Thesis
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Department of Geography
University of Nigeria
NSUKKA

ANALYSIS OF TOPOLOGICAL CHARACTERISTICS AND DRAINAGE PARAMETERS IN THE ABOINE BASIN OF NIGERIA

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BY

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CERTIFICATION

Mr. Joel Ekwutọsị Umeụdụji, a postgraduate student in the Department of Geography, specializing in Fluvial Geomorphology, has satisfactorily completed the requirements for research work for the degree of Doctor of Philosophy (PhD) in Geography. The work embodied in this thesis is original and has not been submitted in part or full for any other diploma or degree of this or any other University.

PROF. G.E.K. OFỌMATA
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APRIL, 1994. Joel Ekwutọsị Umeụdụji

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ABSTRACT

The analysis focused on 27 fourth-order networks of the Aboine basin with a combined magnitude of 1,333 and covering an area of 2,123.13 km^2. Along the diameter, a topological analysis of 421 links in 27 sequences truncating between magnitudes 4 and 6 revealed 55.11% trans-links and 44.89% cis-links. Statistical inferences from our index of topological elongation - the E-index ($\bar{E}$ = 6.52; S_k = 0.67; K_t = 2.7) and the predominance of trans-links over cis-links gave an indication of the typically dendritic nature of the Aboine network, free of structural control.

With the 1:50,000 topographical maps, the blue line method was complemented with the contour crenulation technique. PCA collapsed 15 morphometric properties to 4 orthogonal components explaining 88.04% of variance in data, leaving out 11.96% to minor factors such as non-linearity and inherent operator variance. After the application of varimax rotation, the communality index (h^2) revealed that N_1, D_d, R_c and $\underline{h}$ are the diagnostic variables underlying the four components, in order of their importance

(and respectively). N_1, the source variable of the first component had a factorial complexity of unity, with component one alone explaining as much as 96.83% out of the 97.84% accounted for by the four components. The four components also explained 83.16%, 89.31% and 86.45% of variance in the source variables (D_d, R_c and $\underline{h}$) for components two, three and four respectively. However, the communality index was notably very low for relief-related variables (particularly the HI, h^2_{HI} = 0.68587) indicating that the PCA did not adequately take care of the third dimension of the basin morphology. Accordingly, this inadequacy of using essentially two-dimensional morphometric techniques for the analysis of three dimensional basin solid geometry was further mitigated by hypsometric analysis.

Hypsometric indices (HI = 0.33; EI = 0.67) indicate that since after the Tertiary planation, as much as 67.00% of the basin solid mass has been removed by the agents of denudation leaving only 33.00%, hence stressing the need for conscious human control so as to stabilize the Aboine basin slope.

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CHAPTER 1

INTRODUCTION

Fluvial geomorphology, the domain of which is the analysis of process-form relationships in individual channels and the entire drainage system (Schumm, 1977a), has continued to remain a viable field in the total system of related sciences. Every scientific field has its outstanding personalities, leaders of research and inspirers of students (Embleton, 1983) as well as distinctive landmarks that guide the practitioners. The articulation of fundamental ideas in fluvial geomorphology has led to notable revolutions in the discipline. The first major theoretical milestone was Horton's (1945) pioneering work on network geometry. The second is in the area of hydraulic geometry launched by Léopold and Maddock's (1953) locus classicus, and given further impetus by the work of Schumm and Lichty (1965). The above two ideas have, for quite long and formidably, formed the theoretical underpinnings of extant drainage basin enquiries. However, Tuan (1991) fears that a theory can be so highly structured that it seems to exist in its own right, to be almost 'solid' and thus, paradoxically able to cast a shadow over the phenomena it is intended to illuminate. This is why it is necessary to re-evaluate the paradigmatic setting of fluvial geomorphology (particularly in the area of network geometry) using an empirical case.

1.1 The Problem:

With respect to its contemporary scope, content and purpose, it is a consensus that geomorphology is the scientific study of the types and origins of landforms and land-forming processes (Small, 1978; Pitty, 1982; Verstappen, 1983). The discipline grades imperceptibly into related fields such as engineering, hydrology, geology, geography and soil science. Geomorphologists are essentially concerned with landforms, the materials upon which landforms occur, the processes that mould the forms as well as the evolution and history of the landscape (Goudie, Anderson, Burt, Lewin, Richards, Whalley and Worsely, 1981).

The processes in question are essentially exogenetic (Scheidegger, 1970) and not only actively create but constantly modify surficial topographic features. Competence in the analysis of these processes is claimed to be contingent upon familiarity with the principles of thermodynamics, fluid and plastic mechanics as well as hydrology and meteorology. Consequently, Strahler (1950) argued that since geographers did not conventionally excel in these areas, geographically trained geomorphologists are handicapped to work in the field of process.

It is most probably this line of thought that spurred Wooldridge (1958) to assert somewhat authoritatively that geomorphology is fundamentally concerned with the interpretation of forms rather than the study of processes. But spatial forms, as responses, are much more meaningful when interpreted in the context of the processes that engendered them. Today, geomorphology has richly drawn from modern developments in the cognate sciences to enhance its methodology and sharpen its conceptual tools.

The scientific study of landforms necessitates an understanding of the causative processes. Much light has been shedded on the modus operandi of processes, especially from the field of physics. There is a general tendency for matter and energy to gravitate towards an equilibrium. Since the topographic surface is highly irregular and energy is not uniformly distributed, the resultant redistribution of energy generates processes that tend to smoothen topographic irregularities. Hence, a clear appreciation of the mechanics and properties of matter is fundamental to the science of landforms. Also, from the related field of geology, geomorphologists borrow and greatly utilize modern stratigraphical techniques of dating and reconstruction to account for palaeo-processes and forms.

With the aid of the computer and rarefied mathematical techniques, geomorphologist's now competently not only x-ray and account for current processes but also simulate the operation of such processes both retrospectively and introspectively. The processes actually give dynamism to the otherwise static resultant forms. The implicit indepth cause-effect analysis is one thing that methodologically gives modern geomorphology its exploratory identity. Geomorphologists comprehensively integrate the knowledge of the past and present landforms in order to account for the future trend in landscape development.

Geomorphic processes are very numerous in kind, varied in both combination and degree of operation and are significantly regionally and climatically differentiated. This is in consonance with the concepts of climatic geomorphology and morphogenetic regions articulated by many scholars, particularly Peltier (1950), and popularized by others notably Stoddart (1969). Accordingly, it was postulated that a particular climate is characterized by a certain combination of processes which develop a distinctive assemblage of landforms. Such landforms are quite distinct from those developed in other areas with different climatic conditions. King (1966) pointed out that the task facing geomorphology is to elucidate the causative processes through an understanding of the resultant forms. Based on the degree of landform genesis and modification, fluvial processes distinctly emerge as a notable assemblage of operators in the humid tropics. These fluvial processes powered by the kinetic energy of streamflow operate within particular confines referred to as drainage basins.

A drainage basin is seen here as a geomorphic unit which supplies water and sediments to a river channel or a set of channels (Leopold, Wolman and Miller, 1964; Ruhe, 1975; Faniran, 1986). The river has been viewed as a locus of erosion hydrodynamically balancing and distributing energy and work within the drainage basin (Curry, 1972). But little do we realize the actual import of channelized running water in the form of rivers as a major agent in the transformation of the landscape. A major task for this investigation is not only to highlight but to address both the covert and overt dimensions of the operations of channelized streamflow. Also deserving exploration is the transformation accomplished by these operations, linearly along the tree-like network system, as well as on the entire planimetric drainage basin surface.

Landscape dissection engendered by rivers actually proceeds inexorably and is highly susceptible to intensification by any external interference. It could then be the complicating influences of various land uses that have compounded fluvial erosion espeically in south-eastern Nigeria. It is worthwhile to empirically analyse the causative factors and thereby explore the possibility of restoring an equilibrium to the landscape system. Many riverine land use activities reveal a lack of appreciation of the socio-economic benefits of optimal, balanced utilization of the natural land and water resources. The situation can be remedied from a geomorphological perspective through the application of basic geomorphological principles that introduce stability to the landscape system.

Geomorphological criteria are very essential for both the evaluation and extrapolation of an area's hydrological characteristics in space and time (Verstappen, 1983). In Nigeria, we evidently have many River Basin Development Authorities. However, ironically, pure, investigative and theoretical researches to yield basic hydromorphological details are still lacking. Empirical drainage basin investigations should give rise to basic hydromorphological details that could guide land uses. There is some sense in an assertion that nowadays, perhaps, man is the most important geomorphological factor (Demek, 1973). Man's role as an agent in transforming the landscape is increasingly being recognized. Accordingly, Park (1981) observed that man's use of drainage basins can trigger off changes in processes and accordant adjustments of landforms. The knowledge of the potency of man's actions is a challenge to human ingenuity to attempt controlling landscape development through environmental impact assessment and monitoring.

The drainage basin is a system and man's actions indirectly through land uses or directly through channelization are practical interruptions in the landscape system. A system is seen as a set of objects together with the relationships existing between those objects and their attributes (Coffey, 1981). In the absence of interruptions, there is an equilibrium between the basin geometry and fluvial mechanisms. This delicate balance between forms and processes results in a state of equilibrium defined by Howard (1982) as a single-valued temporally invariant functional relationship between the values of input variables and the values of output variables in a geomorphic system. In this case, the output variables can be represented by fluvial processes given impetus and sustenance by external factors (such as rainfall and human activities). The outputs are the responding internal parameters such as basin geometry and channel forms. The process-form balance is prone to distortion by human interference. Induced process-intensification can strongly indicate a lack of appreciation of basic drainage basin dynamics.

A geomorphological enquiry is primarily an attempt to provide a rational explanation for a particular phenomenon or a combination of phenomena with which some beclouded relationships are associated. Such an elucidating activity is conventionally either inductive or deductive. Many geomorphological investigations are empirical, and therefore, predominantly inductive in nature. Explanations through the deductive method are a priori, fewer and more rigorous. Through this channel the necessary culmination of effort is to arrive at an explanation through the construction of theories, but it should be noted that this line of thought has not been fully addressed by geomorphologists. This bias in emphasis signifies a lacuna corroborated and re-enforced by a paucity of theoretical work in geomorphology. There is need to fill up this gap by embarking on investigations (such as the present one) that will give rise to basic theoretical building-blocks which will serve as a convenient stepping stone for the erection of theories.

The hallmark of any science is the quest for theories (that can even culminate in laws) with which natural phenomena are to be explained within the prevailing paradigm. The foundation for quantitative analysis of drainage basin parameters was solidly laid by Horton (1945) through the introduction of an ordering system for streams and the formulation of some statistical laws to explain the spatial pattern of stream numbers and lengths within the ordering system. But since the sign of virility in any nascent and progressing discipline is the refining of existing conceptual tools, it is not surprising that the Horton-opus has undergone a considerable degree of modification and reformulation (Strahler, 1952a; Scheidegger, 1965, 1970; Shreve, 1966, 1974; Woldenberg, 1967; Gregory, 1976; Javis, 1977; Smart, 1968, 1978).

A critical examination of the works of the above analysts reveals a lack of consensus in their desparate attempts to abrogate the Horton-formulation. There is need to synchronize these contending viewpoints. The derivation of such a synthesis ranks high in the hierarchy of reasons that stimulated this empirical enquiry. The efficacy of the existing and contending approaches would also be tested by appraising the strength and rigour of the underlying logic of explanation.

Apparently, there is a proliferation of approaches to the analysis of drainage basin parameters. The situation makes the choice of the most proper paradigm extremely difficult. A distressing state of confusion (and even crisis) exists as to the exact nature of the relationship between drainage basin indices and planimetric properties, particularly between drainage density and drainage area (Pethick, 1975; Gardiner, Gregory and Walling, 1977; Ferguson, 1978; Gerrard, 1978; Richards, 1978). The existence of a crisis can motivate a case study to clarify uncertain relationships and reconcile conflicting views. The task of reducing an unexpected outcome to a logical one is indeed, a challenging 'problematic'. If geography is a science that describes and explains areal differentiation of phenomena (Harvey, 1969) through the setting up of an internally coherent procedure for rational argument, then it is worthwhile to probe the cause of conflict and resolve same with respect to the ambiguity that surrounds drainage density and drainage area association.

Intellectual advancement is a continuing process of modification, rejection, addition and replacement of conceptual tools (Wrigley, 1965). This implies an upward gradation, and clearly shows that there is no finality in science. Conceptual developments in any scientific discipline are a reflection of the prevailing paradigms. Frolov (1984) defined the term 'paradigm' as a totality of theoretical and methodological premises defining a concrete scientific study, embodied in scientific practice at a given stage. A paradigm summarizes the scientific achievements that, for a time, provide model problems and solutions to a community of practitioners (Kuhn, 1962). Fluvial geomorphology has roosted under a number of paradigms and this is an interesting development in such an active field. Any paradigm that leaves unanswered more than it successfully explains, invariably leaves itself open for replacement (Kuhn, 1962; Anderson and Burt, 1981). The rate at which conceptual tools are fashioned out, refined, or entirely discarded in favour of better alternatives is a good indication of intellectual vigour in the discipline. Geomorphology is evolutionary and has witnessed a number of monumental works but in the words of Young (1979), such achievements were sufficiently open-ended as to leave a wide range of problems yet to be solved. Knowledge in the discipline (as in other related fields), is progressive and cumulative rather than definitive. With the advancement of knowledge and the development of new analytical tools, old problems are solved, new vistas illuminated and new challenges disclosed.

We may recall that Anderson (1957) described area as the devil's own variable, and in the same diffident manner, Bunge (1966) claimed that shape had proved to be an elusive geometric characteristic to capture in an exact quantitative fashion. Unfortunately, for over three decades, the crippling, defeatist belief in the unfruitfulness of shape and areal analyses has almost established itself as a consumate orthodoxy which rides roughshod over area-related investigations. Accordingly, a notable challenge that stimulated our work is to appraise fundamental areal ideas with the aid of mathematical tools of analysis.

Geomorphometry is a methodological sub-discipline of geomorphology and is generally viewed as the science which treats the geometry of landscapes (Chorley, Malm and Pogorzelski, 1957; Mark, 1975; Evans, 1981; Richards, 1981).

But geomorphometric parameters are very many, and different analysts have utilized different combinations of these parameters. Having as many combinations as there are analysts simply betrays a glaring subjectivity-undertone. But a streamlined, rigorous, and pragmatic analysis will produce the necessary objectivity and this is amenable to empirical demonstration.

In North Western Devon, Smart (1968) conducted a morphometric analysis using five parameters which are the length ratio (R_L), area ratio (R_A), as well as $\bar{L}_1$, R_{b2} and $\bar{A}_1$ (Appendix A). Previously, in Malaysia, Eyles (1966) used thirteen parameters. Gardiner (1973) made use of fifteen parameters in England, while Kirkby (1976) utilized ten. In Nigeria, Ebisemiju (1979a, 1979b) worked with seventeen and thirty-seven parameters respectively. Again, Marcus (1980) conceded that six parameters sufficed for such an analysis in New Hampshire. This apparent proliferation of geomorphometric parameters (possibly including some redundant ones) raises a number of questions: Which parameters and how many of them should be used to adequately characterize a drainage basin? Do environmental conditions influence the combination of the relevant variables? Does the scale of analysis unduly stress the role of some variables at the expense of others? In principle, a quest for answers to the above questions as well as illumination for the beclouded and stunning issues is a quest for explanation. Any exercise that rationally sets out to explain a provoking 'problematic' is scientific, and therefore, justifies its raison d'etre.

From the foregoing, it can be inferred that an investigation motivated by the need to pragmatically demonstrate and test the suitability and application of morphometric techniques is both viable and necessary. The empirical and methodological resolution of the motivating issues forms the core of our present investigation. The 'what' (in terms of object or substance investigated) should not be over-stressed at the expense of the 'how' (in terms of methodology). The present work is poised to demonstrate and highlight the under-emphasized complementarity between the methodology of analysis and an appreciation of the objects or issues analysed. In addition to addressing the above issues in such a way as to yield concrete theoretical formulations, some other more specific tasks will also be accomplished.

1.2 Objectives of the Study:

Exploratory researches have a conventional aim of generally advancing the research frontiers and broadening the scope of knowledge in the discipline in question. The testing of existing analytical tools with a view to improving their efficacy is always of fundamental concern. While attempting to resolve the motivating issues embedded in Section 1.1, some more specific tasks were addressed. These are

i] Utilizing network topological indices to appraise topographical transformation in a homogeneous drainage basin.

ii] Isolating significant relationships and identifying relevant variables that account for the Aboine drainage basin morphology.

iii] Using a three-dimensional analysis of the basin solid geometry to complement a two-dimensional morphometric analysis (with the Aboine basin as an empirical case).

Accomplishing the tasks outlined above necessitated the adopting of, and sticking to a rigorous procedure of scientific investigation. Hence, it is imperative at this juncture, to review the conceptual background to our investigation.

1.3 The Theoretical Framework:

As an organized activity, science searches for facts, pursues knowledge through observation and experimentation and also makes theoretical deductions that eventually lend themselves to empirical verification. According to Kuhn (1962), normal science has three main aspects. These are: the pursuit of facts, the comparison of factual data with predictions, and the articulation of the disciplinary matrix by the resolving of ambiguities. Similarly, Howard (1982) saw science as the art of pragmatic idealization wherein the complex interactions of mass and energy in nature are represented by simplified models employing verbal, mathematical, mechanical or electrical analogues. In principle, the science of geomorphology is characterized by the creation and transformation of mass (or forms) by the energy and operation of surficial fluids (or processes). Generally, scientists meticulously examine their objects of study, classify them, establish a pattern and, to be able to discern and account for relationships, they formulate theories which form the basis for laws. The applicability of these laws depends, to a large extent, on the explanatory powers of the underlying theories.

The ultimate aim of science is to propound theories capable of illuminating phenomena. Ramsey (1960) viewed a theory rhetorically as a language for discussing those facts which the theory hopes to explain. In a very broad sense, a theory is a generalized authentic knowledge which particularly presents an integral picture of reality by outlining relationships (Frolov, 1984). Theories are indispensable to science in that they systematize knowledge (Amedeo and Golledge, 1975).

A radical transformation of the spirit and purpose of geography logically gave an impetus to theorizing. The building of theoretical models was inspired by a genuine need to make geography more scientific. According to Burton (1963), the rigorous dictates of scientific method, the need to develop and test theory with prediction, make mathematics the best available tool in the process of theorizing. The formulation of theories is the ultimate aim of science, this is irrespective of whether the method is inductive (a posteriori) or deductive (a priori). It is interesting to note that the two methods of theory-formulation are not necessarily mutually exclusive. By implication, it is possible to blend and tap the merits of the two in a single investigation and this is the philosophy that underlies our present approach.

The pre-occupation of fluvial geomorphologists has been to procure an explanation (through the use of theories) for the interrelationships among drainage basin variables. This is why morphometric analysis entails a great deal of measurement or the assigning of numerical values to drainage basin attributes. These attributes essentially relate to the topological and planimetric aspects of the drainage basin. It should be recalled that morphometry as a technique is the measurement and mathematical analysis of the configuration of the earth's surface and the shapes and dimensions of its landforms (Clarke, 1966). In the provision of a framework for outlining available techniques specifically for drainage basin morphometry, Gardiner (1981) recognized five stages. These are: network delimitation, sampling, measurement, variable definition and analysis. Drainage basin morphometry is increasingly encompassing all aspects of the fluvial system (Gardiner and Park, 1978; Gregory, 1981, 1982, 1983).

