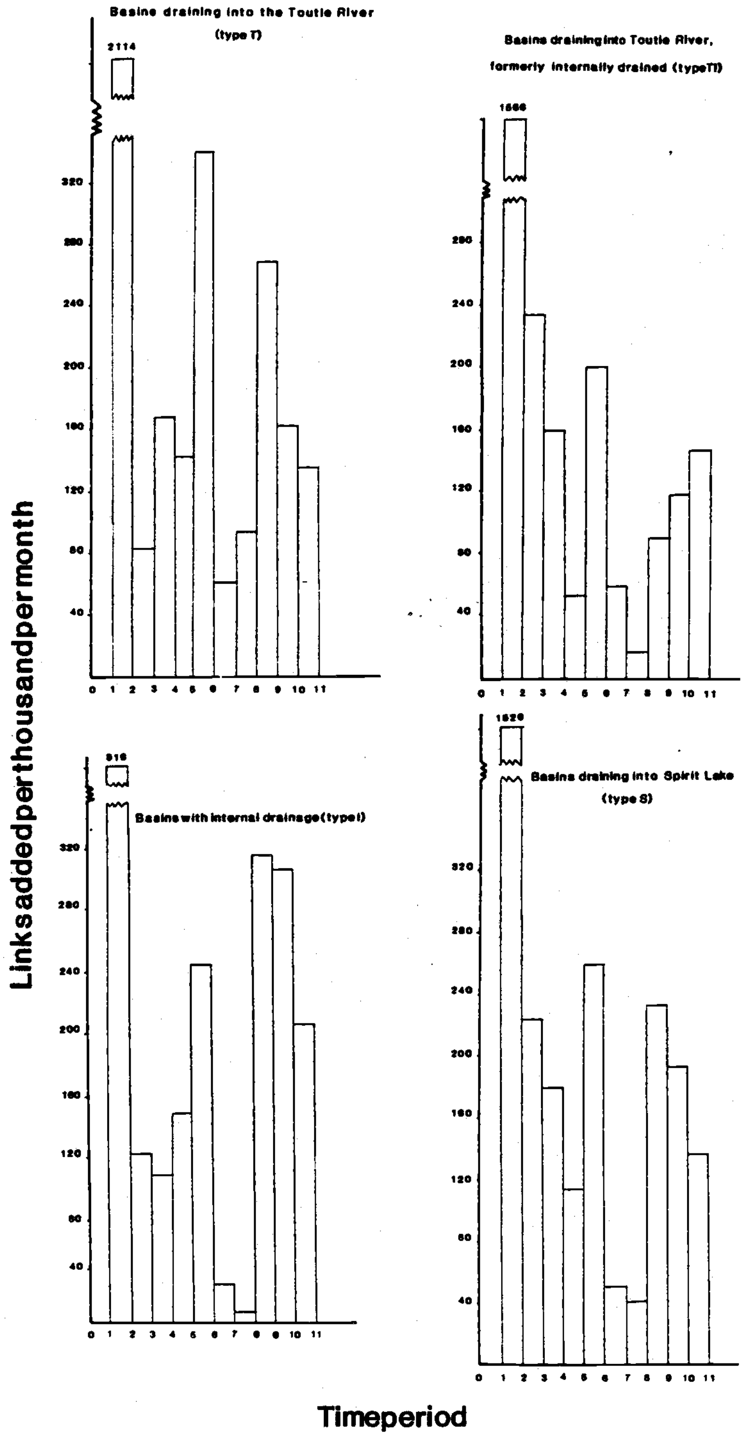


Figure 7.4 Magnitude growth rates by drainage type, over time

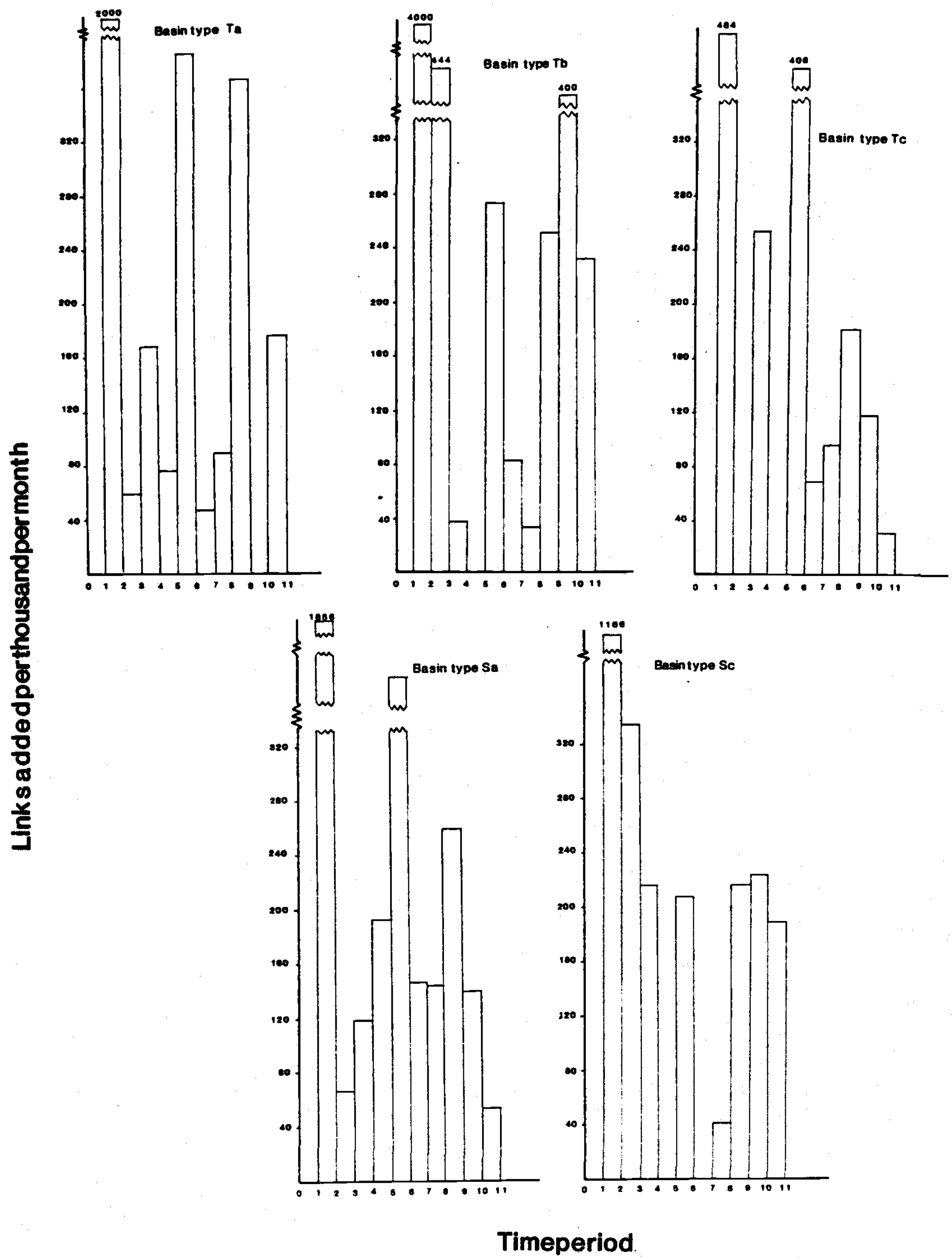


Figure 7.5 Magnitude growth rates, by basin type, over time

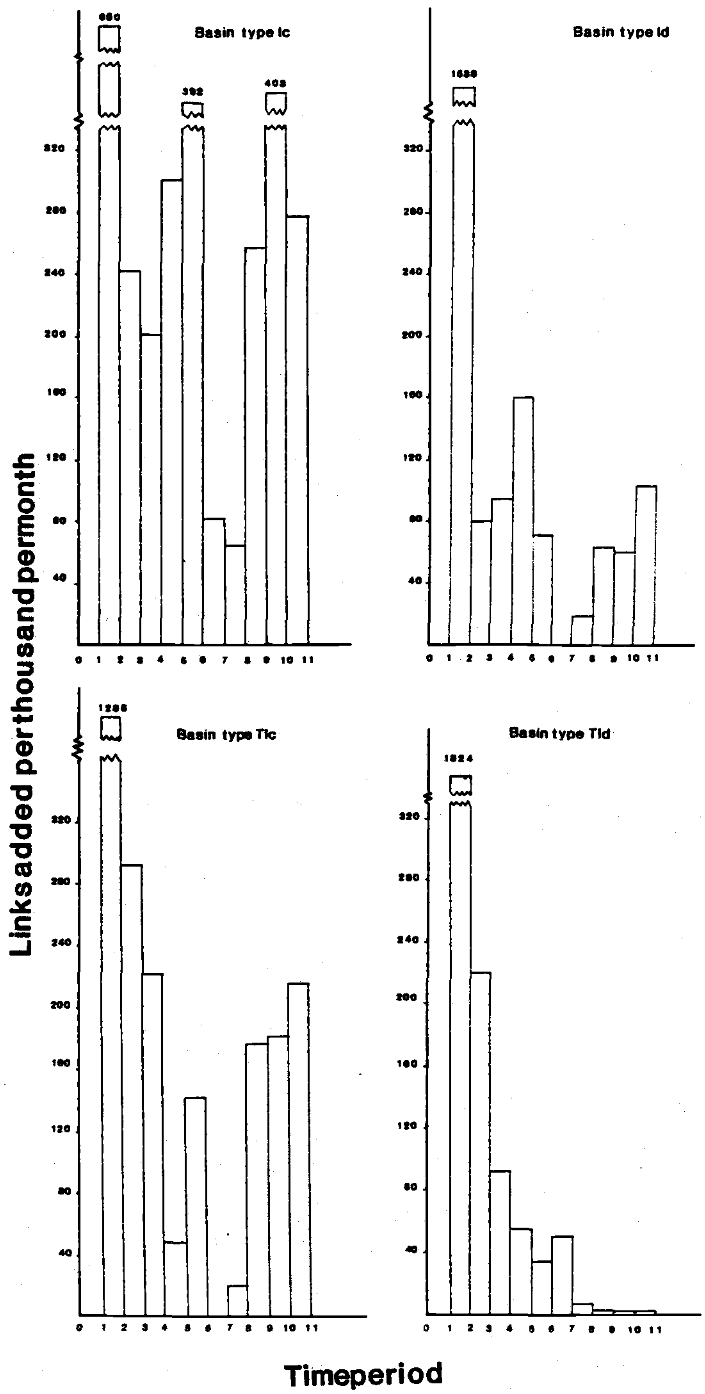


Figure 7.5 Magnitude growth rates, by basin type, over time, cont'd.

magnitude expansion for basins draining to the North Fork Toutle River (type T) and basins formerly drained internally but now captured by the North Fork Toutle River (type TI) that was greater than and different from the Spirit Lake (type S) and Internally (type I) drained basins. Only TI basins showed any notable differences (Figure 7.6), having both a lower mean rate in the post-incision period and an increasing rate of magnitude expansion during that period. The other three drainage types had an increased mean rate (although not significant, and a decreasing rate of growth with each successive observation set.

Plausible explanation for the trend in growth rate leads to a partial answer to the actual rate differences. The rate of incision of the North Fork Toutle River was extremely rapid, with 20-25m entrenchment in the first two months. Reaction by the basins draining directly to the river was in phase with the incision but propogated up the network. On the other hand the captured basins awaited the migration of successive knickpoints before "rejuvenation" processes were initiated. Spirit Lake levels dropped five meters in two months and the groundwater table followed suit but more slowly. Thus type S and I basins experienced similar, if less pronounced, conditions to those of T-type basins.