In an attempt to establish order among an apparently chaotic array of network variables, Gravelius (1914) conceived of an embryonic system of stream classification. In his ordering scheme, the biggest river in the drainage basin is automatically assigned the first-order (from the mouth to the source). All the channels tributary to this first-order stream are classified as second-order streams while the tributaries of the second-order streams form the third-order streams, and so on.

This idea was later developed into a considerably acceptable model by Horton's (1945) pace-setting work, in whose system, individual rivers emerging from their sources are preliminarily and provisionally taken to be of the first-order. Two of such streams meet to form a second-order stream which is followed headward through the major trunk and assigned second-order up to its source. Two provisional second-order streams meet to form a third-order stream which is again followed through the major trunk and re-assigned third-order stream up to the source, and the process is continued for other higher orders. In other words, the ordering is at first provisional after which there is a re-classification. The highest order stream (third-order, in this example), is produced backward or headward through the major trunk to the source and given the same order up to the source, and the same process is applied to other subsequent lower orders. This system has been severely criticized on the bases that the headward re-classification at bifurcations is purely subjective; some fingertip streams are re-classified and given orders more than one; and finally that streams of fairly the same size or magnitude are not assigned the same order.

As any nascent specialism is often characterized by a continuous refinement of analytical tools, Strahler (1952a) modified the Horton-opus to the status of a prevailing paradigm. In this system, all the fingertip channels terminating in sources are classified as first-order streams and the confluence of two (and only two) first-order streams yields a second-order stream or link. Again, only two second-order links are required to form a third-order stream, and so on.

Javis (1976) came up with a clarification noting that the streams of equal order which are needed to form a higher-order stream are called 'order-formative' streams while the other streams of the same or lower order which join a higher-order stream without increasing its order are referred to as 'order-excess' streams.

Even though the traditional Strahler-ordering system has gained the widest currency, it has been criticized on the following grounds: the ordering system depends entirely on the scale of the map used; it is only when two order-formative streams join that a higher-order stream is formed and tributaries of low-order do not increase the order of the mainstream. The fact that the stream order does not increase with every increase in magnitude implies a violation of the distributive law. For instance,

$$3 = 2 + (1 + 1) \qquad (1)$$

and

$$2 = 1 + (2 + 1) \qquad (2)$$

Nevertheless, the hydrological properties change at each junction (Scheidegger, 1965; Shreve, 1966; Woldenberg, 1967; Smart, 1968).

These issues that are held to detract from the Strahler-system have led to attempts at formulating different alternatives. Notable among them is Shreve's (1966, 1967) ordering system founded on magnitudes. In this system, fingertip channels remain as first-order streams (as in Strahler's). Two first-order streams join to form a link of the second-order, and if a first-order stream joins a second-order link, the result is a third-order link. This system satisfies the distributive law and may appeal to hydrologists, <u>prima facie</u>. It is highly topological in considering only the number of links and forks without considering chennel geometry and actual volumes of the tributaries. The resulting magnitude values can give exaggerated impressions of discharge when used in comparative analysis without being verified.

Smart (1968) argued that the ambiguities and inconsistencies in extant ordering schemes account for the large amount of scatter observed in geomorphic data on drainage basins. It was dissatisfaction with most ordering techniques that prompted Smart (1978) to enunciate a general rule whereby order u covers a magnitude range of M in which:

$$M = 4^{u-1} \qquad (3)$$

as follows:

1st-order, $u = 1$, $4^{1-1} = 4^0 = 1$, i. e. any
stream with a magnitude of 1 falls
under 1st-order stream.

2nd-order, $u = 2$, $4^{2-1} = 4^1 = 4$, i.e. any
stream whose magnitude ranges between
2 and 5 falls under the 2nd-order stream.

3rd-order, $u = 3$, $4^{3-1} = 4^2 = 16$, i.e. any
stream with a magnitude ranging from 6
to 21 falls under the 3rd-order class,
and so on.

But this system does not depart so much from the Strahler-scheme. In trying to accentuate this new formulation, Smart (1978) warned that the widely used Strahler-ordering procedure with a Horton-ancestry, erects an elaborate facade which hides the more fundamental properties of the network. Gerrard (1978) also warned that as long as this traditional stream-ording procedure is being used, results arrived at are likely to remain inconclusive, and therefore equivocal, particularly as regards the relationship between drainage density and basin area. Apparently, he (i.e. Gerrard, 1978) was only contributing to the dialectics per se rather than proffering a solution by propounding a new ordering system. Schaefer (1953) noted that a methodological discussion is essentially dialectical in that much clarification is to be derived from the mutual criticisms of the contending viewpoints.

But characteristically, most attempts at abrogating the Strahler-scheme have not been expressed in such a way as to secure the appreciation of drainage basin analysts. This could be because their proposed ideas have proved to be very complicated and enshrouded in esoteric and mystifying mathematics as could be attested to by the works of Shreve

(1967), Woldenberg (1967) and Smart (1978). As a result, the Strahler-scheme has endeared itself to many and hence established itself as a dominant technique among drainage basin analysts. This could be because of its relative simplicity and the fact that it lends itself to mathematical computations. Moreover, as will be seen in Section 3.2, convenience for sampling is a unique, unparallelled quality that advantageously distinguishes the Strahler-scheme from the other ordering systems.

In addition to enunciating an ordering system, Horton (1945) demonstrated the search for, and formulation of theories. Accordingly, he came up with two laws of drainage composition. The first law of drainage composition, otherwise called the law of stream numbers, states that the numbers of stream segments of each order form an inverse geometric sequence with the order numbers. The second law, the law of stream lengths, states that the average lengths of streams of the different orders in a drainage basin tend to closely approximate a direct geometric series with the order numbers. A relationship between basin area and basin order was also implied. This forms the basis for the third law, called the law of basin area, which Schumm (1956) explicitly stated: the mean basin areas drained by streams of each order tend closely to approximate a direct geometric sequence with the order numbers.

The three statistical laws have been widely used as theoretical models for exploratory and explanatory drainage basin investigations (Smart, 1968; Haggett and Chorley, 1969; Scheidegger, 1970; Knighton, 1984). Such investigations come under the traditional Horton-analysis which is regarded as an attempt to quantitatively describe drainage basin composition in terms of five parameters, which are: the bifurcation ratio, length ratio, area ratio, mean length of the first-order streams and the mean area of first-order basins. Ebisemiju (1979a) suggested that future morphometric analysis of drainage basins should concentrate on four diagnostic variables which are the total drainage density, total number of streams, basin relief and the average length of first-order streams.

Some drainage basin analysts have suggested a total dismantling of the Horton-edifice. Smart and Werner (1976) have attempted demonstrating the effectiveness of a Random Model for explaining and predicting geomorphic relationships. Smart (1978) had noted, in more general and modern terms, that drainage composition refers to the topologic and geometric properties of channel networks. This is obviously predicated upon Shreve's (1966) assertion that all topologically distinct channel networks with a given number of sources are equally likely. It is an ideal against which real-world networks are to be compared. Such topologically random channel network is infinitely large and sub-networks of the same magnitude are equinumerous. An individual network cannot be topologically random (Shreve, 1974). This idea of randomly branching networks is an off-shoot of random walks in mathematics. Where variables are normally distributed, it has a very high explanatory and predictive power. But geomorphometric variables are generally not normally distributed, and so the various rotations and transformations required by the random model do not always prove to be more than mere mathematical exercises. Smart (1978) suggested the application of a new stream ordering and claims that the random model is a statistical standard against which natural drainage networks should be compared.

Sayer (1982) has remarked that new approaches or paradigms have been proposed almost before the earlier ones have been digested. Even though this situation implies an intellectual vigour in such an active and virile field as fluvial geomorphology, nevertheless, the continued adoption of the traditional method, despite both the apparent and alleged flaws, calls for a critical re-examination of the original Horton-Strahler-formulation using empirical data.

Having appraised drainage basin analysis against the backdrop of its paradigmatic theoretical setting, the implied conceptual ambiguities and inconsistencies merit a critical re-examination. This underscores the need for a more precise theory capable of further refinement to a level at which it will be suitable to guide the community of drainage basin analysts. In advancing this quest, the Strahler-ordering system will serve as a stepping stone. Our choice of this framework was predicated upon its amenability as a convenient basis for exploratory work. As will be seen in Section 3.2, the Strahler-system practically supersedes all others on the criterion of convenience for sampling. The nature and operation of drainage basin parameters could have some geological, geomorphological, hydrological and climatological underpinnings. The verification of this assertion, following the tenets of scientific investigation, necessitates a thorough review of the scope and nature of current drainage basin analytical techniques.

1.4 Review of Cognate Literature:

Geomorphology has been notably making several distinctive advances that Dury (1966) remarked that the field is viably producing swift and copious results. Brown (1975) observed that physical geography is internally unbalanced because geomorphology plays too dominant a role in the subject. It was the recognition of this sign of life and vigour that prompted the British Geomorphological Research Group (BGRG) in 1976 to give a verdict that geomorphology is alive and well, and with good prospects (Thornes, 1978).

The growth in any lively discipline can be objectively assessed by the rate of increase in the number of workers and the output of published work (Embleton, 1983). It is important to discern the general direction of research, identify monumental and spectacular achievements and weigh the validity of their contribution to science. We must admit from the outset, that this task of assessment is a very difficult one, more especially in fluvial morphometry which is an interface between hydrology and geomorphology. It has been observed that interfaces between disciplines blossom out from time to time as major fields of development, but it is not uncommon for some of the interfaces to remain as less formal areas of interdisciplinary activity, shunned by all except the colonizers of the pioneer fringe (Clayton, 1971). The ambiguous status of network morphometry as a frontier in relation to conceptual progress (or stagnation) can perhaps be best appreciated by reviewing the scope of work in different areas of the world.

1.4.1 Background to Drainage Basin Studies:

Horton's (1945) seminal work undoubtedly formed a prime stepping stone for drainage basin studies. His legacy not only lay in the fact that he procured terminologies through his stream classification but also in his daring attempt at taking a major theoretical leap by formulating the first and second laws of drainage network composition. Schumm (1956), who worked in Perth Amboy, New Jersey, formulated the third law (the laws have already been stated in Section 1.3). Many later works show varying degrees of ancestry to Horton's original formulation, since its acceptability (or otherwise) formed the basis for later works.

1.4.2 Drainage Basin Studies in the US:

In the United States of America (precisely at Columbia University), Strahler (1952a) refined the Horton-ordering system into a formidable basis for analytical work. This new Strahler-system has dominated the scene for nearly four decades, even though from IBM Watson Research Centre, New York, Smart (1968, 1978) made some attempts to dismantle the Horton-Strahler orthodoxy.

Representing a significant departure from the traditional ordering system, Shreve (1967) recognized magnitudes in his own stream classification. Also using the 180km² Middle Fork of Rockcastle Creek, Kentucky, he investigated the relationship between mainstream lengths and basin areas in addition to defining and clarifying the use of many topological indices (Shreve, 1974).

Still in the US, Leopold et al (1964) carried out a Horton-analysis of the Arroyo Caliente basin, a tributary of Arroyo de los Frijoles basin in Santa Fe, Mexico, and of the Watts Branch, near Rockville in Maryland. They also tested the three laws of drainage composition, which they found were obeyed. Later, Leopold (1978) examined the channel properties and explained temporal changes in the channel geometry of ephemeral streams, using the Asunto de Arroyo in Santa Fe as a case study. In Southern Illinois, Coates (1958), comparing his field map on 1:600 with the United States Geological Survey (USGS) map on 1:24,000, observed that, generally, first-order streams mapped at the latter scale are actually third-order streams.

Morisawa (1962) studied the Home Creek in Ohio. Her findings for the Appalachian Plateau rivers revealed that Horton's first law was fairly obeyed. Her data for six of the Appalachian Plateau rivers were re-analysed by Scheidegger (1968), who confirmed her findings and went further to note that the first law of drainage composition is an entirely topological statement, unlike both the second and the third laws which are based on assumptions of a metric nature.

The basin characteristics of the Wabash river, a tributary of the Mississippi, were studied by Ranalli and Scheidegger (1968). They came up with a coding system through which distinguishing code numbers or letters could be assigned to stream segments and junctions. This classificatory and descriptive system gave a fillip to subsequent topological investigations. While studying the Pecatonica river basin (710km²) in Iowa, Onesti and Miller (1974) observed that the geology, structure and variations in the physical characteristics of the stream basin greatly influenced the interaction of variables in the fluvial system. In a work carried out on eight Strahler-third-order basins of the Hubbard Brook, New Hampshire, Marcus (1980) characterized first-order basin morphological zones into the headwater- and channel-way zones. After applying the Factor Analytical Technique on six morphological variables derived from the valley-head and channel way, he inferred that a basin's bifurcation location influences channel way morphology, while valley-head morphology is more influenced by the position of the divide.

1.4.3 Drainage Basin Studies in Europe:

Some researchers in the U.S have investigated drainage basins in Western Europe. Based at Buffalo, Javis (1972, 1976a, 1976b, 1977) did much to demonstrate how drainage network properties within the same order level may vary significantly between distinct geomorphic regions. His contrasting areas were the Upper Tweed basin in the Southern Uplands of Scotland and the area around the Heddon drainage basin on the Culm Measures of North Western Devon (England).

Many other morphometric investigations have been carried out in these two regions, particularly by some members of the BGRG (Chorley, 1958; Gardiner, Gregory and Walling, 1977, 1978; Richards, 1978). Also, Werritty (1972) verified the accuracy of stream link lengths derived from topographical maps in Devon and West Somerset, while Gregory (1976) empirically estimated drainage basin adjustments induced and accelerated by man in Tonne, Somerset. The multiplicity and intensity of morphometric investigations in the British Isles should not be really seen in terms of an over-concentration of studies or research-overkill. This is because the works follow the tenets of scientific investigation. Methodologically, the works form a continuum and the cumulative effects of continuous refinement of analytical tools give a clear indication of the high level of drainage basin enquiries in Britain.

Though a case can be made for less exciting and uninteresting reading due to a monotonous reference to the Heddon, Upper Tweed and their contiguous basins, nevertheless, the high concentration of works in the region in question makes for an adequate coverage of British river basins. This is very much unlike the situation in Nigeria where no morphometric work has been done in many river basins of which the Aboine basin is a good example.

Subscribing to the opinion that most geomorphic models (whether analytical or deductive) essentially attempt to explain process, Anderson (1973) used fifteen basin parameters to build a multiple regression model. He then used this model to explain drainage basin form in Troutbeck Catchment, Westmorland, England. The changes in drainage net over time have also been explored in the Upper Hodder basin (Lancashire) by Ovenden and Gregory (1980). While conceding that drainage networks vary with map scale, map convention and data format (data format comprises maps, air photographs and field survey), they used a series of Ordnance Survey (OS) maps to illustrate network extensions and contractions experienced by Croasdale Brook between 1847 and 1977. They finally stated that map-based stream network analysis should take the date of survey into consideration since stream networks are not temporally invariant.

Many other empirical researches have been carried out to refine and advance the methodological status of drainage basin enquiry (Scheidegger, 1968; Gerrard and Robinson, 1971; Gardiner, 1973; Gregory and Walling, 1973; Schumm, 1977a, 1977b; Gerrard, 1978; Gregory, 1978; Hutchinson, 1982; Pitty, 1982; Knighton, 1984).

In Central Europe (precisely Romania), an attempt was made at formulating a morphometric model for the Ialomita drainage basin which is a tributary of Danube basin. The basin has an area approximately equal to 10,000km², with a basin length of 325km and an average basin width of 31km.

It was also observed that the morphometric laws were reasonably obeyed in the sub-basins within the Ialomita network. Finally, an indication was given that further research should attempt assessing the exact import of environmental factors in defining morphometric elements (Zavoianu, 1985).

1.4.4 Studies in South-Eastern Asia and Australia:

In the Fowlers Gap and Wollondilly regions of Australia, Abrahams and Campbell (1976) attempted estimating the degree of variations among source-links and tributary source-links in natural channel networks. They based their statistical analysis on the fact that a source-link has a magnitude of one, while a tributary source-link has a magnitude greater than one. After the application of the Chi-Square contingency test, the Kolmogorov-Smirnov two-sample test, and the Mann-Witney U-test, it was deduced and concluded that there were relatively more short source-links than tributary source links.

In Malaysia, Eyles (1966) considered Malayan topographical maps (1:63,360) as generally unsuitable for detailed studies of the linear and planimetric aspects of drainage basin geometry. Supplementing the topographical maps with aerial photographs, he concluded that map representation tends to mask differences in stream lengths, and even argued that first-order streams were not represented on the Malayan (1:63,360) maps. In another work, it was observed that the inadequacy of stream representation on West Malaysian maps was not just a function of map scale, but was also related to land slope (Eyles, 1971).

1.4.5 Morphometric Work in Nigeria:

In Nigeria, only very few morphometric studies have been carried out and these covered very extensive areas. An example is Wigwe's (1966) exploratory work on drainage composition and valley forms in parts of Northern and Western Nigeria. Later, in trying to test and refine some analytical techniques, Faniran (1969) provisionally attempted demonstrating the use of drainage intensity as an index of drainage basin surface geometry. A notable characteristic of the two works cited above is that, being predominantly seminal, they philosophically aimed more at opening up a new research frontier rather than the testing of margins of precision _per se_. Though such works were highly exploratory and provisional, they formed a prime stepping stone for subsequent cognate investigations.

Also in Nigeria, Ebisemiju (1976a, 1976b) observed that an attempt to reduce overcrowding of the medium- and small-scale maps with details has led to an incomplete presentation of stream networks. Based on this, he argued that stream network ordering shown in blue lines on our topographical maps gives a totally wrong picture of the actual stream networks. Using the 1:50,000 topographical series, he supplemented the blue line networks with more channels identified through the contour crenulation technique. The resulting pattern was verified by stereoscopic examination of aerial photographs and field survey. His works were carried out on the Udi-Awgu Cuesta of South-Eastern Nigeria, covering the Obe, Oji and Ozom rivers which are tributaries of the Mamu river which, in turn, is a tributary of the Anambra river (Ebisemiju, 1976a, 1979a, 1979b). He pointed out the issue of proliferation of geomorphometric parameters, but his rationale for regarding the total drainage density, total number of streams, basin relief and average length of first-order streams as the only diagnostic variables may not be readily accepted, at least without verification in other drainage basins, possibly with different environmental settings.

In Western Nigeria, drainage development was investigated on the Idanre Hills (Jeje, 1974). It was a popular belief that there was an inverse relationship between relief and texture of dissection in granitic rocks. This derives from and was popularized by Thorp's (1967) study of the Younger Granites of Kudaru Hills (between Zaria and Jos) in Northern Nigeria, from which it was concluded, through unquantified evidence, that such a relationship existed. But in yet a granitic area in the interfluves of Owena and Osofu rivers, Jeje (1974) tested the correspondence of relief with drainage density and stream frequency, and statistically inferred that there is no clear relationship between the indices of relief and those of dissection.