An attempt was made to differentiate the within-time-period basin-by-basin growth rates using analysis of variance and the spatially normalized data base (Table 7.9). Only two time periods allowed basin type differentiation. For the period $1 \rightarrow 2$ basin type Sa had a significantly greater rate than the others, while in period $10 \rightarrow 11$ basin type Sc stood out from basins Ta, Tc, TIc, Ic and Id and in turn

Table 7.9 ANOVA table for magnitude growth rates by time

data units as $\frac{\text{increase in magnitude}}{\text{original magnitude x months of observation}}$

data base

	1	2	3	4	5	6	7	8	9	10
Ta	.76	0.01	.07	.02	.19	0.01	.06	.19	.17	.12
Tb	.64	0.0001	.17	.07	.19	0.02	.04	.12	.06	.01
Tc	.8	.15	.03	.0002	.11	0.08	.04	.30	.31	.11
Sa	.65	.03	.06	.1	.19	0.08	.02	.13	.07	.03
Sc	.76	0.13	0.15	.004	.16	0.01	0.01	.05	.07	.37
TIc	.71	0.13	.16	.02	.013	0.01	0.01	.07	.13	.17
TId	.78	.14	.08	.001	0.03	0.01	0.005	.0001	0	0.1
Ic	.4	.09	.2	.02	0.21	0.01	0.04	.04	.15	.1
Id	.63	.02	.06	.2	.08	0.02	0.01	0.005	.09	.11

	→ 2	→ 3	→ 4	→ 5	→ 6	→ 7	→ 8	→ 9	→ 10	→ 11
$\bar{X}$	.68	-0.08	0.11	0.05	.14	0.02	0.03	.1	.12	.12
S	.12	0.06	0.06	0.07	.06	0.02	0.02	.1	.09	.10
ΣX	6.13	0.70	0.98	0.44	1.29	.2	0.24	.91	1.03	1.12

ANOVA Table

3.01	9	0.33	F = 56.02
0.48	80	0.01	
3.49	89		

LSD(0.05,80df) = 0.14

∴ only observation period 1 → 2 can be distinguished from the others all these were distinguishable in terms of faster rates from the rest. No conclusive explanation was found for these groupings of differences.

Overall the results of the ANOVA tests, with five different types of data base including a seasonally adjusted base, were considered inconclusive. It was apparent that both spatial and temporal variability in the study area were of such size with respect to mean values that the ability to differentiate was swamped by the wide range of observations for each class.

Examination of growth by assessing the changes in network magnitude over time has the potential for an allometric approach. The linear nature of growth portrayed by this study is not allometric. The incorporation of a decay rate as the network approaches the watershed boundary cannot be detected. Indeed what is observed suggests that when exterior links filled the headwater region, magnitude growth comes to an abrupt halt. Link density and drainage density apparently play no part in this termination. As is clear from Tables 7.7 and 7.8 there are no consistent trends, no decay rates of internal densities that prevail across basin types or basin areas. To propose an allometric growth model that cannot forecast growth cessation using morphometric measures defeats the tenets of its construction.

Further research into the factors which contribute to this linear growth rate seem appropriate. The expected peak of growth and its decay with network convergence on the divide were not observed. It cannot be stated with certainty that the linear magnitude growth mode is not a function of the pecularities of these studies basins.

7.5 Growth Pattern

The growth pattern is described in terms of the production of a new ambilateral class from a subnetwork of the prior timeperiod--the outlet-to-source or growth-up methodology of Section 4.5.2. One aim of this approach is to trace the link-by-link growth of a pattern to elucidate any particular pattern growth paths that might be preferred. Accomplishment of this task with any level of statistical validity would have required a much larger study sample than that which was available. In the growth of a magnitude 3 subnetwork to a magnitude 8 subnetwork, there are a total of 2,630 definable paths, each with a calculable probability.

Summaries of the observed growth pattern are presented in Table 7.10. Pattern change does not occur in TId type basins until n=6 or 7, the maximum diameter ambilateral class prevailing until that size is obtained. The next growth stage is the formation of a shorter path class, frequently by addition to the TS link closest to the outlet. Growth by this route has a fairly high probability (p = 0.242 for n=7, class 3456) using the known path method; by the TDCN ratio method class 3456 only has a probability of 0.059.

Only one growth path is available by which maximum diameter networks can be formed. Once departed from this path there is no return. Using the study data it was noted in Section 7.3 that 66-68% of the time new links were added to existing S-type links, and that growth on interior links occurs 15-18% of the time. Thus for an n=7, d=7 network the difference between the growth path probability and both the TDCN probability and study frequency for growth to n=8, d=8 network is considerable (0.61 vs. 0.149 vs. 0.31-0.86). That the observed occurrence of n=8, d=8 networks is only 0.153 suggests not that the random model method is correct--if it were why does it consistently underpredict maximum diameter networks for n<8--but that some mechanism is at work which then favors growth on the TS links.

Retrenchment of the North Fork Toutle River was shown (Section 6.2.3) to cause an increase in the number of n=2, n=3 subnetworks of n=7 ambilateral classes; nota bene, this was achieved using Smart's (1978) method. Exclusion of time periods 9, 10, and 11 from the location of growth data has an effect on the study value, dropping the percentage of growth at S links to 72% of the time. This is a significant difference ($t_{crit} = 2.04$, $t_{tab,0.05,2000df} = 1.97$) but does not improve the prediction of growth from class 3456 to a class in n=8. Nor can it be attributed to prediction under the random model; the maximum diameter classes as a whole (n<8) have significant positive deviation from the random model expected frequency ($\chi^2 = 87.43$, $\chi^2_{tab,0.05,44df} = 55.76$, χ^2 calculated using contingency table method).

At the other extreme, the minimum diameter group show definite temporal trends, but only the "internal drainage" basins consistently possess these patterns within the random model predictions. Again, the number of paths by which a minimum diameter network can be formed are extremely limited. For class 22244 only five paths exist. The precursor class 2234 is only observed approximately 33% of its predicted value. For class 2234 its origins come from class 233, which is significantly more abundant than expected, and class 224 which fits the random model expectation. Class 233, it would appear, evolves into class 2334 (significantly more abundant than expected) rather

Table 7.10 Observed network development by the growth-up method

Growth path	#observed	Growth path	#observed
3 → 23 → 224 → 2234	11	→ 34 → 234 → 2235	15
→ 2235	0	→ 2245	13
→ 2245	0	→ 2334	12
→ 2246	1	→ 2345	1
→ 233 → 2234	4	→ 2346	0
→ 2334	17	→ 235 → 2235	15
→ 2336	3	→ 2246	2
234 → 2235	1	→ 2336	16
→ 2245	2	→ 2346	0
→ 2334	4	→ 2356	12
→ 2345	9	→ 245 → 2245	4
→ 2346	5	→ 2246	11
→ 235 → 2235	21	→ 2356	8
→ 2246	0	→ 2456	5
→ 2336	14	→ 345 → 2345	1
→ 2346	0	→ 2346	0
→ 2356	1	→ 2356	12
3 → 24 → 224 → 2234	10	→ 2456	9
→ 2235	21	→ 3456	46
→ 2245	7	3 → 23 → 224	22
→ 2246	0	→ 233	28
→ 235 → 2235	3	→ 234	13
→ 2246	4	→ 235	36
→ 2336	10	3 → 24 → 224	17
→ 2346	1	→ 235	36
→ 2356	4	→ 245	7
→ 245 → 2245	2	3 → 34 → 234	81
→ 2246	0	→ 235	64
→ 2356	11	→ 245	15
→ 2456	5	→ 345	179

N.B. There were also 34 observations of incompletely charted paths. These paths were the result of multiple link addition to subnetworks that could not be resolved into simple link addition. These incomplete paths are not included because of the additional space required. However, incomplete paths have higher probabilities than completely charted paths (except for maximum diameter systems) because the intermediate steps are all included; the true path is, of course, unknown, and all possibilities must be included.

than either class 2336 or class 2234. Once again an ambilateral class with a pathnumber that could produce a mid-sized, mid-distribution hydrograph peak has emerged as a favored pattern.