It should be noted that unlike the work of Ovenden and Gregory (1980), temporal analysis of drainage networks has not been attempted in Nigeria. This is because practically, we have only one series of 1:50,000 topographical maps. The air-photo-coverages of 1950, 1959, 1961, 1962 and 1963 (Appendix B) individually covered distinct parts of the country. These disparate coverages cumulatively formed the data format for the derivation of our current 1:50,000 topographical map series which came out in 1965. If each of the different coverages was nation-wide, then several series of 1:50,000 maps would have been produced. It is only when two or more topographical maps with different base years are available that a morphometric temporal analysis can be meaningfully carried out. Such a temporal analysis would normally evaluate the legacy of denudational agents. Since these agents are relentless in operation, resultant changes in topography and drainage will be evident through a comparison (or superimposition in the case of network) of the distinct maps with different base years. The 1977 air photographs by Meridian Air Maps Limited only yielded 1:1,000 provisional map series for vegetation studies. But if topographical map series on 1:50,000 could be derived from the 1977 aerial coverage, then this can be used in conjunction with the 1965 series for a temporal analysis. The time separating the two major air surveys (i.e. those referred to in Appendix B on one hand and those of 1977 on the other) is just about two decades. This may not be long enough for normal topographic and network transformation processes to produce significant changes. But man's increasing role in accentuating geomorphological proceses now validates temporal analysis even over a very short span of time.

The above review reveals a glaring paucity of drainage basin investigations in Nigeria. Such a situation, characterized by insufficient studies, stresses the need for more morphometric analyses of our drainage basins under varied geological settings. Also, the above literature unveils a dire need to further sharpen basic conceptual and analytical tools. As an interface, a case can be made that network morphometry has suffered undue neglect from both hydrologists and geomorphologists. Thus, in terms of life and currency through a continuous refinement of conceptual tools, this interfacial discipline is analogous to the proverbial goat owned in common that dies of hunger consequent upon mutual neglect. There is need to check the accuracy and utility of topographical maps and streamline the procedural derivation of analytical indices.

It is also important to fill up the identified research lacunae. Since this work will build upon what has already been done, refine and enhance the methodological status of the discipline and possibly open up new vistas, it is well-intended, and therefore justified. Accordingly, we have chosen an unexplored area within which the necessary empirical exercise could be carried out.

1.5 The Study Area

The Aboine river is the largest right-hand tributary of the Cross River. Its confluence with the Cross River is located in the area east of Afikpo in Abia State and west of Itigidi in Cross River State. The Aboine basin comprises all the tributaries and areas that contribute water and fluvial materials to the Aboine network. The major branches are the Iyi-Azu-Ake-Eze, Ikwo, Mvuna, Asu, Nyaba, Idodo, Ora, Ashinu, Itumu and Akaduru rivers (Figure 1). The Ashinu river takes its rise from Benue State, the Ikwo and Iyi-Azu-Ake-Eze rivers rise from and drain areas in Enugu and Abia States, while the other rivers rise from and drain areas in Enugu State.

Geologically, the area is underlain by a variety of sedimentary rocks, including the False-bedded Sandstones, the Lower Coal Measures, the Asata-Nkporo Shale Group, the Awgu-Ndeaboh Shale Group, the Eze Aku Shale Group and the Asu River Group (Figure 2). However, no significant flexures have been noticed in the entire area with the result that drainage basin morphological differences are mainly attributable to variations in soil, lithology and geomorphic processes rather than being structurally accounted for. Akintola (1982) noted that these sedimentary rocks which consist of sandstones and shales also have thin beds of limestone and are generally of the Lower Cretaceous age.

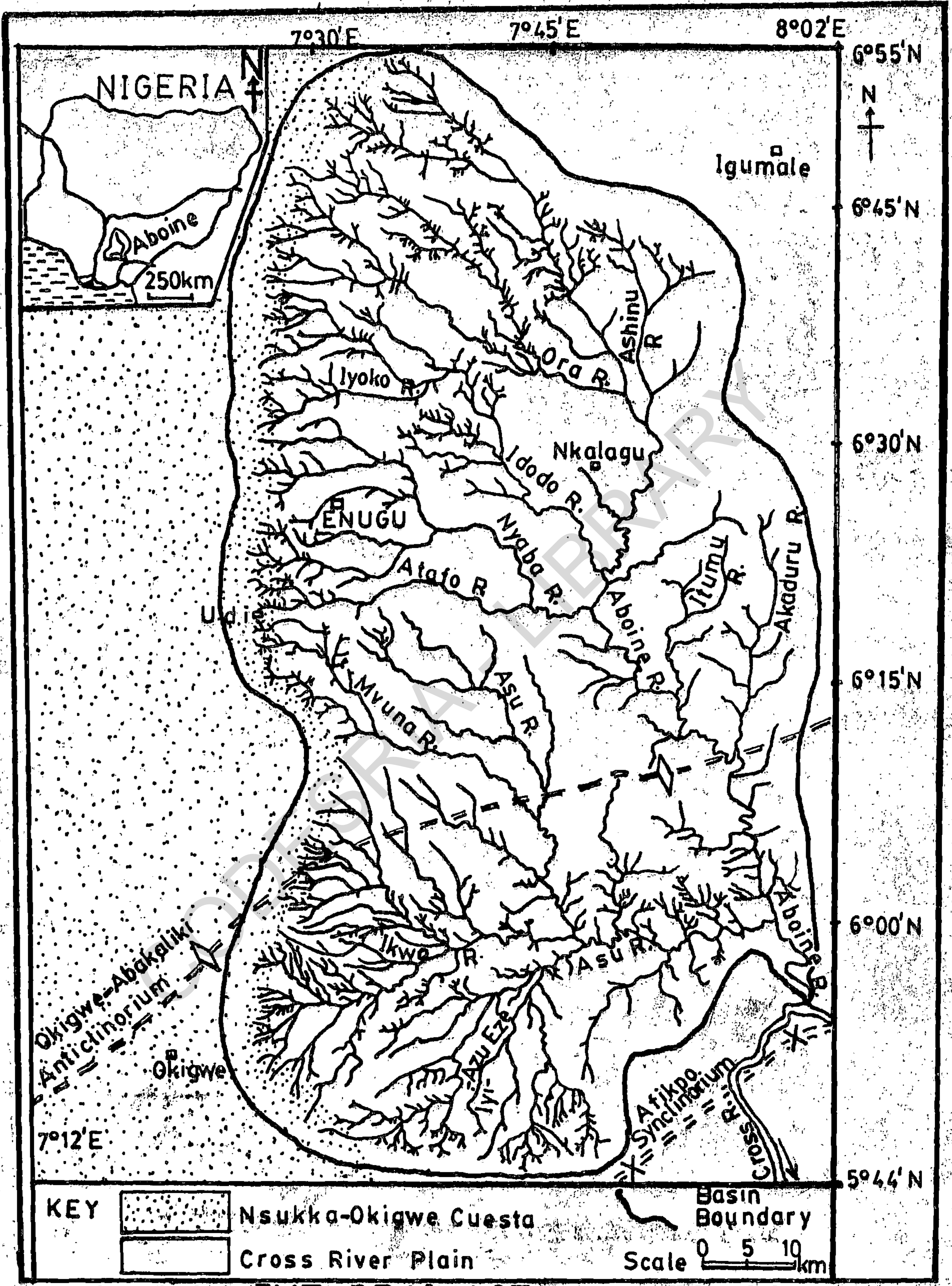


FIGURE 1: THE DRAINAGE AND TOPOGRAPHY OF THE ABOINE BASIN (INSET - NIGERIA: SHOWING THE ABOINE RIVER AS A TRIBUTARY OF THE CROSS RIVER).

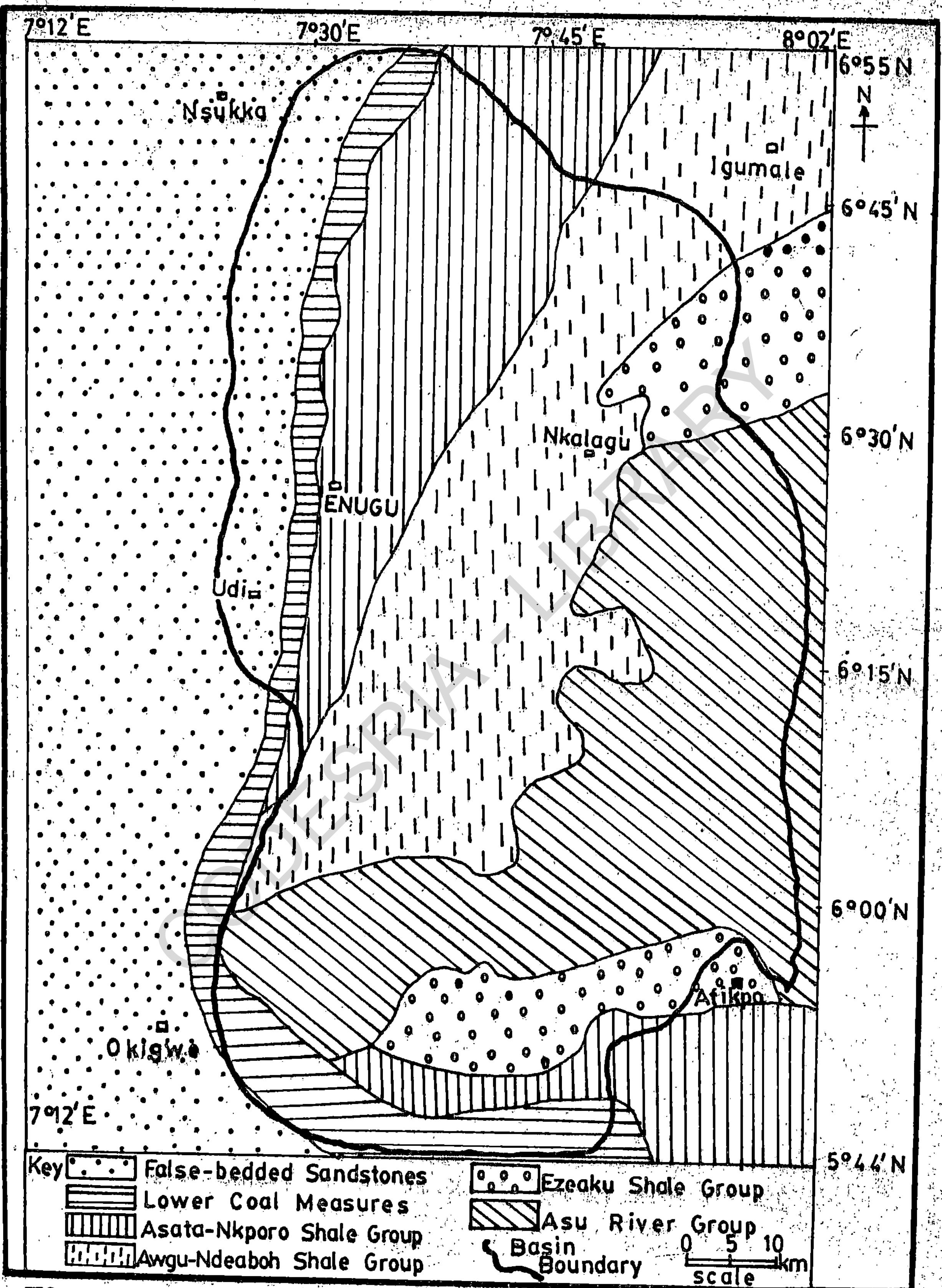


FIGURE 2: THE ABOINE BASIN: GEOLOGY.

Orajaka (1975) summarized the area's palaeo-geological history, noting that during the early part of the Turonian Stage (Upper Cretaceous period), the area experienced an extensive transgression, followed by tectonic movements that gave rise to the Okigwe-Abakaliki Anticlinorium and Afikpo Synclinorium (Figure 1). Apparently, rivers tributary to the Aboine river traverse the Okigwe-Abakaliki Anticlinorium while on the other hand, the Afikpo Synclinorium (having a part of the Cross River Valley) is only marginal to our study area as it lies near the outlet of the Aboine basin. The regression that followed the Turonian tectonism resulted in the accretion of the geological formations already enumerated above, as well as the laying down of marine sediments and fossils, such as the limestones at Nkalagu. Intercalations and fragments of nodular iron-stones and ferruginized indurated shales and sandstones characterize the area. Akintola (1982) claims that in much of Southern Nigeria, the sedimentary rock basins have mostly remained relatively undisturbed since their formation, though on the surface, where the sedimentaries were slightly tilted, continued fluvial activities have carved out prominent scarplands. The relative quietude experienced by the area in terms of tectonism is an indication that there is no strong structural control on the drainage evolution of the area and this underscores the suitability of the Aboine network for an investigation in drainage basin morphometry.

The Aboine network is a classic example of super-imposed drainage system. The relentless operation of fluvial denudational processes on an existing geological sub-structure accounts for the concept of super-imposition. Accumulations of a vast thickness of younger sediments may mask ancient structures over a long period of geological time. The phenomenon of super-imposition is evident when consequent streams initiated on a certain geological formation vertically corrade their courses through an unconformity and subsequently encounter an older and substantially different structure. A super-imposed drainage is often recognizable from the discordant relationship existing between the drainage system and the newly exposed structure (Small, 1978; Hutchinson, 1982). Vast areas of the African continent buried under thick sedimentary deposits are currently being stripped. The resultant super-imposed drainage systems bear little or no relation to the structure of the undermass nor the fossil surface (Faniran, 1986). The rivers in a super-imposed system are much younger than the underlying structure and this is typical of the Aboine basin.

The area has a relatively simple topography comprising the Cross River Plains and the Nsukka-Okigwe Cuesta. The resistant sandstones in the Lower Coal Measures and the lower part of the False-bedded Sandstones formed the escarpment, whose eastern scarp-face has been intensely indented at the headwaters of the numerous deep river valleys. Most of the tributaries of the Aboine river have their headwaters on the scarp-face of the cuesta and cascade down eastwards and south-eastwards into the Cross River Plains (Figure 1).

Ofomata (1975) noted that this plain forms a uniform, sandy sloping drainage basin slightly tilted towards the south-east. Furthermore, the plain is underlain by folded argillaceous sediments of the lower part of the Cretaceous sequence and the streams flow across the folded shales.. This discordant relationship between streamflow and the structure of the undermass is traceable to drainage superimposition.

Available meteorological details clearly indicate that the area has a humid tropical climate. Specifically, Inyang (1975) identified the climate of this area as Köppen's A_f type. Distinctively, within the A_f climate, there is a minimum of seasonal variation in temperature and precipitation - both remaining high throughout the year (Ojo, 1977).

The mean annual rainfall recorded in the region ranges between 1,600mm and 2,500mm (with three to four dry months, the driest month having at least 29mm of rainfall). The copious rainfall not only sustains a maze of permanent water courses but also accentuates fluvial processes. The mean monthly temperature ranges between 27°C and 28°C.

The area's geological sub-structure is acted upon by a hot climate characterized by an abundant rainfall and the result is a thoroughly weathered, thick veneer of regolith. The deep chemically weathered material forms the basis for the derivation of the soils of the area. Pedologically, red and red-yellow ferralsols are characteristic of the area and the plant cover ranges from secondary equatorial forests to forest-savanna vegetation.

From empirical observations, Ebisemiju (1985a, 1987a, 1987b) warned that drainage basins with a wide range of environmental conditions should not be lumped together in studies aimed at highlighting the interdependence of morphometric attributes. This derives from the fact that homogeneity of physiographic conditions is a veritable yardstick for validating morphometric findings. Even though forty-four Strahler-fourth-order basins were identified, only twenty-seven of them were selected (Figure 3)

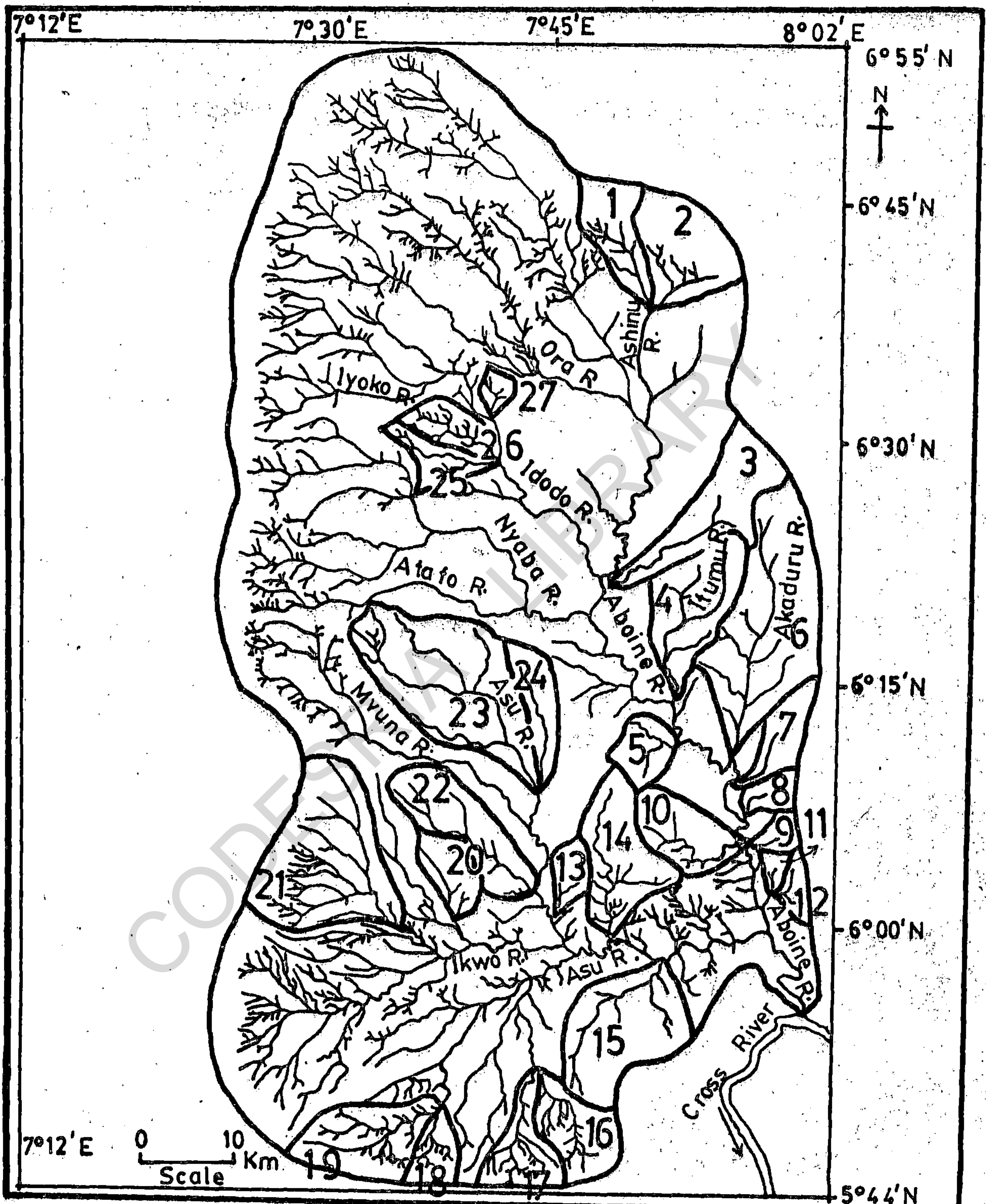


FIGURE 3. THE ABOINE BASIN: SHOWING THE LOCATIONS OF THE TWENTY-SEVEN FOURTH-ORDER SUB-BASINS STUDIED.

based on the criterion of uniformity in environmental conditions. As confirmed by Figure 2, the twenty-seven basins are basically underlain by shale formations giving rise to a thick veneer of deeply weathered arenaceous materials with the parent rocks rarely being exposed.