Also of this pathnumber group is class 2235. This class can arise from classes 234, 235, and 224. It has already been noted that class 224 is within the random model bounds, but, of all its progeny (2235, 2234, 2245 and 2246) only class 2235 exceeds expectation. All the others are not observed with a frequency that would be expected under the random model. Of the n=8 classes which can be derived from classes 2235 and 2334, it is the pathnumber 124422 which is most abundant and exceeds expectation, with pathnumber 122442 being well represented. Only class 22335 is underrepresented--it has a pathnumber, 12462.

A clustering of all the networks with "central tendency" of pathnumber indicates that as a group, over all time periods, they are observed more frequently than expected. Pathnumbers which lead to excessive peakedness or to "delayed tendency" are less frequently observed than expected.

Based upon the evidence of this study, it is concluded that pathnumber is a useful topological property by which the growth of network pattern in the Spirit Lake area can be explained.

Why, then, if pathnumber explains the tendency toward a topologic pattern in the study networks, do the other, less favorable patterns exist? The answer may be two-fold. First this study and the methods of analysis used, has partitioned networks into subnetworks and examined their patterns. The internal arrangement of subnetworks may be of such a manner that the overall pathnumber has the desired tendency. This is easily examined.

Consider first the pathnumbers described for n=7 subnetworks in Table 6.6. A proposal was made which ranked pathnumber preference in terms of hydrograph peakedness and time-to-peak. If two 12442 pathnumber subnetworks converge at a downstream link the result is a 124884 system. Similar additions can be performed for all n=7 combinations, and other sets of smaller subnetworks.

Non-ideal combinations exist at the diameter extremes, but mixing of diameter extremes leads to moderate pathnumbers. Mixing of moderate pathnumbers preserves the status quo: a moderate and maximum diameter mix produces a pathnumber with a long base-flow tail. Ultimately, the internal arrangement of subnetwork patterns will produce a basin-wide network that has characteristics which reflect the pathnumber most suited to a site-specific hydrologic response. As yet this type of research has not appeared in the literature.

Figure 7.6 presents the internal arrangement of ambilateral classes ($n \leq 7$) for five selected networks of basin type Ic and three of type Ta. These networks were selected because of their relatively large magnitudes. As 37 study basins have magnitudes less than 20 a selection of eight of the largest is not unreasonable.

This sample shows that the internal arrangement of ambilateral classes favors moderate peaked, mid-timing type pathnumbers as one progresses toward the outlet from headwater regions. Not insignificant in the maintenance of such pathnumber are the small subnetworks ($n \leq 3$) which are present on the "main stems" of large subnetworks. Because it has already been shown that internal growth constitutes less than 20% of all growth and that this value does not change over time, it may be argued that either the presence of these small

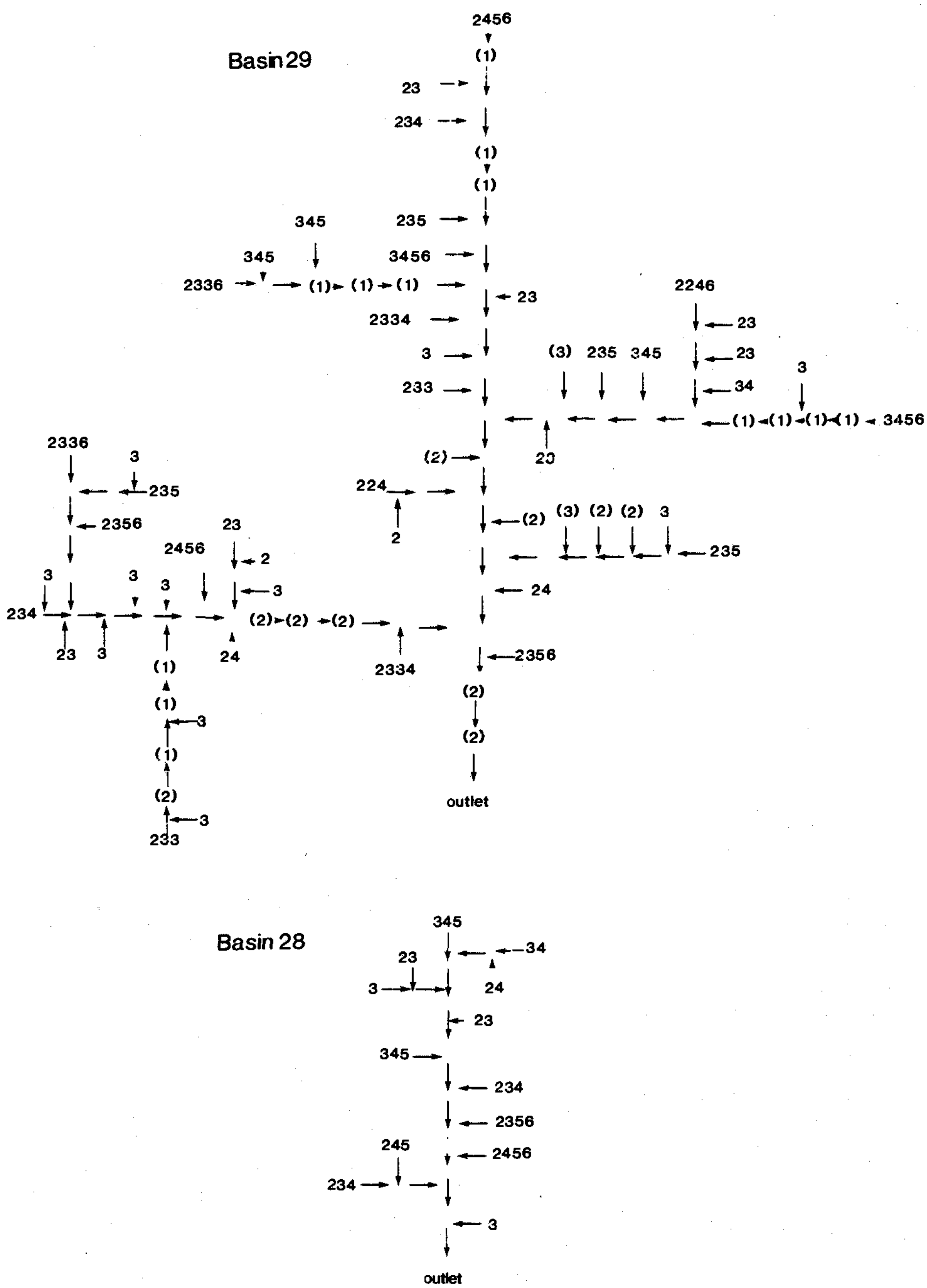


Figure 7.6 Internal ambilateral class arrangement of eight selected networks

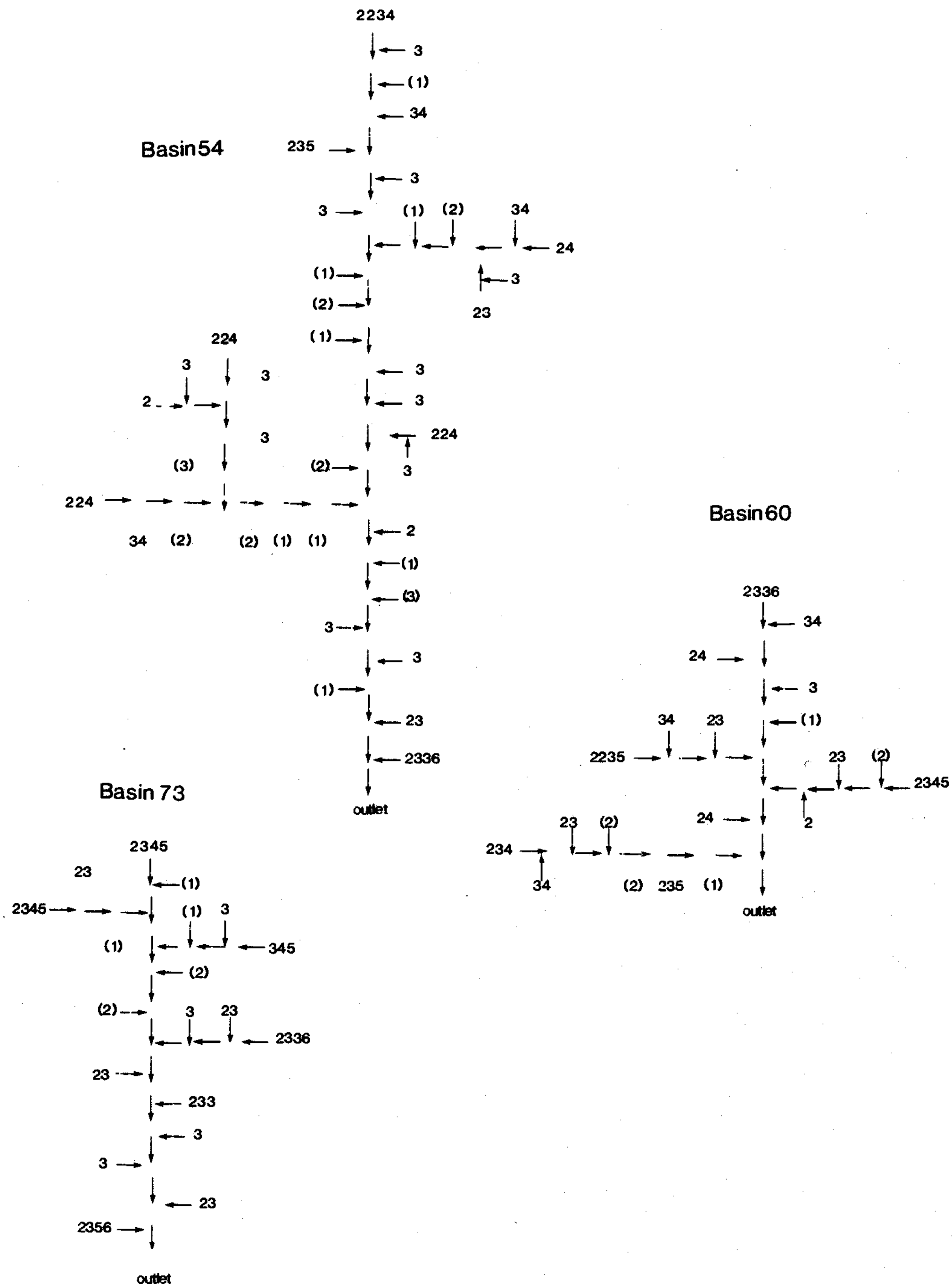


Figure 7.6 Internal ambilateral class arrangement of eight selected networks, cont'd.