The basins not only have a common geological denominator, but are as well mainly located on the Cross River plains adjoining the Nsukka-Okigwe Cuesta. Thus, the resulting topography is characterized by a uniformly distinct fluvial system. The surficial topographic expression of the structural material is continuously transformed by fluvial processes. Channelized and unchannelized overland flows, as well as through flows, are the main agents that power these topographic modifications. Using the Aboine basin as an empirical case, Section 1.6 summarizes the structure of the whole work, while the next chapter (Chapter 2) examines how the work was done.

1.6 Thesis Plan:

There is no doubt that topological, morphometric and hypsometric analyses are almost synonymous with extreme laboriousness, tedium and rigour. The structuring of the thesis and the general language of rendition should create an overt (as well as a covert) impression of the empirical rigours on which the thesis is based. The present thesis is parsimoniously divided into six chapters, and the distinctive essence of the work is articulated in the abstract.

Chapter One (the Introduction) defines the locus of the present work in relation to the current paradigm in drainage basin morphometry. The motivating problem, the objectives, theoretical framework, cognate literature as well as the geographical area for empirical demonstration are all embodied in this chapter.

Chapter Two (Methodology) essentially lays the foundation for the logic of explanation by illuminating the nature and process of derivation of the building-blocks (data) on which the inferences were ultimately premised. The chapter is also characterized by streamlined procedures which authenticate the data and so, enhance the validity of the inferences.

The third Chapter (Topological Characteristics) concentrates on the application as well as the testing of the efficacy of several topological techniques. The chapter empirically uses these specific techniques to establish the dendritic nature of the Aboine basin, hence vindicating its choice for a morphometric investigation.

The fourth Chapter (Drainage Basin Parameters) centres on morphometry with the aid of rarefied mathematical tools including multiple correlation and principal component analysis. The chapter demonstratively isolated the diagnostic variables while simultaneously sifting and eliminating redundant ones.

Chapter Five (Hypsometric Analysis) attempts to ameliorate an operational inadequacy (the use of two-dimensional techniques to analyse a three-dimensional figure) inferred from Chapter Four. Accordingly, the chapter (i.e. Chapter Five) represents a pioneering effort leading to the derivation of vital hypsometric indices for the Aboine basin.

Finally, Chapter Six (Conclusion) recapitulates the essential findings that emerged from the work, as well as their implications in relation to further morphometric work. Generally, an attempt was made to coherently link the chapters and to strike a balance between the use of syntax (verbal language) and geometry (the language of spatial forms). The derivation of numerous mathematical syntheses (equations) attests to the scientific undertone of the work. The bibliography (of 177 items) signifies an awareness of related works while the appendices show the details of the data utilized.

CHAPTER 2

METHODOLOGY

Sequel to the quantitative revolution, quantification is part of the conventional wisdom in geography (including geomorphology), but as to whether a conceptual revolution has occurred is still open to debate. When concepts are balanced by techniques, the theoretical status of the discipline is enhanced. In order to achieve this balance, Chapman (1977) recommended that entitation should precede quantification, arguing that geography has consistently and dismally failed to tackle its entitation problems. Drawing from recent development in cybernetics, he (that is Chapman, 1977) attempted providing some theory of empirical enquiry through Geographic Information System (GIS), which was further explored by Bennett and Chorley (1978) to demonstrate the extent to which available and conceivable systems technology can aid the development of an integrated theory. A notable shift from logical positivism to phenomenology (Chapman, 1977) underlies much of current geographical methodology.

Empirical work is planned in such a way as to strengthen the logic of explanation, utilize rigorous arguments, reasonable inferences and internally coherent methods (Harvey, 1969). This methodological stance characterizes much of geomorphological enquiry which runs the full gamut of investigations ranging from field, laboratory, and office observations to theoretical work, as cumulatively modelled in Figure 4. It is conceded, as Richards (1981) pointed out that operator variance in an unwelcome manner, creeps into morphometric measures through the nature of measurement itself and the specification of measurable features. However, an attempt was made in the present work to specify operational definitions in order to minimize operator variance (as would be subsequently seen in Sections 2.1 to 2.5).

2.1 Topographic Base:

The preparation of an adequate topographic base for a geomorphological survey is necessarily preceded by a reconnaissance which is invaluable for proper planning of relevant field work. Such a reconnoitring survey provides the basic information necessary for streamlining the various phases of the data collection procedure. Success in inference considerably depends not only on the method of analysis but more importantly

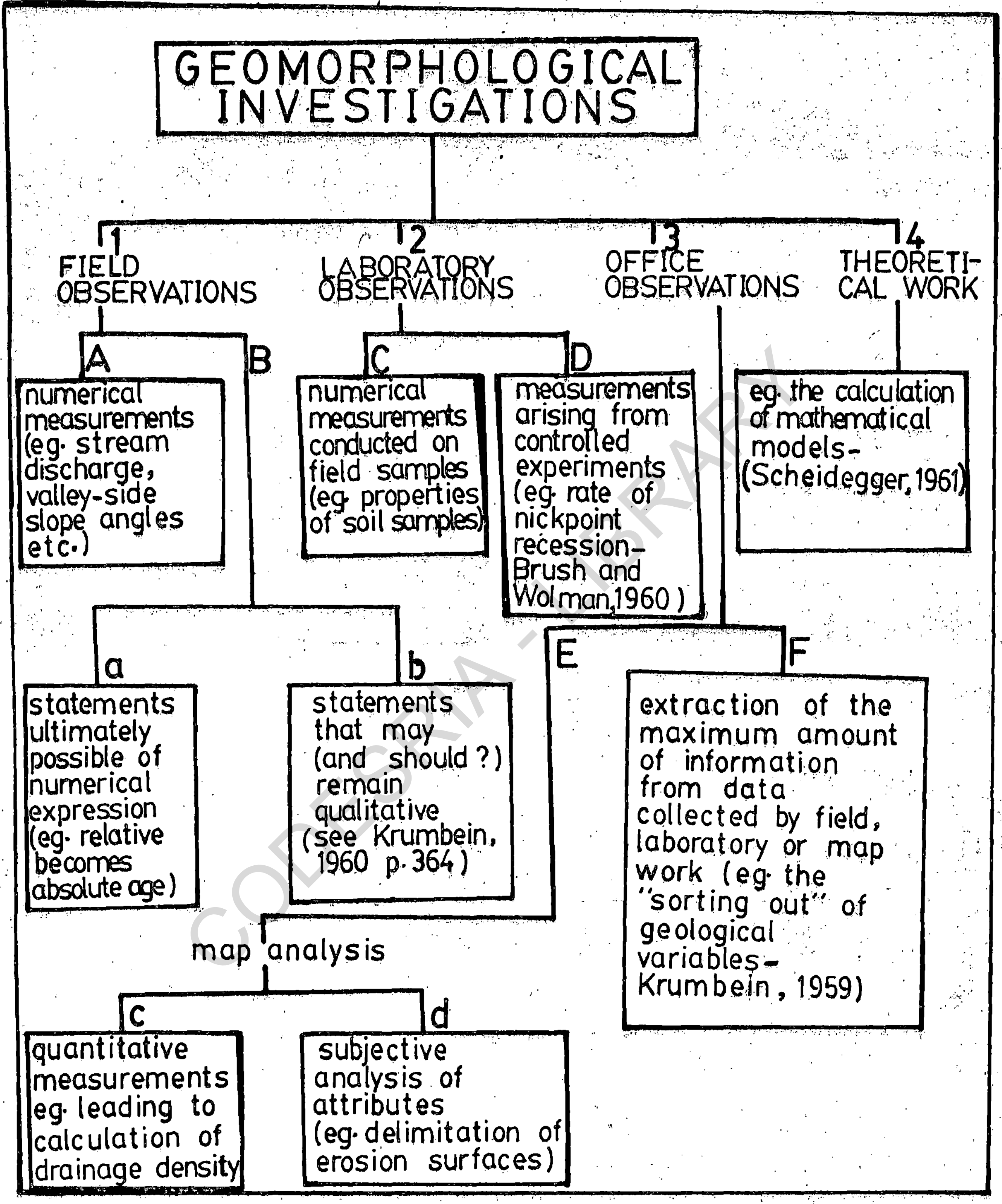


FIGURE 4: THE MAIN BRANCHES OF GEOMORPHOLOGICAL STUDIES(AFTER KRUMBEIN,1960· CHORLEY, 1966; ANDERSON & BURT,1981).

on the nature and quality of data generated. To ensure the generation of the right type of data, the process of data collection should be properly spelt out and followed systematically. Hence the need for planning prior to the actual field work cannot be over-emphasized.

For very small study areas, Verstappen (1970) recommended that the field work should be preceded by an aerial photosurvey and complemented by laboratory (and office) observations. Since our study area is fairly extensive (2,123km^2), the use of aerial photographs was not considered feasible. Alternatively, administrative/thematic maps with some hydrographical details (Appendix C) were utilized in conjunction with reconnoitring surveys to yield a fair topographical elucidation which served as foundation for the main surveys. The main task was to extract the various data types in relation to the specific objectives already stated in Section 1.2

2.2 Data Types

As an investigation in dynamic fluvial geomorphology, the present work is pre-occupied with the analyses of processes as well as changes in drainage basin forms. There is a two-way relationship between form and process. Certain structural and surface geometric properties of forms favour the operation of particular processes. On the other hand, the operation of the processes leads to the modification of the original forms and the creation of new ones. Within the drainage basin context, rivers are visualized as the most potent locus of surficial modification. Movements such as slumping, rotational slipping, mudflow, soil creep and various forms of catenary activities do not compare in potency with fluvial processes powered by the rivers. These rivers form the objects of our investigation, together with the area they drain and the material on which they flow.

Topological data were primarily derived from the river networks, while planimetric details were obtained from the basin area bounded by contours of interest (as would be seen later in Sections 4.1 and 5.2). The material over which the rivers flow forms the lithology, and geomorphometric details of the landscape were derived through the analysis of the relief. By nature, topological and planimetric details are typically lineal and areal respectively. Geomorphometric details (with particular reference to relief) are significantly volumetric. The data types, of necessity, had to determine the sources from which the data could be generated.

2.3 Data Sources:

The empirical nature of much of geomorphological enquiry underscores the rigour of data collection and analyses so as to validate the inferences ultimately arrived at. A large mass of data can be extracted from secondary sources such as literature, maps and theoretical models. However, secondary data could be given more validity when butressed with data from primary sources such as laboratory experiments, simulation and direct field observation. Retrospectively, the branches of geomorphological investigations were schematized in Figure 4. Both field and laboratory observations yield primary data, while office observations yield secondary data and data from both sources can form the adjunct for theoretical work. Some investigations such as the monitoring of erosion, are primarily field-based, while others such as the simulation of geomorphological processes, or the analysis of geochemical properties of soil samples, are primarily laboratory-based. But drainage basin morphometry (which is our main concern in this work) is conventionally and predominantly office-based. Therefore, maps constituted the most dominant data source for this work while the resulting data had to be corroborated with field work.

Geological and topographical bases were established with the aid of the maps listed in Appendices D and E. The Nigerian 1:250,000 geological series (Enugu Sheet 72, Ogoja Sheet 73, Umuahia Sheet 79, and Oban Hill Sheet 80) were used to determine the details of the geological substructure of the study area. Thirteen 1:50,000 topographical sheets formed the major source for the extraction of drainage networks. The reliability of these maps (both geological and topographical) in terms of their dates of compilation and air-photo sources can also be inferred from Appendices F and B, respectively. The air surveys which started in 1943 and ended in 1954 were specifically for geological purposes. The resulting geological map series on 1:250,000 is therefore the most detailed nation-wide geological coverage on the largest available scale. As geology is virtually constant, the currency of this definitive map series is obviously not in doubt.

The only available, largest in terms of scale, and most up-to-date topographical map series in Nigeria is on a scale of 1:50,000. Quite unlike geology, the topography is more dynamic and susceptible to change by agents of denudation. Since the air-surveys were carried out between 1950 and 1963, some topographical modifications (however small) must have occurred to date. However, the operating processes have not been noticeably accentuated and so the cumulative landscape modification might not be very significant. This does not in any case under-rate the need for another series of topographical maps on the same scale to highlight any temporal change in the topography. The mapping of vegetation resources was particularly the target of the 1977 aerial photo-coverage of the country by the Meridian Air Maps Limited of Ottawa, Canada. It yielded a provisional vegetational map series on 1:1,000 which only serves as an adjunct to the vegetation and land use map series on 1:250,000 and is unsuitable for morphometric work. The obvious limitation of poor network resolution at 1:50,000 was made up by recourse to field verification and the contour crenulation technique (Morisawa, 1957; Ebisemiju, 1976b) as demonstrated in Section 2.4.

2.4 <u>Extraction of Data</u>:

Statistical inferences are usually premised on the analyses of data. The data comprise the basic information units available to the researcher. Since the researcher's final output should be coherently and logically synthesized, the fundamental units must equally be precise and systematic. The quest for data for our present investigation was designed in consonance with the above procedural requirements. This underscores the scientific undertone of our data extraction techniques. Standard methods were strictly followed during the appraisal of the various geomorphometric properties. Using the metric system, numerical values were consistently assigned to the relevant identified attributes. The resulting quantitative characterization is consistent with the philosophy of current morphometric methodology.

Morphometric analysis in relation to drainage network requires a clear stream classification system and, for obvious advantages already examined in Section 1.3 above, Strahler's (1952a) system was preferred. It has been observed that the most difficult problem is to establish and compute the number and lengths of first-order streams (Bauer, 1980; Zavoianu, 1985). This problem obviously derives from the scale of topographical maps used for network extraction. Morphometric analyses have always been carried out using medium-scale maps (Ghana - 1:62,500; Malaysia - 1:63,360; Nigeria - 1:50,000; Sierra Leone - 1:62,500). However, investigators in the United States of

America (using the USGS - 1:24,000) and United Kingdom (using the O.S. - 1:25,000) stand at an advantage in that they use topographical maps that are comparatively on larger scales. This is because the smaller the scale of topographical maps used, the less the degree of drainage network resolution and vice versa. A number of analysts have verified the accuracy of stream networks inferred from topographical maps and the observation is that maps with scales larger than 1:25,000 appear more suitable (Haggett and Chorley, 1969; Eyles, 1973, 1974). Drainage basin morphometry is much older and fairly well-established in the Western Countries due primarily to the significant impetus provided by their sophisticated mapping technology. In the Third World Countries, backwardness in technology proves to be a major constraint with respect to the provision of maps needed for morphometric work.

Furthermore, some degree of complication is introduced by operator variance on the part of the cartographers who compiled the existing topographical maps. Much subjectivity underlies channel extraction especially at the stream sources. These inherent shortcomings are unavoidably embedded in most medium scale topographical maps. Such shortcomings ought to be investigated if subsequent information derived from the original maps is not to be erroneous and misleading.

In this work, the blue line method was first adopted with the aid of the 1:50,000 topographical maps produced by the Federal Surveys, Lagos. At this stage, the use of the blue lines had to be provisional since the limitation of poor network resolution was still to be remedied with a complementary technique. Our study area has perennial stream channels as opposed to arid areas with intermittent streams. This implies that the drainage network would resolve on aerial photographs irrespective of the season when the aerial coverage was carried out (Appendix B). The blue lines of topographical maps are based on the networks that resolved on the aerial photographs. To some extent, the blue line method is suitable but the obvious drawbacks merit a serious consideration. Based on field verification, a consensus among drainage basin analysts ranging from Coates (1958) to Zavoianu (1985) shows that first-order streams are predominantly not represented on medium-scale topographical maps. Consequently, the blue line method was supplemented with the contour-crenulation technique. This is applied where a contour crenulation forms an angle not exceeding 120° in at least two consecutive contours. The contour-crenulation technique was greatly utilized in this work to derive the linear extent of the drainage network. The operational basis is to ameliorate the shortcomings of the blue line method already referred to.

Thus, with these two complementary techniques, the netowrk extent is fairly well-established. All linear measures were carried out with the use of an opisometer. The pattern of contours guided the delimitation of the various basins and inter-basins. The areal measurements were made using squared ($1cm^2$) transparent overlays and each square covers an area of $0.25km^2$ on the ground (Appendix G).

Based on homogeneous physiography, 27 fourth-order basins developed on the Cross River Plains were studied (Figure 3, Appendix H). More than 95% of the fourth-order basins which meet this criterion in the Aboine network were practically covered. The only exception was the area drained by the headwaters of the Ikwo river in the Okigwe/Umuahia area. As we found out from the Federal Ministry of Works and Transport, Surveys Division, Lagos, this area is probably the only area in Nigeria that is surprisingly not covered by the 1:50,000 topographical series. This fact corroborates an earlier observation in which it was noted that (by 1982):

> "1:50,000 sheets have been published or are in advanced state of preparation for all of Nigeria save the Aba-Owerri area (Nos 312 and 321) which is available at 1:100,000" [Barbour, 1982, p. 10).

We decided not to carry out any analysis of the Ikwo headwaters even on the available scale of 1:100,000. This is predicated on an understanding that morphometric analysis at such a small scale will only exaggerate the 'error term' in relation to network extraction. Our operational design was engendered a priori by a strong conviction that morphometric relationships are capable of extrapolation in terms of scale.

Large masses of topological and morphometric data were generated. The topological details are treated in Chapter 3, the hypsometric data are mainly analysed in Chapter 5 while the entire morphometric data that form the basis for Chapter 4, are presented in Appendix I. For a prima facie interpretation, the figures in Appendix I (for each of the 27 basins) are the respective values of the variables (from 1 to 15), and the units of their measurements are also as contained in Appendix A. For example, for basin number 01, the first variable is $N_1 = 33.00$; the second variable is $\sum L_1 = 55.50$km; the third variable is $\bar{A}_1 = 1.28\text{km}^2$ ... the fifteenth variable is HI = 0.203.

The choice of these fifteen variables was necessarily predicated by the need to avoid unnecessary duplication and redundancy in the isolation and combination of variables. Relevant areal, lineal and relief variables that have frequently featured in morphometric analysis were consciously utilized in the present investigation. With the use of appropriate statistical techniques, the data generated had to be analysed in consonance with the objectives of the study.

2.5 Data Analysis:

Leopold et al (1964) summarized the feelings of professional geomorphologists about numbers, graphs and formulae as ranging from acceptance and enthusiasm to bewilderment and forthright hostility. It is argued that in some cases, numerical descriptions can give misleading and erroneous impressions of erudition. This could derive from the fact that quantitative techniques are, most probably, the sharpest tools of analyses with a corollary of causing the greatest harm if wrongly applied.