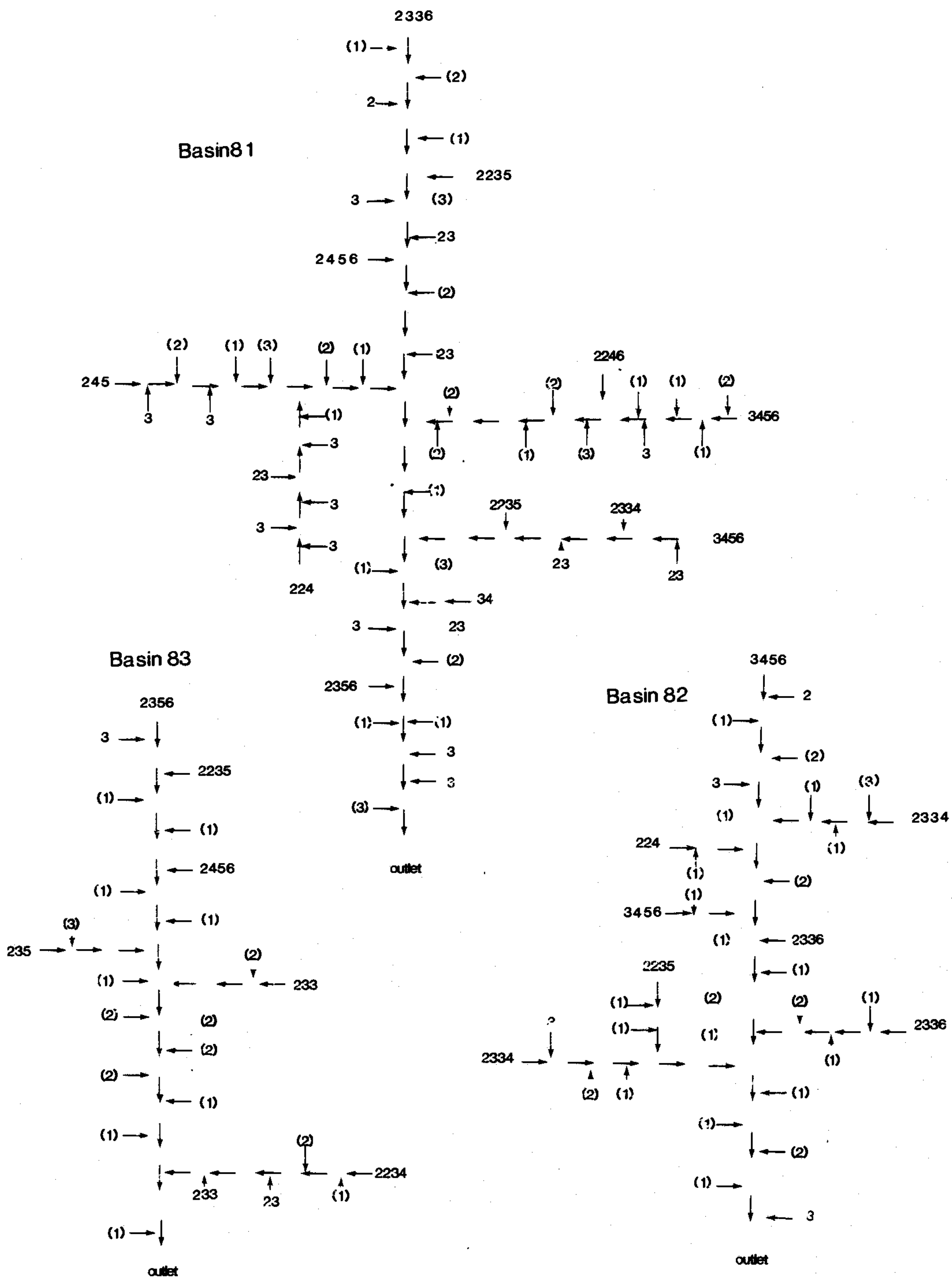


Figure 7.6 Internal ambilateral class arrangement of eight selected networks, cont'd.

subnetworks is the result of asymmetric link alignment at bifurcation (Section 6.3.4) or that there is an internal regulatory mechanism that provides growth of small subnetworks in order to maintain the moderate pathnumber.

Yet there are a significant number of late-peaking networks and also several mixed networks. The existence of these networks may be due to the subleties of basin hydrology, aspects, which, as yet, cannot be detected through pattern analysis. This second explanation is perhaps the most far reaching in that it points toward a more thorough examination of basin hydrology and the spatial arrangement of particular features in these basins in order that network patterns be more thoroughly understood.

7.6 Summary of Network Growth Observations

In this chapter growth of channel networks was considered in terms of the type of growth, the location of growth, the rate of growth and growth pattern. The results were not conclusive but cast further doubt on the validity of the random model for this study area.

The type of growth was found to be independent of basin type and constant over time except for basin type TId. Bifurcation on exterior links was predominant, with approximately 62% of all growth, with branching on exterior links adding 20-22%, and branching on interior links contributing the remaining growth. Subsurface piping may be responsible for some of this trend.

Eighty percent of all growth was located on exterior links, thus substantiating the headward growth theory, and relegating random growth models to a position of disinterest. Of this exterior link growth a further 80% could be attributed to growth on S-links. The temporal occurrence of these locational preferences was not examined in detail, but was found to be in the region of 75-83% preference for S-links. A non-random growth of TS links was not observed because there was not a prevalence of 345 subnetworks, a highly likely ambilateral class under preferred TS-link growth.

Growth rates are most marked by the change exhibited between the pre- and post-incision states, the post-incision rates being significantly greater. Incision thus sped up the attainment of a fully developed network. The by-basin differentiation of growth rates showed drainage type having effect but not geology.

Growth pattern was shown to prefer mid-range ambilateral classes. There was a difference in the number of maximum diameter classes observed using the growth-up methodology from the top-down methodology.

CHAPTER 8

Conclusions: Present Paths--Future Directions

> ...the purpose of any scientific morphological theory in general is to get description on an economical basis... to reduce the arbitrariness of the description...
>
> Rene Thom (1980)

Throughout this research description of channel-network pattern has considered both spatial and temporal aspects in terms of network topology. Other bases of pattern analysis have not been employed, though the development of theory in this area presents many new opportunities to the geomorphologist whose concern is the evolution of landform. As a reference point, working hypotheses were configured in terms of Shreve's model of random network topology, the most contemporary descriptor of channel pattern. This model was critically examined in terms of the study area data for the following:

1) Basin-type influence on random network topology
2) Changes in topological network pattern
3) Effect of North Fork Toutle incision on network organization
4) Network growth rates
5) Network growth types
6) Location within networks of growth areas

1) The results of the basin-type investigations did not consistently uphold or dispel the random topology model. A commensurate conclusion contends that the influence of the different geologic materials was not sufficient to produce geologic control of network organization. However, basins formed on debris-avalanche material tended to establish networks extremely rapidly, and the predominant form of the network was elongation. Basins located in

the deep pyroclastic flows had low link densities, but not low drainage densities, and the network pattern contained more minimum diameter subnetworks than would be predicted using the random model. None of growth rate, growth type or growth location were affected by the basin type.

The expected influence of drainage type on the resulting networks was not observed. Magnitude distributions were generally outside the 95% confidence band of the random model, with all drainage types experiencing a surfeit of higher magnitudes. This observation is attributed to the large number of subnetworks of magnitudes smaller than four. The presence of such subnetworks is partially due to the 20% of all network growth occurring on interior links, and partially the result of asymmetric growth orientation with respect to the main longitudinal axis of the watershed. Basin type did not influence the network pattern as portrayed by the ambilateral class.

Although basin type did seem to affect some topologic properties, it did not do so in a manner that convinced, which casts doubt on the validity of the random model as a scientific morphological theory, but at the same time allowed further investigation of the networks using the random model as a basis for comparison.

2) Network pattern was examined using the ambilateral classification both for the spatial and temporal distribution. No trends were observed in the spatial distribution of ambilateral classes. Deviations from the random model prevailed across all basin types, but these were not consistently observed for any one class.

An attempt was made to assign the pathnumber hydrologic significance and hence to explain the observed patterns in these terms. As both maximum and minimum diameter networks were less frequently observed than would be expected under the random model, this was considered justification for using pathnumber to describe network organization at the small subnetwork level.

Once entire drainage basins were considered, the small sample size did not permit evaluation of the pathnumber hypothesis using statistical techniques. It did appear from the eight drainage networks considered in some detail that the presence of a maximum diameter network in the headwaters region was countered by other subnetworks with less elongation in the immediate downstream vicinity. Minimum diameter subnetworks were also ameliorated by other subnetworks of less pronounced path convergence. The association of the internal pathnumber organization with geometric stream length distributions is a likely area for further investigation of this approach to network pattern.

3) Incision by the North Fork Toutle River occurred after pumping operations began at Spirit Lake, to affecting basin networks in a complex manner. All ambilateral classes when grouped by magnitude fail the chi-squared test, with the resulting interpretation that the minimum and small diameter classes are most affected. The lowering of base level, either by channel incision, lake-level reduction or depression of the groundwater table, alters the prevalence of pattern types from the pre- to post-incision networks.

The geomorphic implications of this observation are both theoretical and applied, and have consequence in short- and long-term studies. Network pattern has been shown to have both random and non-random components. In the overall infinite network of Shreve, the random elements will dominate the networks. On the local scale, network pattern is a consequence of both local basin characteristic, internal and external factors, and of the regional geomorphic and tectonic histories. It is not claimed that such an understanding of spatial and temporal interdependencies is new knowledge; indeed this theme has pervaded earth science through the ages. Explicit demonstration of this concept previously has not been shown for channel networks, although clearly, Parker (1977) Dunkerley (1977), Abrahams (1980ab, 1984b), Flint (1980), Jarvis (1976a) and Smart (1972, 1973 and 1978) have all encountered the a posteriori network which incorporates the episodic change in energy levels (Schumm 1975) conditional for complex landscape evolution. Relict and inherited subnetworks may contribute to basin-wide randomness, or they may prove to be the causes of deviation from the random model.

Given a change in network organization status similar to that encountered at this study area, a managed watershed would experience a reduction in contributions from maximum and minimum diameter networks. This may occur across entire subnetworks, or just through dormancy induced in external links that, when absent, leave a subnetwork without the diameter extremes. Hydrograph shape will be affected in a likewise manner.

4) Channel network growth rates were shown to be independent of basin type, to be seasonal reflections of the precipitation input and to have been affected in differing manners by the pumping operations at Spirit Lake. The rate of growth is dependent on basin area but not on basin slope. As the growing network approaches the basin divide, the effect of the boundary is to slow down the spatially

normalized growth rate. Only in the basins which were initially internally drained but were captured following retrenchment by the North Fork Toutle River did the growth rate increase as the network approached the divide. This is probably a result of the change in drainage status.

5&6) The type of growth which occurred in these networks was primarily of the headward growth type, with bifurcation creating the greatest number of new links. Branching on internal links occurred only 20% of the time, but was constant over time. Also S-links (those which combine at their downstream end with one internal and one external link) were preferred growth sites among external links between 75% and 82% of the time. The obvious consequence of this specified growth is to produce subnetwork patterns with pathnumbers in the preferred range of moderate hydrograph, peak height and mid-response-range time-of-arrival. As there is a fundamental auto-correlative relationship between the observed pathnumber distribution and observed location of network growth, substantiation of the hypothesis governing preference of growth location is not possible herein.

The major finding of growth on exterior links substantiates previous unquantified observations, and furthermore both quantifies and qualifies the particular exterior links involved. Also the ratio of 4:1 exterior to interior growth preference is at odds with the theoretical argument of Dacey and Krumbein (1975) and is non-random in terms of the growth-up model and the top-down approach (Smart 1978). The probabilities assigned to individual links have not been determined for interior links, although it appears that there is a preference of growth at interior links of low magnitude. All links are not equal in their likelihood to support new network growth.

Pattern on the landscape has not been described in such a manner that it "...reduce(s) the arbitrariness of the description" (Thom 1980). The immensity of this task was beyond the resources available. That pattern is organized and not truly random has not been proven; the random model has not proved an adequate model for concise description of the patterns encountered here. Pathnumber, as a subset of the ambilateral class and also with greater filtering and smoothing capabilities through information loss, has been seen as a useful tool for evaluation of small subnetwork organization. Distributions of the pathnumber at this scale are not random. There is a tendency to favor pathnumber that have a moderating influence on flow convergences in the downstream direction.

Even the attempts presented here to trace network development over space and time are directed at the after-the-fact morphological results of a basin-wide deterministic growth pattern, which is highly dependent on surficial topography and subsurface flow nets. Further research in this area should be directed toward understanding the importance of the very early pattern development on subsequent network growth and patterning. To some extent this may be established through controlled field-scale experimentation. Much more rigorous ground control and survey would need to be established at the start of an experiment, although aerial monitoring can be employed satisfactorily for the temporal observations.

The advent of integrated Geographic Information Systems (GIS), such as that recently available at Oregon State University, Department of Geography, would improve data handling and retrieval and facilitate rapid integration of the various data sets extracted in the secondary data section of this study (Section 4.3). Once ground control had been established, image processing would be entirely automated. The future of geographic research lies in the ability to successfully exploit this tool.

Earlier, Chapter Six was introduced with a quotation from David Harvey expressing concern with the geographer's--and indeed with any spatial scientist's--lack of understanding of the nature of scale-dependency on process in the environment. This study has indicated that the spatial scale of determination in channel network pattern is at the subnetwork or link scale; random influences at the micro-scale have not been shown to outweigh these local scale factors. There is still much research needed in these areas. It may be, as physicists have already shown for theories concerning the nature of matter, that separate scale-dependent levels will be found for the same theory of channel network organization. Current trends in stream length research suggest that these dependencies are already being uncovered, especially in terms of downstream variations in link lengths and the size of the main stem.

Landform evolution theory is still in its infancy. The development of the channel network at local and regional scales plays an important role in control of the morphological arrangement of landforms. Hillslope form is in part dependent of the nature of the channel, but in turn the occurrence of the channel is the result of initial hillslope influences. What is observed today is the result of long-term development stemming from that initial conditioning.

Geomorphic theory should not employ morphological parameters without carefully considering their long-term interdependencies. The random model allowed the geomorphologist to avoid the intricacies of landform history and unknown starting conditions. Future theory, and the research progress toward that theory should direct effort and attention to the temporal evolution of networks.

Finally, in an applications-oriented world, what relevance does the development of landform theory have on environmental problem solving ability. Better theory enables more accurate prediction, given limited data and time for analysis. Costly mistakes are lessened; optimal management schemes are improved.

The random model was an improvement over the previous system of stream order, but it still failed to predict stream lengths in a satisfactory manner, and avoided the question of hydrologic response. Topological analysis provided a rigorous mathematical basis by which the complex patterns of natural networks could be managed by simpler mathematical terms. It has been shown by others that the topological property pathnumber has relevance to hydrograph shape prediction, and that a combination of pathnumber and stream length can predict the timing of hydrograph peaks. Given the techniques available on GIS, calculation of synthetic hydrographs for real networks on a large scale becomes a major water-resources opportunity.