However, quantification has come to stay, having established itself as part of our conventional thought. This is why Burton (1963) concluded that marginal returns for arguing in favour of quantification have virtually become nil. With the current data explosion facing our discipline, quantitative techniques have proved very useful in yielding the desired synthesis. This advantage has been accentuated by the advent of modern electronic computers, leading to a widespread use of package programmes.

Since a bandwagon use would always lead to flagrant abuses, Haggett (1969) warned that the use of package programmes without a proper appreciation of the underlying assumptions and limitations can lead to the transformation of one complex and puzzling mass of data into another complex and puzzling mass of data. This re-echoes Hägerstrand's (1967) assertion that actually the computer is a friendly animal. This is so because the computer readily accepts any set of information (data), manipulates it and displays the result in whatever way the user specifies. Thus, the manipulation is done irrespective of both the nature of data and the underlying assumptions of the statistical technique employed. However, in this work, the operational requirements of the individual statistical techniques were carefully examined to ensure strict compliance, with the aid of the computer.

A major aspect of the work involved the generation of data for fifteen variables (see list of variables, Appendix A) for each of the twenty-seven fourth-order basins. The resulting 15 x 27 raw data matrix (see Appendix I) necessitated the choice of appropriate multivariate statistical techniques. Factorial analysis was considered appropriate. This primarily derives from the exploratory and analytical nature of this work as well as the need to cope with the multiplicity of variables. The basic concepts and operational procedures of factorial analysis have been demonstrated in literature (Gould, 1967; Kim, 1975; Elffers, 1980; Johnston, 1980).

Factorial analysis is distinctive in its data-reduction capability. It highlights the underlying pattern of relationships through the use fo a smaller set of factors as source variables to account for the observed relationship in the data. This type of analysis is useful in terms of exploring and detecting the pattern of variables. It proves useful for the testing and confirmation (otherwise, refutation) of the hypothetical structure. It has also formed the basis for the derivation of new indices and possibly, new variables that can be used in further analysis.

Factorial analysis actually subsumes many alternative procedures. The need to reduce a large mass of data and explore the underlying dimensions necessitated the use of Principal Components Analysis (PCA, Appendix J). In drainage basin morphometry, impressive results have been recorded from the application of PCA by Mather and Doornkamp (1970) and Ebisemiju (1979a, 1979b). In the preparation of a correlation matrix through the principal axis method, the computer carried out the type of factor analysis based on correlations among the 15 variables. The resulting multiple correlation matrix (15 x 15) had unity along the diagonal, and this is procedurally normal. While extracting the initial factors through data-reduction, a new set of variables were defined as an exact mathematical transformation of the original data. The factors/components were finally orthogonally rotated to a terminal solution. The rotation was accomplished through the Varimax method which maximized the variance of squared values of loadings in each component. Finally, the operation produced a simplified but theoretically meaningful pattern of components.

Factorial analysis yielded the basic morphometric indices for explaining the drainage basin surface geometry of the study area. The analysis was strengthened by hypsometric analysis (see Chapter 5). The hypsometric and morphometric parameters complemented the topological analysis of Chapter 3.

CHAPTER 3

TOPOLOGICAL CHARACTERISTICS

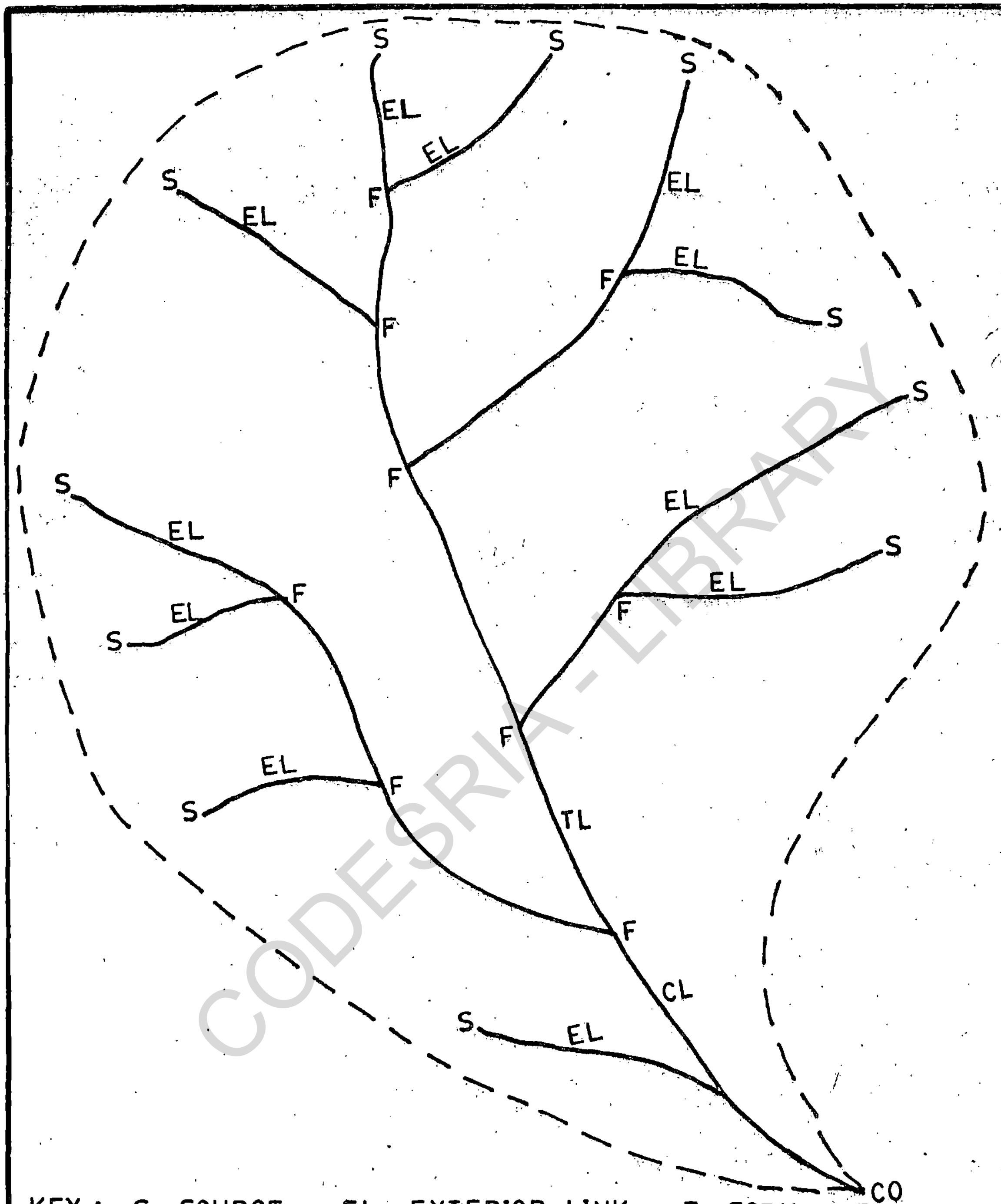
Cole and King (1968) noted that drainage pattern is one of the most conspicuous patterns on the topographic surface. The organization of the stream networks can be analysed in a number of different ways. The present chapter centres on less-quantitative aspects of stream network analyses which are topological in nature. Highly, quantitative methods involving rarefied mathematics would be treated in Chapter 4.

3.1 The Concept of Topology:

In a conceptual definition, Harvey (1969) stated that topology is a qualitative form of geometry and that it is primarily concerned with the continuous connectedness between the points of a figure. Being very basic to geometry, topology provides a very simple linear and numerical perceptual concept of space from which other higher and more rarefied geometric properties can be derived.

Since links are very basic to our analysis, it is important to summarize their operational definitions and other terminologies involved in this work. Sources are the farthest upstream points in a network and a fork refers to the confluence of two channels. Any length of channel without an intervening fork is called a link. More comprehensively, a link simply defines the channel length stretching from a source to the first fork or in-between two consecutive forks or between the last fork and the channel outlet. When a link terminates in the upstream end in a source, it is called an exterior link, and when it terminates in the upstream end in a fork, an interior link results. When two consecutive tributaries at the upstream and downstream ends enter the main channel from the same side, the link formed on the main channel is known as a cis-link and conversely, if they enter from opposite sides, a trans-link is formed. The basic terms introduced above are further illustrated in Figure 5.

In any network, the maximum number of links from a source to the outlet is termed the diameter (d) which is a topological mainstream length index. The number of exterior links in a network is equal to the magnitude (M) of the network (when the exterior links are assigned a magnitude value of one). The magnitude of a network is equal to the number of sources ultimately tributary to it. An empirical relation exists in which a dendritic network



KEY : S = SOURCE ; EL = EXTERIOR LINK ; F = FORK ; TL = TRANS-LINK (INTERIOR LINK) ; CL = CIS-LINK (INTERIOR LINK) ; CO = CHANNEL OUTLET.

FIGURE 5 : A HYPOTHETICAL STREAM NETWORK (M=11, d=7) ILLUSTRATING BASIC TOPOLOGICAL TERMINOLOGIES.

with magnitude, M (i. e. having M sources or exterior links) must have M-1 interior links and 2M-1 total links (Shreve, 1966, 1967, 1969; James and Krumbein,1969; Mock, 1971; Smart and Wallis, 1971; Ferguson, 1980; Flint, 1980; Javis and Sham, 1981).

3.2 Stream Ordering:

Many stream ordering systems have been proposed and applied in drainage basin studies. In addition to reviewing these systems and their unique properties (Table 1), Gardiner (1981) noted that samples for morphological studies can be conveniently taken using the Strahler (1952a), Shreve (1967) and Smart (1978) systems; topological investigations can be carried out using the Shreve (1967), Scheidegger (1965), Woldenberg (1967) and Smart (1978) systems, while the system developed by Gregory and Walling (1973) is most appropriate for process investigations.

In our investigation, the Strahler (1952a) system was used as the basis for identifying the drainage basins. Table 2 shows the result of this ordering. In order to draw some statistical inferences from the data, the number of stream segments (N) was regressed upon stream order (u) and the result is graphically presented in Figure 6. The inverse

TABLE 1: Major methods of stream ordering and their special properties (Modified after Gardiner, 1981, p.50)

	ORDERING METHODS						
PROPERTIES	Horton's (1945)	Strahler's (1952 a)	Shreve's (1967) $M=N_1$	Gregory and Walling's (1973) $G=2M-1$	Scheidegger's (1965) $S=\frac{\log 2M}{\log 2}$	Woldenberg's (1967) $W=\left(\frac{\log M}{\log R}\right)+1$	Smart's (1978) $u=4^{u-1}$
1. Convenient for sampling		✓					
2. Completely objective		✓	✓	✓	✓	✓	✓
3. Integer orders only	✓	✓	✓	✓			✓
4. Does not violate distributive law			✓	✓	✓	✓	✓
5. Each junction should change order			✓	✓	✓	✓	
6. A network should have only one defined ordering		✓	✓	✓	✓		✓

TABLE 2; A Summary of stream numbers in the Aboine network following the Strahler (1952a) ordering system

Basin S/No	Stream Orders			
	4th-Order	3rd-Order	2nd-Order	1st-Order
1	1	2	9	33
2	1	4	17	62
3	1	3	14	58
4	1	3	18	64
5	1	3	14	46
6	1	8	36	150
7	1	2	11	43
8	1	4	14	58
9	1	3	12	44
10	1	5	23	82
11	1	2	8	24
12	1	3	9	35
13	1	2	5	18
14	1	6	26	110
15	1	2	5	17
16	1	2	6	27
17	1	3	9	36
18	1	2	6	16
19	1	2	5	25
20	1	2	10	39
21	1	4	19	67
22	1	3	13	51
23	1	4	27	106
24	1	2	15	46
25	1	2	7	34
26	1	2	9	24
27	1	2	7	18
Total	27	82	354	1333

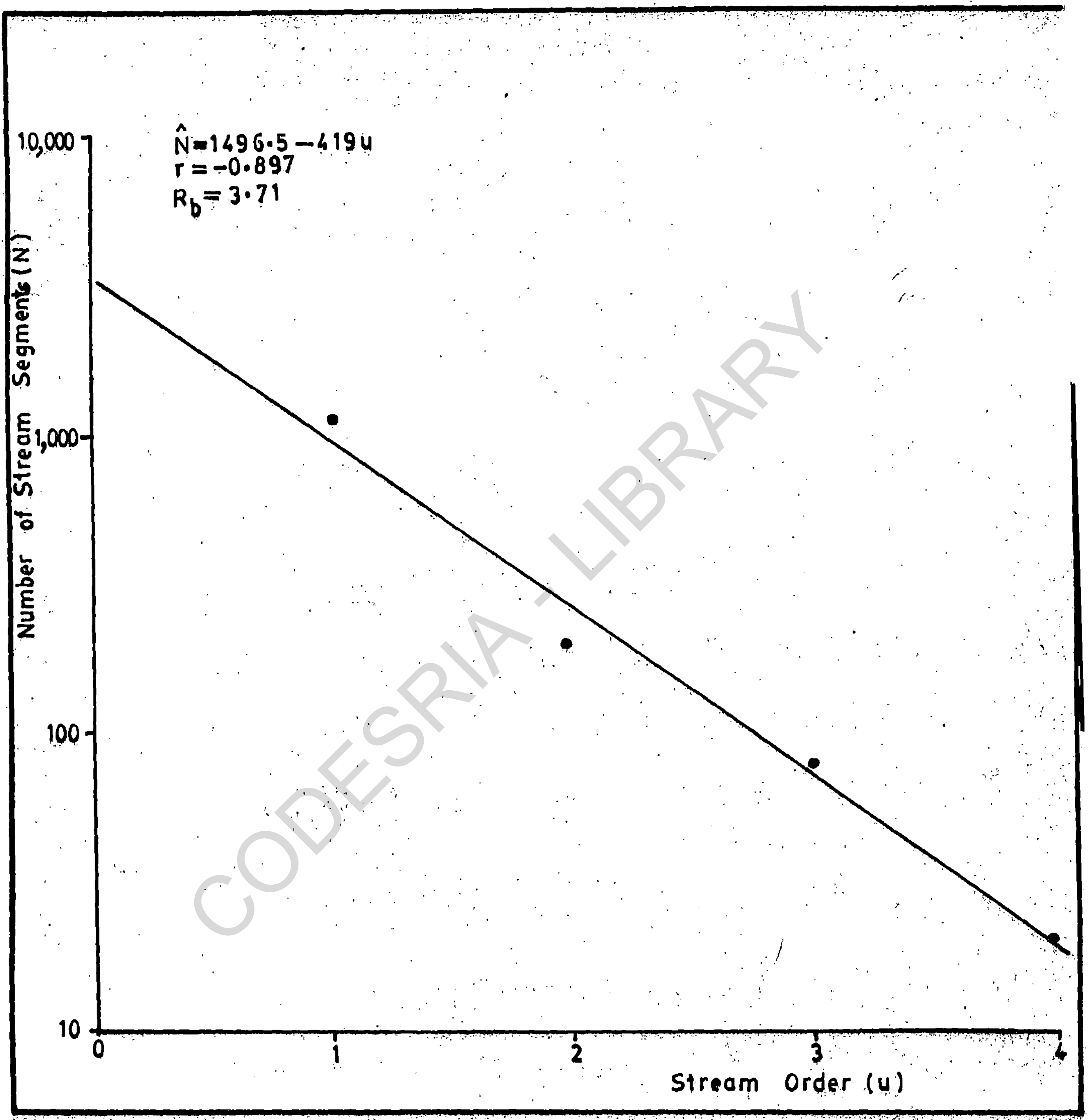


FIGURE 6: REGRESSION OF NUMBERS OF STREAM SEGMENTS ON STREAM ORDER FOR THE SUB-BASINS OF THE ABOINE NETWORK.

relationship (r = -0.897) found to exist between stream number and stream order shows that the first law of drainage composition is obeyed by the sub-basins of the Aboine network. That the law was obeyed is not of much interest *per se* when compared with the fact that our observation is in agreement with findings arrived at elsewhere (Morisawa, 1962; Leopold *et al*, 1964; Knighton, 1984). Subsequently, our topological analyses followed Shreve's (1967) magnitude-based system.

3.3 Models for Topological Work:

Approaches to topological network analysis have recently proliferated. Quite spiritedly, it has been claimed that a

> "faithful application of the Horton-Strahler stream ordering approach has singularly failed to resolve issues, owing to the low and variable information content of network order specification".
> (Javis, 1976b, p. 1224)

At one end, some purely probabilistic models have been advanced with random walks theory as their mathematical basis. For instance, Shreve (1966, 1974) argued that network topology evolves at random in the absence of climatic, structural and topographic constraints. This formed the basis for Topologically Distinct Channel Networks (TDCNs) each of which is equally probable in the absence of constraints. The number of TDCNs of any magnitude according to Shreve (1966) is:

$$N_{(M)} = \frac{1}{2M-1} \left(\frac{(2M-1)!}{M!\,(M-1)!} \right) \qquad (4)$$

where N is the number of TDCNs
and M is the magnitude.

For example, a magnitude 9 network has approximately 1430 TDCNs. Two networks are said to be topologically indentical if one of them can be made congruent to the other simply by continuously deforming the links without removing them from the plane (Shreve, 1966; Kirkby, 1976). TDCNs, in contradistinction to topologically identical ones, are those whose map projections cannot be deformed continuously in the plane of projection so as to become congruent (Shreve, 1974).

The random model relies on Feller's (1957) random walks theory of 'first returns', and its greatest obstacle to the attainment of a wide currency is the fact that it has overdrawn from its association with the theories of groups and complex variables as well as the algebra of complex numbers. The result has been that after the various transformations, transpositions and rotations operationally required, the mystifying model only yields a mystifying result which proves more of a mathematical exercise, almost adding nothing new to existing knowledge. The challenge is for the formulators of such highly theoretical concepts to translate them to the level of practical application. Research endeavours should not just yield pure intellectual ideas but the ideas should be meaningfully reducible to practicality in the sense that the associated theoretical superstructure should be rooted in practical reality. The <u>how</u> of an investigation should be complemented by the <u>why</u>, and neither the techniques nor the connotations of the results should receive lop-sided emphasis. This recalls an earlier indictment of the quantifiers for being more interested in the language of their communication than the substance being communicated (Olsson, 1975).

It has been argued that the Strahler-ordering system is conceptually too broad and simplistic and that, on the other hand, the random model is too detailed and complicated. The greatest impediment to the random model at the empirical level, however, seems to be the size of data necessitated by such an analysis. Accordingly, it was noted that

> "a major difficulty with the topologically random model is that the sample size necessary for direct statistical analysis is prohibitive for all except the smallest networks".
> (Mock, 1971, p. 1558).

This, most probably, was what motivated Smart (1969) to develop an intermediate measure, termed ambilateral classification scheme, which derives from the fundamental assumption of the random model. The ambilateral scheme preserves much of the topologic information. Nevertheless, a major limitation is involved and this is because the scheme can only be empirically demonstrated in very small networks. In large networks, the sample size becomes prohibitive as in the case of the random model. A similar mode of analysis was pursued by Kirkby (1976), who treated the network as a family tree by describing topological properties in terms of numbers of links or 'generations' from the network outflow.

While scanning a network through the random walks process, Ferguson (1980) proposed an index defined by the maximum excess of interior- over exterior-links. This is the L-index which is used to determine the degree of network symmetry.

Since the above topological measures founded on the basic assumptions of the random model cannot be applied to networks of large magnitudes, Javis (1972) proposed a new, sophisticated and more generally applicable measure, the E-index, defined as:

$$E = \sum M.H_i / \sum M.H_e \qquad (5)$$

where M is the magnitude of a given point and H is its link distance; the subscripts i and e denote summations over the interior and exterior points respectively.

Still in its seminal form, the denominator of equation (5) is the product of magnitude and link distance. But since the magnitude of all exterior links is constant (being unity in our classification system), M is certainly redundant and should not be retained in the denominator, hence our modification:

$$E = \sum_{i=1}^{n} MxD_i / \sum_{i=1}^{n} D_e \qquad (6)$$

where M is the magnitude of a given fork or confluence and D is its link distance, while i and e are the same as in equation (5).

The E-index is a precise structural measure for the analysis of network graph. Contrastingly, the other indices such as Shreve's (1966) random model and Smart's (1969) ambilateral scheme, are enshrouded in mystifying mathematics and lack general empirical demonstration. The E-index was therefore adopted, together with a combination of other measures capable of describing drainage network structure in terms of links following James and Krumbein 81969), and in terms of elongation or compaction by using network diameter and magnitude.

3.3.1 Link Analysis:

Table 3 shows the results of link analysis of the twenty-seven fourth-order networks of the Aboine drainage basin. A total of 421 links were examined in twenty-seven sequences along the mainstream diameter. The process had to be truncated at links with magnitudes ranging between six and four. This method which terminates analysis between magnitudes four and six is not only procedurally justified but also necessary since tributary handedness becomes ambiguous at very low magnitudes. Trans-links along the diameter totalled 232 (or 55.11%) and cis-links totalled 189 (or 44.89%). The preponderance of trans-links over cis-links is a clear indication that the Aboine drainage network is typically dendritic. Geologically, there is not much structural control on the drainage evolution and this fact gives accent to the suitability of the Aboine network for topological work.

Our results are in consonance with other findings under similar circumstances. For instance, in the Middle

TABLE 3: Link analysis of the fourth-order sub-basins of the Aboine network

Basins	Cis-links	Trans-links	Diameter	Magnitude	E-index
1	7	11	21	33	6.58
2	7	12	21	62	7.31
3	11	15	28	58	10.18
4	13	12	28	64	9.45
5	8	7	17	46	6.12
6	17	22	44	150	13.38
7	7	13	25	43	7.84
8	9	9	23	58	6.87
9	5	11	20	44	5.99
10	11	15	32	82	12.97
11	1	5	11	24	4.00
12	6	4	13	35	4.55
13	5	1	10	18	3.34
14	13	18	36	110	12.05
15	4	1	9	17	2.84
16	4	7	17	27	5.37
17	1	8	15	36	4.54
18	1	2	7	16	2.48
19	4	4	12	25	3.45
20	6	8	19	39	5.74
21	5	8	19	67	6.89
22	11	11	26	51	7.51
23	13	10	30	106	10.53
24	5	8	17	46	5.00
25	7	4	16	34	5.87
26	3	4	12	24	1.61
27	5	2	11	18	3.65
	Total = 189 (44.89%)	Total = 232 (55.11%)	$\bar{d}$ = 19.96	Total = 1333	$\bar{E}$=6.52

Fork of Kentucky, free of geologic controls that might distort the almost classical dendritic pattern of the stream network, a census of streams of magnitudes ≥ 10 revealed link frequencies of 293 (or 60.40%) trans-links and 192 (or 39.60%) cis-links (James and Krumbein, 1969).

3.3.2 Network Diameter:

The mainstream diameter is conceptually defined by the maximum number of links from the network outlet to the source. The determination of the diameter starts at the outlet and proceeds upstream taking the path of higher magnitude at the bifurcations. The diameter as shown in Table 3 are highly varied, ranging from 7 to 44, with a mean of 19.96 and a standard deviation of 8.93. The diameter gives an indication of the extent of the drainage basin within which fluvial processes operate. It is an index of topological elongation and Javis (1972) and Sham (1981) have observed that the most elongated structure has the largest diameter, while the most compact structure has the smallest diameter.

3.3.3 Network Magnitude:

Since the initial link-generating process operates by bifurcations of the growing tendrils on the network margins, James and Krumbein (1969) recommended that if stochastic process models are to be developed, observational measurement data should be related to stream process rather than channel response. Network magnitude refers to the number of sources in a drainage basin which, in turn, gives a numerical indication of the spots where active headward erosion and network extensions are more likely to predominate. For the 2,123km^2 drained by the fourth-order networks, the total magnitude was found to be 1,333. For the 27 fourth-order networks, the magnitudes range from 16 to 150 with a mean of 49.37. Shreve (1974) noted that magnitude is closely proportional to drainage area (A_d), and, for the Aboine basin, the degree of correlation was found to be positive (r = 0.75).

The strength and direction of relationship between magnitude and diameter E-index and diameter, and E-index and magnitude were calculated with the aid of the techniques of bivariate correlation and linear regression. The equation of a least-square line was calculated using a linear regression of the form:

$$\hat{y} = a + bx \qquad (7)$$

in which

$$b = \frac{\sum_{i=1}^{n} xy - n\bar{x}\bar{y}}{\sum_{i=1}^{n} x^2 - n\bar{x}^2} \qquad (8)$$

and $a = \bar{y} - b\bar{x}$ (9)

where $\hat{y}$ stands for the predicted value of the dependent variable, x is the independent variable, while a is the intercept and b is the gradient of the least-squares line.

The correlation between diameter and magnitude was found to be high and positive ($r = 0.92$) and Figure 7 is a graphical representation of the resultant scatter diagram. Diameter was regressed on magnitude, leading to the derivation of an equation of least squares line:

$$\hat{d} = 7.12 + 0.26M \qquad (10)$$

where $\hat{d}$ is the predicted value of diameter and M is the magnitude, which is also the independent variable.

The regression operation was brought to a logical conclusion through the application of a goodness of fit test on the regression equation. This involves the calculation of the standard error of estimate, a general form of which was defined by Spiegel (1972) as:

$$S_{y.x} = \sqrt{\frac{\sum (y - \hat{y})^2}{N}} \qquad (11)$$

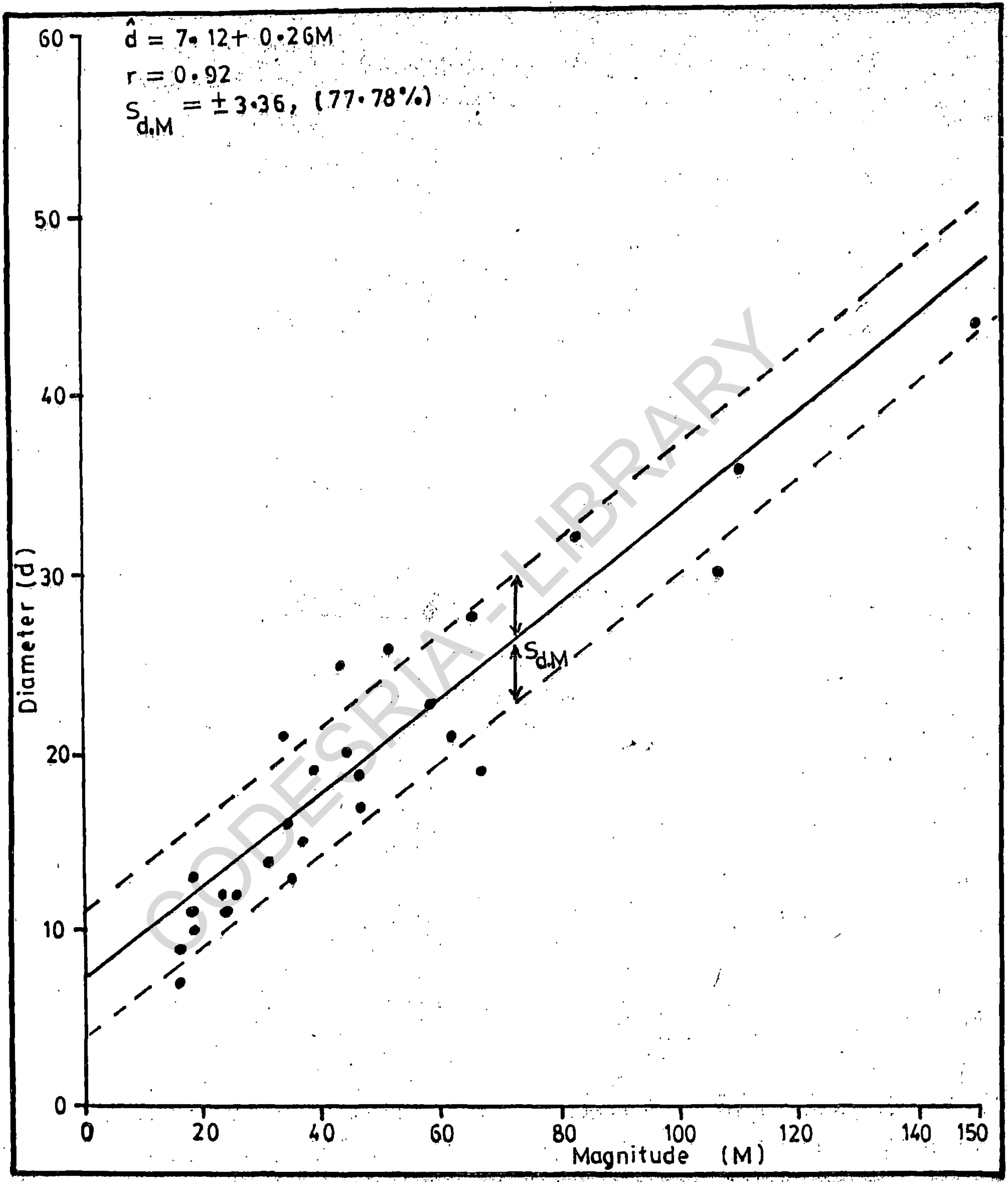


FIGURE 7: RELATIONSHIP BETWEEN DIAMETER AND MAGNITUDE AMONG THE FOURTH-ORDER BASINS OF THE ABOINE NETWORK.

where $S_{y.x}$ is the standard error of estimate of the dependent variable (y) on the independent variable (x), $\hat{y}$ is the predicted value of the dependent variable using the regression equation and N is the number of pairs of variables.

An application of equation (11) to the relationship between diameter and magnitude led to the derivation of the standard error of estimate of diameter on magnitude ($S_{d.M}$ = ± 3.36). In Figure 7, the relationship between the regression line defined by equation (10) and the scatter of the observation points is further elucidated by the standard error of estimate. Accordingly, up to 77.78% of the coordinates are scattered within a distance of one standard error of estimate ($S_{d.M}$ = ±3.36) from the regression line. This least squares regression line is therefore a good fit for the data points and the 22.22% of the points outside the range defined by the $S_{d.M}$ could be attributed to sampling fluctuations and minor measurement errors.

3.3.4 Network Elongation:

A consensus of opinion exists among drainage network analysts that the magnitude parameter reflects the amount of drainage development headward from any given point on the network, while the link distance reveals the structural configuration of the network downstream from the given point. Javis (1972) algebraically synthesized these details into the E-index (equation (5)), suitable for the estimation of the degree of topological elongation (and compaction) among drainage networks. In addition to being an index of symmetry (or otherwise), the structure of links in a network can be topologically analysed to highlight the lineal and areal extent of the basin concerned. Network extent (in terms of elongation and compaction) is closely related to the underlying geology and lithology. The 2,639 links of the Aboine fourth-order networks were analysed using the E-index (equation (6)). A multiple correlation of the variables utilized (Table 4) revealed that E-index correlated positively with magnitude (r = 0.90). Magnitude correlated positively with drainage area (r = 0.75) and E-index also positively correlated with drainage area (r = 0.58). Figure 8 shows the scatter diagram of which a linear regression yielded the equation:

$$\hat{E} = 2.08 + 0.09M \qquad (12)$$

where the value of the predicted E-index is represented by $\hat{E}$, and M stands for magnitude.

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where the value of the predicted E-index is represented by $\hat{E}$, and M stands for magnitude.

TABLE 4: A 15 x 15 multiple correlation matrix derived for the Aboine basin

	N_1	$\sum L_1$	$\bar{A}_1$	R_{b2}	$\sum N$	$\sum L$	$\bar{L}_s$	A_d	h	D_d	R_e	R_c	d	E	HI
N_1	1.00	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\sum L_1$	.90*	1.00	–	–	–	–	–	–	–	–	–	–	–	–	–
$\bar{A}_1$	-.001	.34	1.00	–	–	–	–	–	–	–	–	–	–	–	–
R_{b2}	.29	.23	-.08	1.00	–	–	–	–	–	–	–	–	–	–	–
$\sum N$	.99*	.90*	-.001	.26	1.00	–	–	–	–	–	–	–	–	–	–
$\sum L$	.89*	.99*	.33	.22	.89*	1.00	–	–	–	–	–	–	–	–	–
$\bar{L}_s$	.15	.50•	.78*	.09	.14	.53	1.00	–	–	–	–	–	–	–	–
A_d	.75*	.93*	.49•	.15	.75*	.95*	.67*	1.00	–	–	–	–	–	–	–
h	.20	.42	.32	.23	.20	.42	.40	.43	1.00	–	–	–	–	–	–
D_d	.09	-.20	-.71	.06	.09	-.25	-.80*	.46•	-.23	1.00	–	–	–	–	–
R_e	.03	-.03	-.29	-.35	.05	-.01	-.20	-.02	-.04	.14	1.00	–	–	–	–
R_c	.05	-.02	-.35	-.35	.06	-.02	-.32	-.06	.11	.42	.75*	1.00	–	–	–
d	.92*	.81*	-.02	.37	.92*	.79*	.12	.62*	.07	.18	-.17	-.09	1.00	–	–
E	.90*	.78*	-.05	.36	.89*	.76*	.09	.58*	.09	.22	-.11	-.08	.96*	1.00	–
HI	.15	-.07	-.39	.36	.15	-.08	-.52•	-.22	-.01	.53•	-.03	.04	.18	.23	1.00

No. of cases = 27;
• - significant at .01;
* - significant at .001.

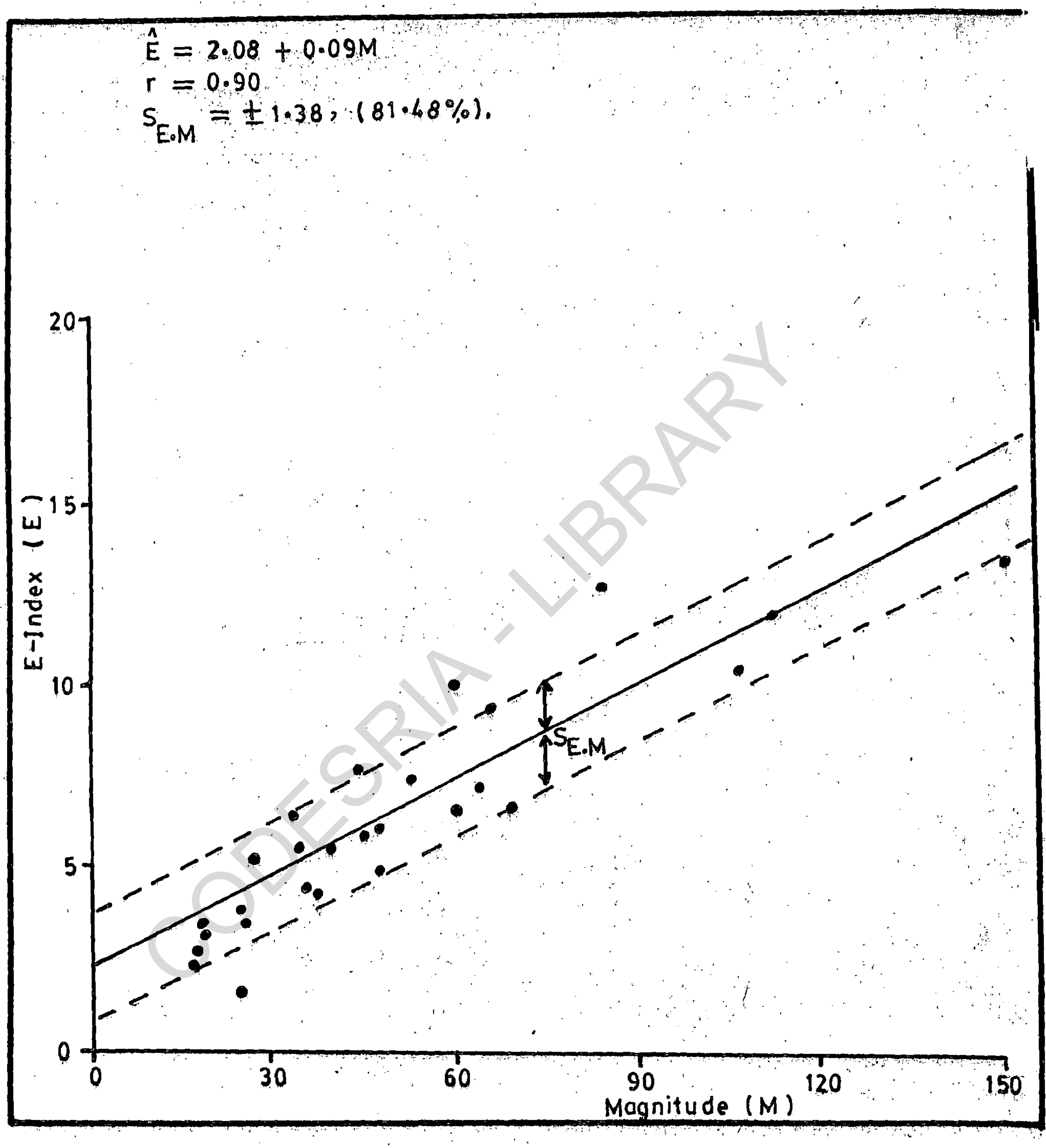

FIGURE 8: RELATIONSHIP BETWEEN THE E-INDEX AND NETWORK MAGNITUDE AMONG THE FOURTH-ORDER BASINS OF THE ABOINE NETWORK.

A goodness of fit test using equation (11) gave the standard error of estimate of E-index on magnitude as $S_{E.M} = \pm 1.38$. It was graphically observed from Figure 8 that 81.48% of the distribution fell within a distance of one standard error of estimate ($S_{E.M} = \pm 1.38$) from the regression line. The E-index was also regressed upon network diameter with which it also correlates positively (r = 0.96). The resulting graph is shown in Figure 9, and the equation of the least-squares line arrived at is:

$$\hat{E} = -0.27 + 0.34d \qquad (13)$$

where $\hat{E}$ is the predicted E-index using diameter (d) values.