He who dwells on the past loses one eye.
He who forgets the past loses both eyes.

Hungarian Proverb

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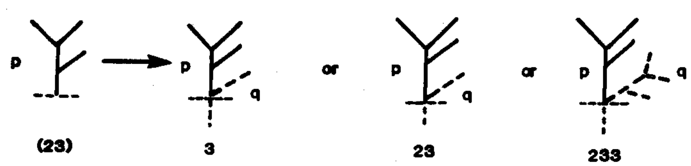
APPENDIX

APPENDIX 1

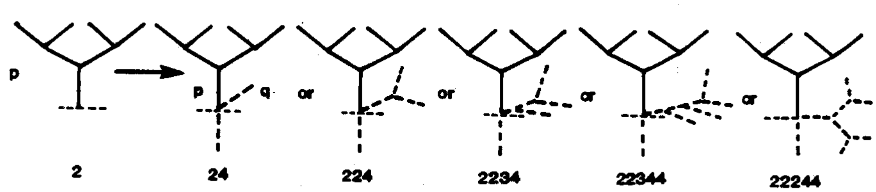
Failure in Smart's Methodology

Smart (1978) uses "from the top down" (Smart 1978, p. 136) methodology to compute his distribution of Ambilateral classes, from which he arrives at anomalous distributions relative to the random model predictions. It should be noted that the combination of subnetworks at a downstream link has more possibilities than Smart's analysis allowed. For instance, the excess of class 3456 can be simply accounted for by the "random addition model."

However, the "from the top down" methodology introduces bias because the addition of subnetworks is always at the system outlet end. Thus we can envisage the combination of the subnetworks, p,q ($p \geq q$)



for p initially of magnitude 3. Similarly the combination of p=q=2 networks can be biased in other directions



The most dramatic aspect of this method is that all classes are only accessed once: there is only a single path leading to their formation. This leads to a new probability matrix. Two methods are available to calculate these probabilities.

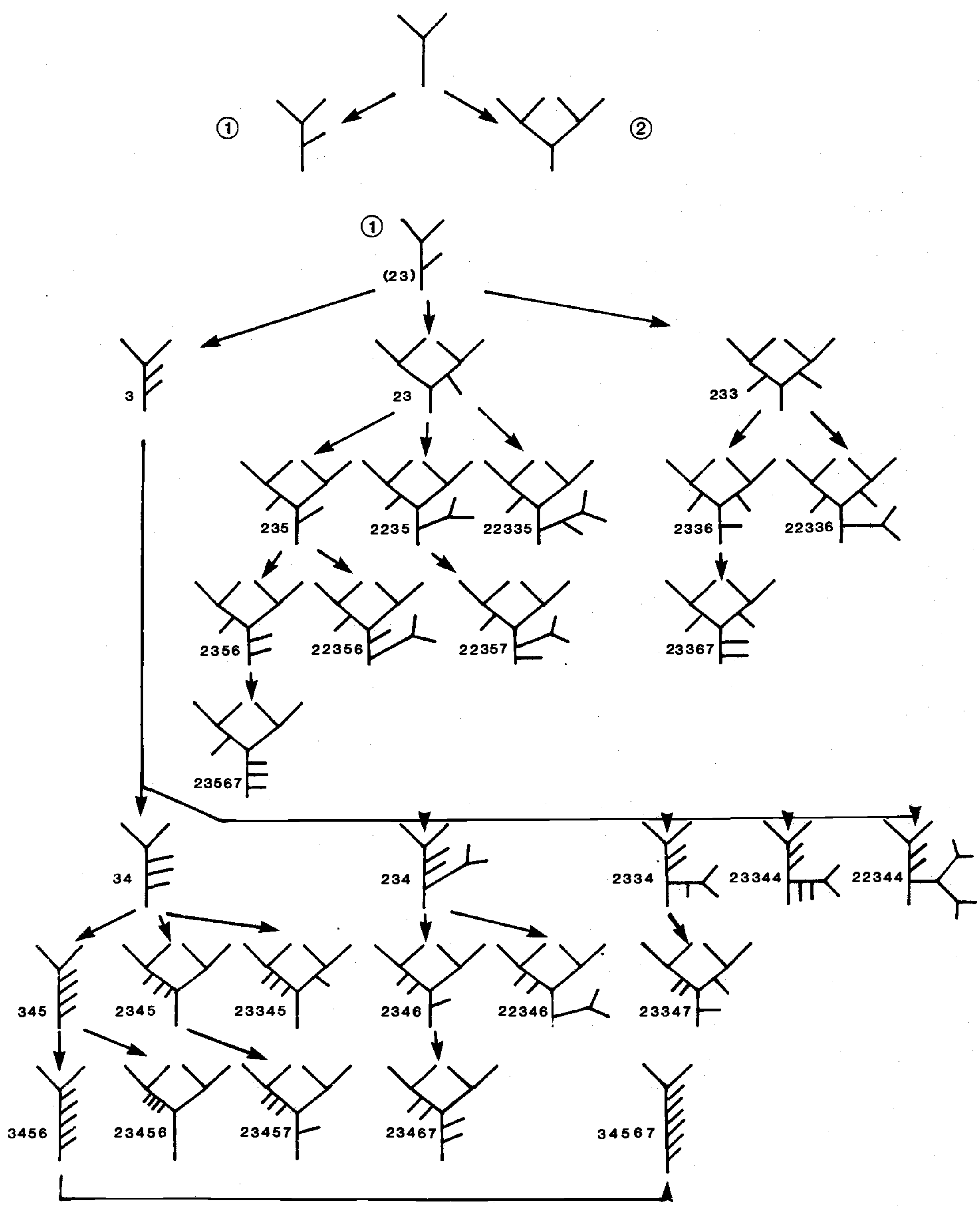
The first assumes that all classes created at a single downstream step are equally probable, thus the probabilities of some n=8 classes are equivalent to some n=4 probabilities. The greater the number of steps involved, the lower the probability of the class. Thus class 23467 requires four steps at

$$50\% \times 20\% \times 50\% \times 100\% = 0.013 = 1.32\%$$

whereas its random model probability is 7.459%.

Alternatively class 22244 has a random model occurrence .23% of the time, but in the outlet link equal probability model it occurs 2.8% of the time.

Appendix 1, cont'd.



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