The validity of the regression analysis was established by calculating the standard error of estimate of the E-index on diameter using equation (11). The operation yielded $S_{E.d} = \pm 0.82$, with 92.59% of the data points being concentrated within a distance of one standard error of estimate about the regression line. Apparently, the linearity of the scatter diagram (Figure 9) is indicative of the goodness of fit of the regression line defined by equation (13). This linearity of co-ordinates also suggests a clear, unambiguous causal dependence of the E-index on diameter.

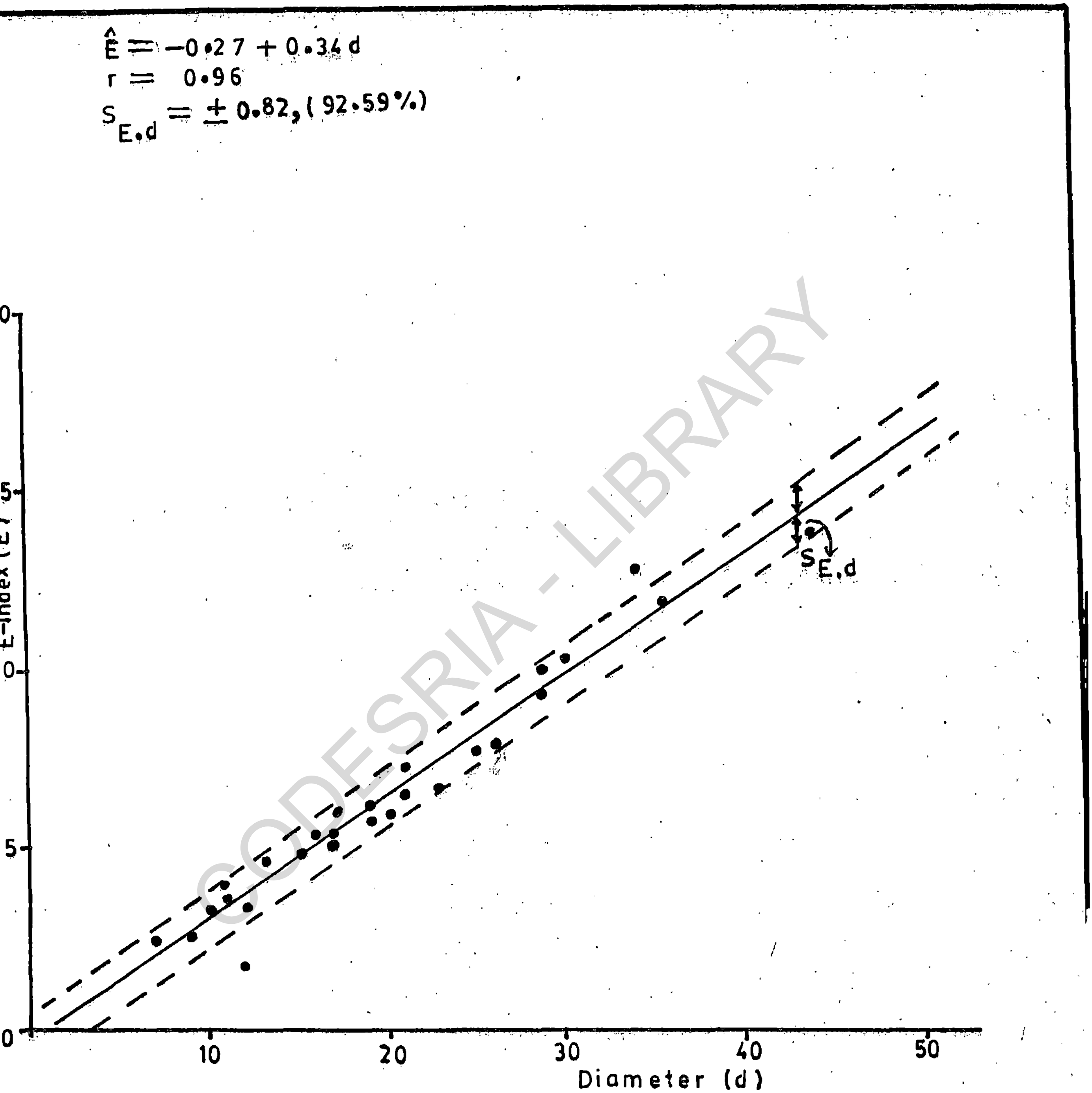

FIGURE 9: RELATIONSHIP BETWEEN THE E-INDEX AND NETWORK DIAMETER AMONG THE FOURTH-ORDER BASINS OF THE ABOINE.

Furthermore, since the E-index is at the core of our topological analysis, its distribution was analysed in order to reveal its degree of symmetry and peakiness. In ascertaining how symmetrical (or asymmetrical) the distribution was, we applied the momental skewness test (Ebdon, 1977) of the form:

$$S_k = \frac{\sum_{i=1}^{n} (x - \bar{x})^3}{n\delta^3} \qquad (14)$$

where δ is the standard deviation and $(x - \bar{x})^3$ is the cube of deviations from the mean for the 27 cases (n).

Equation (14) yielded a skewness of 0.67. The technique of skewness actually measures the extent to which the values are distributed about the mean. A symmetrical distribution has zero skewness. When more of the values are below the mean, the distribution is positively skewed (and vice versa). The distribution of the E-index in the Aboine basin is positively skewed, with 15 basins having their indices below the mean ($\bar{E}$ = 6.52). The E-index is relative, and is essentially useful for comparative analysis. Though more of the networks are relatively compact, yet the elongated ones, which are fewer in number, are 'weighty' enough to balance the distribution. In nature, the smaller the order of streams, the more the number and vice versa. The E-index positively correlated with the drainage area (r = 0.58), revealing relatively more compact (and, therefore, smaller) basins and fewer elongated (and, therefore, larger) basins.

The peakiness of the E-index distribution was also tested using the kurtosis test given by:

$$K_t = \frac{\sum_{i=1}^{n} (x - \bar{x})^4}{n \delta^4} \qquad (15)$$

> where $(x - \bar{x})^4$ is the deviation (from the mean) raised to the fourth power for the twenty-seven cases (n), and δ is the standard deviation.

With equation (15), a normal distribution yields a kurtosis of 3.00, a peaky distribution gives a value much greater than 3.00, while a very flat distribution yields a value much less than 3.00. In the 'kurtic' language, very peaky distributions are described as leptokurtic and on the other extreme, very flat ones are platykurtic, while those moderate distributions whose values do not significantly depart from 3.00 are described as mesokurtic. An application of equation (15) to the distribution of E-index in the

Aboine basin yielded a kurtosis of 2.7 which does not depart so much from 3.00. However, this value of kurtosis is indicative of a slightly flat distribution and can be attributed to chance variation in sampling.

The above topological analyses gave indications of network structure and, by implication, channelized fluvial processes. These topological analyses were complemented with volumetric and planimetric analyses of drainage basin geometry in order to validate inferences in relation to general basin fluvial process-form relationships.

CHAPTER 4

DRAINAGE BASIN PARAMETERS

The operation of river and hillslope processes forms a central theme in fluvial geomorphology. In the humid tropics, topographical modifications are prominently fluvial, to the near exclusion of other agencies. Owing to the geographical location of our study area, nivational and coastal denudational processes do not operate, while aeolian activities are virtually unimportant. Continental geomorphic processes in the humid tropics are accentuated by the lubricating action of water. This is in addition to the fundamental role played by water in the disintegration of the geological substructure into a veneer of regolith on which denudational processes operate.

It has been argued that fluvial activity is probably the most important single class of processes which shape the earth's surface (Mark, 1975). The processes are exogenetic and geomorphology concentrates on their mechanisms of operation and legacies in terms of forms. A good number of geomorphologists would prefer exploring the forms descriptively to the more rigorous exercise of analysing the causes of the forms. Analysis of causal relationships invariably involves a critical look at the underlying processes associated with the particular forms in question. The competence of geomorphologists to investigate surficial processes *per se* is not in doubt. Process-form analysis is basically at the core of geomorphic thought but the implications of some inherent ambiguities underscore the need for more careful and scientific analysis. This is because, though forms are responses to causative processes, recent trends of thought in relation to equifinality (Berry, 1983; Culling, 1987) and the polygeny of forms indicate that, in the absence of empirical verification, the use of forms to predict process *a priori*, could be misleading. Process-form analysis should therefore be carried out with much caution.

The analysis of landforms has led to the evolution of peculiar methodological concepts. Quite prominent, both as a concept and as a methodology, is geomorphometry, which is the science that treats the geometry of the landscape (Chorley *et al*, 1957). In other words, geomorphometry quantitatively attempts to describe the form of land surface (Mark,1975). Specific geomorphometry applies to specific surface features, while general geomorphometry applies to the land surface as a continuous rough surface (Evans, 1972, 1974, 1981; Javis, 1981). When geomorphometry is applied to a drainage basin as the fundamental geomorphic unit, the approach is technically termed drainage basin morphometry which, according to Gardiner (1981), primarily involves network delimitation, sampling, measurement, definition of variable and analysis. Strahler's (1952a) fourth-order basins formed the spatial framework for sampling within which various variables were assigned numerical values following some definite rules. In consonance with current morphometric procedure, the variables have been operationally defined and listed in Appendix A.

4.1 Basin Parameters:

The problem of proliferation of morphometric parameters was alluded to in Section 1.1. This proliferation mainly stems from the fact that a geomorphological problem is often causally linked with, and defined by numerous variables simultaneously. The contributions of these individual variables in the total or joint variance of the problem in question vary. Moreover, multicollinearity is characteristic of spatial data. Many of the variables correlate with each other, with the result that many parameters applied end up measuring basically the same element in different ways. Different analysts could work from different perspectives and use different parameters to perform essentially the same fundamental operation. They may have a common philosophical underpinning and yet trace different methodological loci due to the analyses of different combinations of variables. The existence of multiple variables implies an element of redundancy in some of the variables. Proliferation of parameters detracts from a parsimonious analysis. In addition, with too many parameters, the danger of subjectivity may increase in the process of identifying the diagnostic variables and discarding the redundant ones.

Attempts to cope with the multiplicity of variables through objective and scientific manipulation of data have led to the development of factorial analysis. Factor-analytical techniques are unparallelled in their data-reduction capability. Kim (1975) discussed the operational requirements for these techniques which are further given firm mathematical footing by the application of orthogonal (varimax, quartimax and equimax) and oblique rotations which ensure a rarefied transformation of the raw data matrix into some easily interpretable indices. These indices serve, inter alia, for exploratory and confirmatory (hypothesis-testing) purposes. Thus, an explanation is provided in relation to the structuring of the variables as well as their individual and joint contributions to the variance of the variable structure.

The multivariate techniques of factorial analyses have been widely applied to empirical morphometric investigations. The results arrived at have proved both encouraging and elucidating. While attempting a regionalization of landforms in Indiana, Lewis (1969) collapsed numerous variables to six principal components which accounted for 92.98% of the total variance in the morphometric variables. Mather and Doornkamp (1970) reduced 18 variables to six factors accounting for 94.93% of the variance among 130 third-order networks of the Katonga and Kagera basins in Southern Uganda. An analysis of 17 properties of 62 mono-lithologic third-order basins of the Oji, Ozom, and Obe rivers of South-eastern Nigeria gave rise to four source variables explaining 87.33% of the variance in data (Ebisemiju, 1979a). 52 of these basins were re-analysed with respect to 37 morphometric variables by principal component analysis, explaining 92.32% of variance in data (Ebisemiju, 1979b). An order-by-order PCA of 8 morphometric parameters has been utilized to highlight the effect of spatial scale changes on the interaction of morphometric properties of the basins of Udi-Awgu Cuesta underlain by sandstone formations (Ebisemiju, 1985b). In an investigation of the runoff response to basin parameters in ten selected basins of south-eastern Nigeria, principal component analysis was used to reduce fifteen basin parameters to four orthogonal components, explaining 92.50% of total variance (Phil-Eze, 1986).

Most of the above morphometric applications of factorial analysis were resolved at the third-order basin level. However, our present work goes beyond the conventional third-order level, and experiments with the fourth-order basins as the spatial basis for morphometric analysis.

Different network properties become more pronounced at different order levels. For instance, network allometry is characteristic of the lowest order segments particularly, the first-order streams. As the order increases, degradational activities may progressively give way to aggradational ones. This is because average gradient correlates inversely with basin order and so there is a gradual diminution of the energy available to the stream channel for abrasion. It has been recognized that headwater and channelway erosional activities equilibriate around the third-order level. This maximization of fluvial, hydraulic activities most probably accounts for the resolution of most drainage network analyses at the third-order level. But a corollary to this is equally true: that applied morphometric works should be resolved at higher-order basins, the morphological properties of which are spatial averages of those of the lower-order basins nested within them (Ebisemiju, 1985b). This is a major reason that necessitated our choice to resolve analysis at the fourth-order level. This choice also reflects the investigator's methodological preference with an exploratory philosophical undertone. The extent to which the scale of abstraction can be a factor in morphometric work was also explored.

A multivariate analysis was carried out with 15 variables for 27 fourth-order basins. The analysis of these lineal, areal and relief properties is in addition to the several variables utilized for the derivation of topological and hypsometric indices. For parsimony, only 15 purely quantifiable lineal, areal and relief variables were analysed to explain basin morphometry. The use of only 15 variables derives from a conscious attempt to minimize redundancy in the combination of these variables. Individual mathematical techniques were applied to purely topological network properties. Due to their peculiarity, relief properties were further analysed with the specialized techniques of area-height analyses.

In the twenty-seven basins, 405 detailed observations generated a massive form of data for the 15 variables which principal component analysis collapsed into four components, explaining 88.04% of the variance in data leaving out 11.96% to minor factors such as non-linearity and inherent operator variance. The results of principal component analysis are shown in Table 5, and the interpretation of the source variables for the components is embarked upon in Section 4.2.

4.2 Interpretation of the Components:

The pattern of loadings by the 15 variables on the four components is shown in the matrix of principal components of Table 5. Only four components were significant (since each of the four had eigenvalues that exceeded unity). But in order to achieve a simpler and theoretically more meaningful interpretation of the loading patterns, the four significant components were rotated to a terminal solution to yield Table 6. Since the 15 x 15 raw data

TABLE 5: Matrix of principal components derived for the Aboine fourth-order basins

Variables	Component 1	Component 2	Component 3	Component 4
1] N_1	.92225	.34198	.05640	-.08761
2] $\sum L_1$	.98292	-.02681	.13442	.01573
3] $\bar{A}_1$	.31173	-.81428	-.01351	.01228
4] R_{b2}	.33412	.15643	-.62859	.44290
5] $\sum N$	.91769	.34454	.08119	-.09948
6] $\sum L$	.97995	-.05464	.15257	.01962
7] $\bar{L}_s$	.48866	-.80555	.04775	.04818
8] A_d	.90834	-.28094	.19726	.01510
9] h	.38172	-.26930	.14053	.79151
10] D_d	-.19909	.88799	-.04022	.04277
11] R_e	-.11841	.28182	.83214	.08257
12] R_c	-.11524	.42086	.80806	.22655
13] d	.86830	.37527	-.16525	-.19459
14] E	.84144	.40945	-.15301	-.15974
15] HI	-.01586	.64202	-.35833	.38082
Eigenvalue	6.56667	3.49298	2.03191	1.11193
% of Variance	43.78	23.29	13.55	7.41
Cum. %	43.78	67.07	80.62	88.03

TABLE 6: Varimax-rotated principal components derived for the Aboine fourth-order basins

Variables	Component 1	Component 2	Component 3	Component 4
1] N_1	.98401	-.06236	.02406	.07482
2] $\sum L_1$	.91930	.29787	.02821	.22477
3] $\bar{A}_1$	.05233	.82967	-.20527	.16537
4] R_{b2}	.25074	-.27110	-.58041	.50413
5] $\sum N$	.98379	-.05847	.04825	.06129
6] $\sum L$	.90864	.32654	.04091	.23030
7] $\bar{L}_s$	.21787	.87416	-.15900	.23537
8] A_d	.77837	.52990	.04619	.23315
9] h	.14917	.25917	.10377	.87423
10] D_d	.06268	-.89055	.16052	-.09396
11] R_e	-.00152	-.11477	.88291	-.00053
12] R_c	.01571	-.27042	.89658	.12594
13] d	.95055	-.14112	-.18734	-.03733
14] E	.92984	-.18200	-.16337	-.01326
15] HI	.08815	-.73899	-.19078	.30917
Eigenvalue	6.13004	3.55515	2.12991	1.39029
% of Variance	40.87	23.70	14.20	9.27
Cum. %	40.87	64.57	78.77	88.04

matrix was normalized, each variable has a variance of unity and the whole data-array has a total variance of 15. In order to find the proportion of total variance accounted for by each component, the respective eigenvalues were calculated. Eigenvalue, denoted by λ is given by:

$$\lambda i = \sum_{j=1}^{15} aj2 \qquad (16)$$

where $\underline{\lambda i}$ is the eigenvalue of each component (in this case, four components) and $\underline{a}$ values are the loadings of $\underline{j}$ variables starting from 1 to 15 on the rotated matrix of principal components (Table 6).

The percentage of total variance accounted for by each component is then calculated using the formula:

$$P = 100\,\lambda i/N \qquad (17)$$

$$\text{ie } 100\,\lambda i/15$$

where $\underline{\lambda\, i}$ denotes the eigenvalue for the components and N is the number of variables (ie 15).

Equations (16) and (17) are fundamental to the interpretation of the four basic dimensions.

4.2.1 Component 1: Stream Network Size Variate:

With an eigenvalue of 6.13004, Component One accounts for 40.87% of the total variance in data. A critical examination of the loading pattern on the varimax-rotated matrix of principal components (Table 6) reveals that the significant loadings (exceeding ± 0.7) are predominantly indicative of the network size, hence this component is designated as Stream Network Size Variate. The significant loadings have been extracted and presented in Table 7.

TABLE 7: Significant loadings on Component 1

Variable	Identification	Loadings
N_1	Magnitude, Number of stream sources	0.98401
$\sum L_1$	Total length of first-order streams	0.91930
$\sum N$	Total number of stream segments	0.98379
$\sum L$	Total length of stream segments	0.90864
A_d	Drainage area	0.77837
d	Diameter	0.95055
E	E-index	0.92984

Eigenvalue (λ_1) = 6.13004

Variance accounted for = 40.87%

The highest loading on Component One is on N_1 which correlates very positively and highly with $\sum N$ ($r = 0.99$). Very pronounced erosion occurs virtually at all the Aboine stream sources and N_1 defines these sources. On the whole, fluvial activities take place along the segments defined by $\sum N$ for the various orders (u) in the basin. N was plotted against $\underline{u}$ (Figure 6) and the plot of mean segment length ($\bar{L}$) against basin order (Figure 10) and that of mean basin area against basin order (Figure 11), all obey the three laws of drainage composition stressing that there is no abnormality in the Aboine drainage evolution. The patterns of these plottings are in agreement with Knighton's (1984) results for the Bollin Dean network. That established fundamental morphometric laws are confirmed is an indication of the scientific undertone of our methodology.

The second highest loading on Component One is on the total number of stream segments ($\sum N = N_1 + N_2 + N_3 + N_4$). The $\sum N$ is a purely topological index which gives a numerical index of the degree of stream network linkages. More importantly, $\sum N$ defines the interaction among 1333 first-order streams, 354 second-order stream segments,

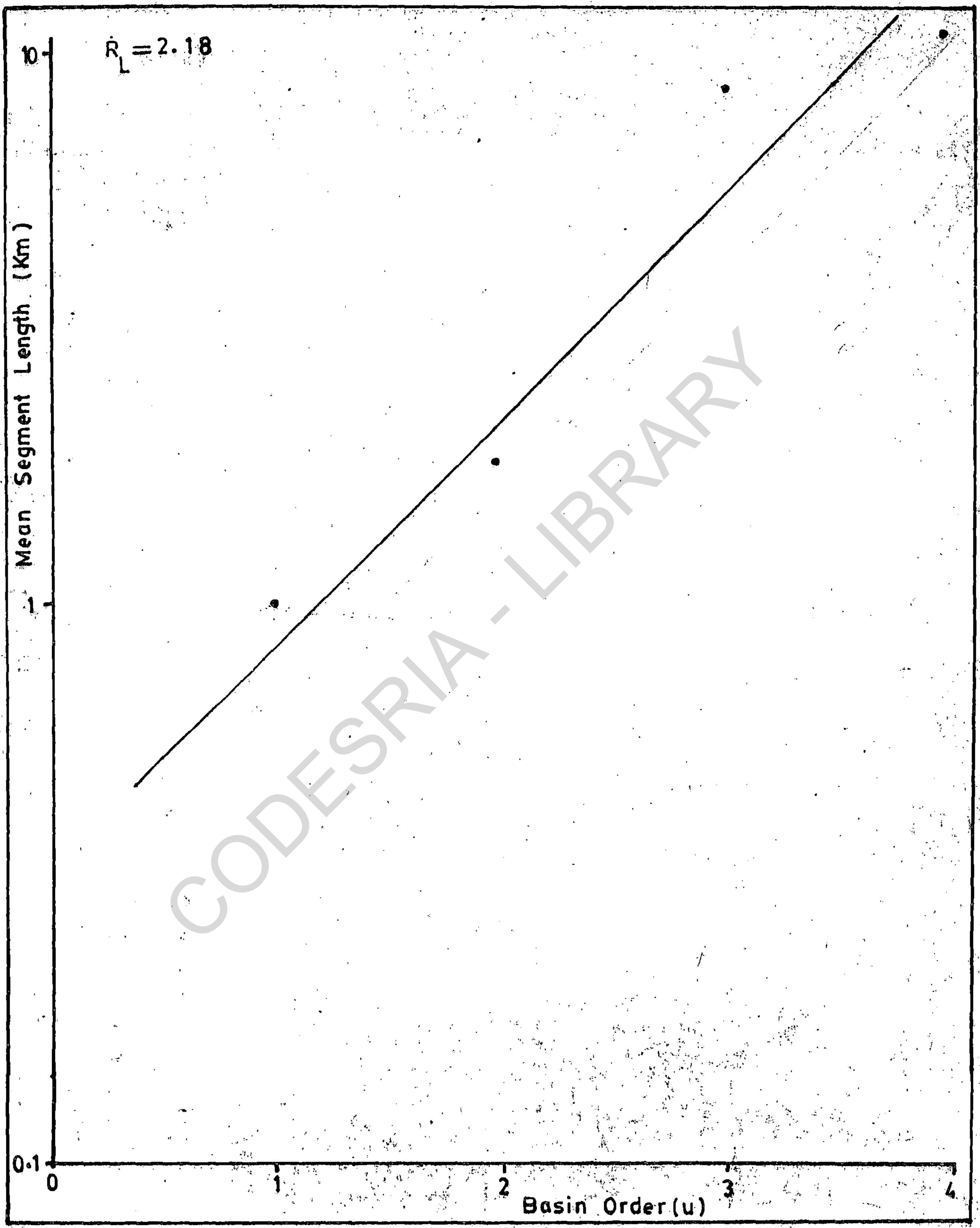

FIGURE 10: THE PLOTTING OF MEAN SEGMENT LENGTH AGAINST BASIN ORDER FOR THE ABOINE NETWORK.

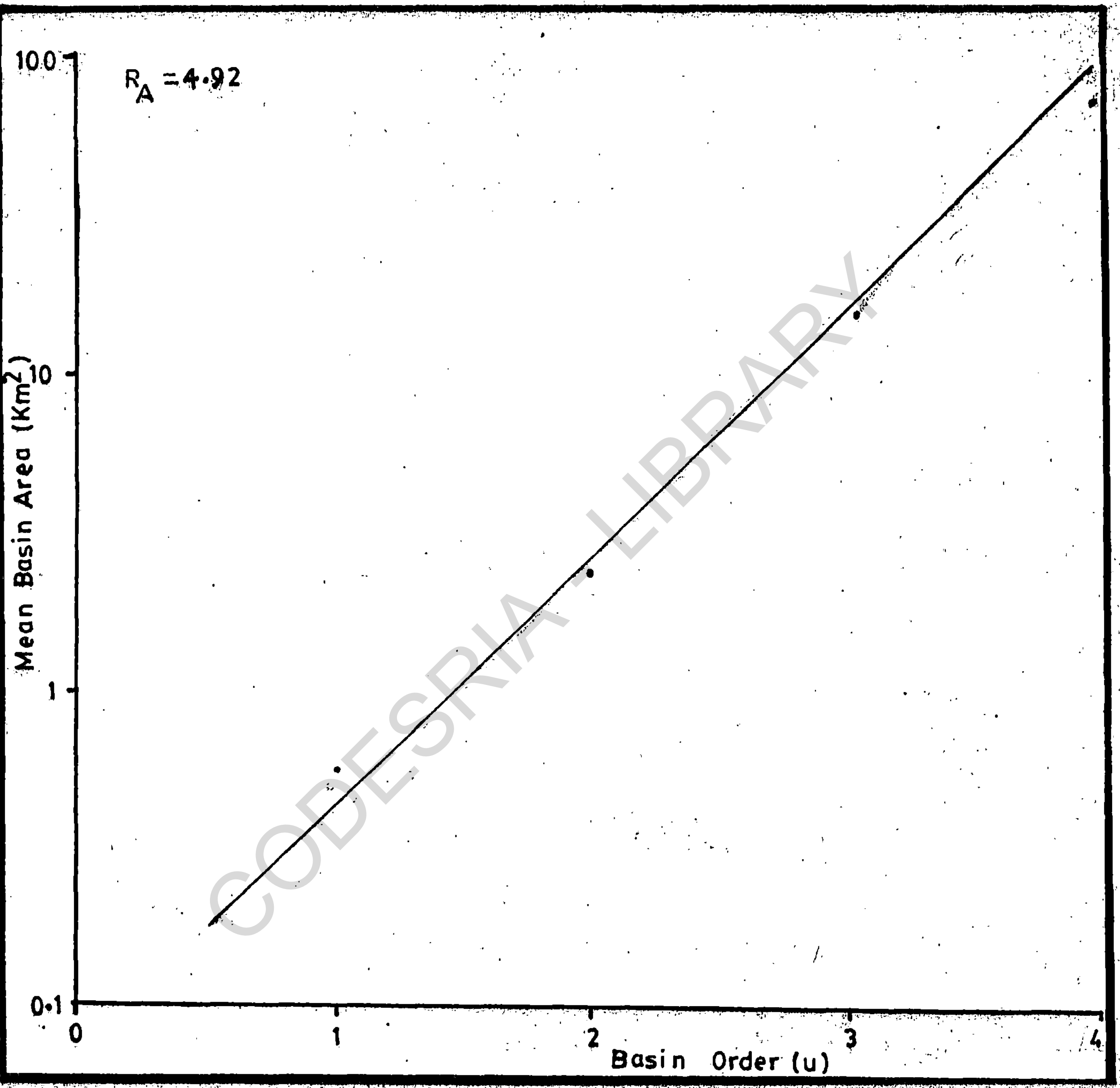

FIGURE 11: SOME ASPECTS OF DRAINAGE COMPOSITION IN THE ABOINE BASIN SHOWING THE PLOTTING OF MEAN BASIN AREA AGAINST BASIN ORDER.

82 third-order stream segments and 27 fourth-order stream segments (Table 2). Such an interaction subsumes a range of fluvial activities operating along both the channel-way and headwater zones of the basin. Table 4 shows that $\sum N$ correlates positively with 13 variables and negatively with only one.

Diameter (d) and E-index (E) are third and fourth respectively on the loading hierarchy of Component One. Notably, these are topological indices (together with N_1 and $\sum N$). Sections 3.3.2 and 3.3.4 have explored the import of network structure on channelized fluvial processes with particular reference to the diameter and E-index respectively. These two variables (d and E) correlate very strongly and positively with each other (r = 0.96). Each of them also correlates positively with 11 other variables and negatively with only 3 (Table 4).

$\sum L_1$ and $\sum L$ are fifth and sixth in terms of loading on Component One. These two variables which are positively correlated with each other (r = 0.504) also individually correlated positively with 10 variables. These indices of actual lengths complement the topological ones, hence revealing the lineal extent of channel processes.

The seventh significant loading of Component One is on drainage area. A_d correlates positively with 10 variables and negatively with four. This is in agreement with Ebisemiju's (1979b) finding in which A_d significantly correlated with 32 out of 36 variables. However, it is important to note that the relationship between A_d on the one hand and many other variables on the other, is frequently characterized by much ambiguity. For instance, empirical results have shown that the exact nature of the link between A_d and D_d has remained very controversial (Pethick, 1975; Ferguson, 1978; Gerrard, 1978). This is due to the unpredictable nature of A_d which has also been characterized as the devil's own variable (Anderson, 1957). In the present work, A_d was found to correlate negatively with D_d ($r = -0.46$). This negative correlation between drainage area and drainage density is an evidence of inverse causal relationship.

The first component of most previous morphometric principal factorings rarely loaded highest on A_d (Lewis, 1969; Mather and Doornkamp, 1970; Ebisemiju, 1979a, 1979b) and in this respect, the present work is in agreement with earlier works. The unique combination of variables that loaded significantly on this component is noteworthy. This combination could be attributed to the resolution of the present analysis at the fourth-order basin level. Most probably, this highlights the degree of accent and importance which the scale of analysis can give to some variables. The influence of some variables can be stifled and concealed by the smallness of the scale of abstraction and analysis.

4.2.2 Intensity of Dissection Variate:

This component has an eigenvalue of 3.55515 and accounts for 23.70% of total variance in data. Table 8 shows the significant loadings (exceeding ± 0.7) which weigh heavily on the total drainage density (D_d), mean stream length ($\bar{L}_s$), mean area of first-order basins ($\bar{A}_1$) and hypsometric integral (HI).

TABLE 8: Significant loadings on Component 2

Variable	Identification	Loading
D_d	Total drainage density	-0.89055
$\bar{L}_s$	Mean stream length	0.87416
$\bar{A}_1$	Mean area of 1st-order basins	0.82967
HI	Hypsometric integral	-0.73899
	Eigenvalue = 3.55515 Variance accounted for = 23.70%	

Component Two is termed the Intensity of Dissection Variate and weighs heaviest on D_d. The total drainage density (D_d) is the quotient of cumulative length and drainage area. It portrays the extent to which a given area is traversed by stream networks. The linear extent of network mainly delineates the operation of channelized fluvial activities. D_d therefore, defines the linear extent of fluvial erosion per unit area. D_d subsumes some other process-elucidating indices such as the constant of channel maintenance (C_{cm}) and length of overland flow (L_g). The constant of channel maintenance ($C_{cm} = D_d^{-1}$) defines the areal extent needed to sustain a unit length of channel while the length of overland flow ($L_g = \frac{1}{2}D_d$) shows the average length of flow path for runoff from the divide to the nearest channel.

Component Two is also highly and significantly loaded on $\bar{L}_s$ and $\bar{A}_1$. The $\bar{L}_s$is a summarizing index showing the average length of all the stream segments for all the various orders. The $\bar{L}_s$ also defines the average linear extent within which channelized fluvial erosive processes operate. $\bar{A}_1$ provides a spatial framework for the operation of the dissecting agents. Network allometry and related indices of lineal dissection are clearly evident on an areal setting primarily defined by $\bar{A}_1$.

From the implication of this combination of indices (D_d, $\bar{L}_s$, $\bar{A}_1$, and HI) on Component Two, it is logical to infer that the Aboine basin is actively being modified by the action of fluvial erosive processes. This inference is further corroborated by the results of our field work. It was observed that very active erosional activities variously expressed in terms of incision, valley-widening and headward erosion are experienced in the headwater zones of many of the basins under investigation. A classical case is the intensive topographic dissection and headward erosion occurring at the headwaters of Ekulu river. Near the Iva Valley Coal Mine, the Enugu-Onitsha Express-way has already been conspicuously scarred by this dissection.

4.2.3 Component 3: Shape Variate:

The third component has an eigenvalue of 2.12991 and accounts for 14.20% of total variance in data. It loads heavily (exceeding ±0.7) on circularity ratio and elongation ratio (Table 9). Sequel to the high loadings on these shape indicators, this component is termed the Shape Variate.

TABLE 9: Significant loadings on Component 3

Variable	Identification	Loading
R_c	Circularity ratio	0.89658
R_e	Elongation ratio	0.88291
	Eigenvalue = 2.12991	
	Variance accounted for = 14.20%	

The multiple correlation matrix (Table 4) shows that R_c correlates positively with 6 variabels and negatively with 8, while R_e correlates positively with only 4 and negatively with 10 variables. Strangely, however, these two variables correlate very positively and highly with each other (r = 0.75). The erratic behaviour of shape variables has greatly retarded the development of shape indices. Methodological evidence from current planimetric works supports Bunge's (1966) assertion that shape has proved to be one of the most elusive geometric properties to capture in an exact quantitative fashion (Boyce, 1964;

Lo, 1980; Moellering and Rayner, 1981, 1982; Austin, 1984). In the same vein, Griffith, O'neill, O'neill, Leifer and Mooney (1986) argued that the growing number of shape indices reflects the inability of any one measure to capture all elements of a given characteristic surface configuration. Furthermore, it is maintained that inconsistencies characterize most current shape measures, with the result that there is no one-to-one correspondence between the value of an index and the shape of the figure it represents. Necessary ideal properties of shape indices include independence of scale, independence of rotation of figure and independence of translation of figure. Also, another property of an ideal shape index is the regeneration of the original shape from the shape index. While recognizing the need to measure the shape (or the characteristic configuration) of an object, Griffith et al (1986 p. 269) noted that current shape indices are mere "red herrings", since they grossly lack the ideal properties mentioned above.

Component 3 loads highest on circularity ratio (R_C). The circularity ratio is a useful comparative index which numerically defines a basin shape by relating its area to that of a circle with same perimeter as the basin (Appendix A). Basin shape is a significant factor underlying the concentration of flood within a defined area as well as the lineal network structure that results. Obviously, both the lineal and areal operations of fluvial processes are, to a great extent, a function of basin shape which is, in turn, defined jointly by R_c and R_e on Component 3. The strong positive correlation between the circularity ratio and elongation ratio is a clear indication that both of them have a similar influence on the operation of fluvial processes within the basin.

A mean R_c value of 0.53 (with a standard deviation of 0.1) was calculated for the Aboine sub-basins. Conceptually and operationally, the nearer an R_c value is to unity, the more compact the basin. Similarly, a completely circular figure has an R_e value of unity and the value tends towards infinity with increasing linearity (Griffith et al, 1986). A mean R_e value of 0.62074 (with a standard deviation of 0.0877) was calculated for the fourth-order basins of the Aboine network. This value does not significantly depart from unity, indicating that the basins predominantly have bovine liver shapes, though not exactly circular, but notably compact. While deriving a shape index - the form factor ($F_f = A_d/L_b^2$), Horton (1941) observed that normally developed basins are pear-shaped. Drainage basins are pear-or bovine liver-shaped when the influence of structure is minimal. Basin shape is a good index of hydrological processes. For example, in a round or compact basin (as opposed to an elongated one), floods are stronger, more concentrated and have higher velocity and erosivity. As a consequence, drainage evolution is rapid in a more compact basin (Zavoianu, 1985). The statistical inference from Component 3, with the aid of the elongation parameter, is in consonance with the results of our topological analyses (Section 3.3.4). The topological E-index revealed relatively more compact fourth-order basins than elongated ones in the Aboine network, strongly suggesting the absence of structural control on the drainage pattern.

4.2.4 Component 4: The Relief Variate:

The only prominent and significant loading on this component is on local relief (0.87423). The difference in elevation between the highest point in the basin and the basin mouth defines the local relief (h) which is also closely related to other indices such as relief ratio (R_h) and ruggedness number (N_R). The R_h is the quotient of h and L_b (that is, the longest linear dimension of the basin = L_b; $h/L_b = R_h$), while N_R is the product of relief and drainage density (ie $N_R = h \times D_d$)

Component 4 has an eigenvalue of 1.39029 and accounts for 9.27% of the total variance in data after the effect of the previous three components had been isolated. This component highlights the link between surface geometry and basin solid geometry. Surface geometry is indicative of linear and areal planimetric characteristics while solid geometry has to do with the volumetric properties. The relief is also a reflection of the solid mass available for transformation by relentless denudational agents. The h makes use of basin length (L_b, a direct derivative of A_d) to show the extent of basin surface within which fluvial processes operate. Slope strongly influences the velocity of surficial fluids as well as the operation of sub-surface catenary processes and plastic mechanics. Pronounced relief gives accent to stream velocity, which in turn, gives more impetus to the kinetic energy of fluvial activities.

The susceptibility of topographic mass to abrasive activities has to do with the nature of the underlying geology as well as the type of climate with respect to the immensity of weathering and denudational processes. The Aboine basin is characterized by a thick mass of deeply weathered material on which fluvial processes act. In Chapter 5, hpsometric analysis will be used to further explore the relief variate so as to reveal the morphological implications of the available solid mass.

At this point, it is necessary to note that the contribution of each of the four components to the total variance was analysed with the help of the eigenvalues. For methodological coherence and logicality, it is proper to complement the exercise with an analysis of the contribution of each of the source variables in accounting for the common variance in data.

4.3 Common Variance

It is important to further examine each source variable to find out the proportion of common variance in each variable accounted for by the components. This fact can readily be extracted from the varimax-rotated terminal matrix of principal components (Table 6).

Varimax rotation was employed in this analysis not just because it is the most widely used method but because it simplifies the columns of a rotated matrix by maximizing the variance. This process of simplification is equivalent to maximizing the variance of the squared loadings in each component (or column). With the varimax-rotated principal component matrix, it is possible to calculate the percentage of common variance explained for each variable using the communality (h^2) index defined as

$$h_i2 = \sum_{j=1}^{4} aj^2 \qquad (18)$$

where h_i2 is the communality for the variable, a values are the loadings of the variable on components j ranging from 1 to 4 on the varimax-rotated principal component matrix.

The results of an application of equation (18) to the source variables yielded the information in Table 10.

TABLE 10: Extracted source variables and their proportions of common variance explained

Components	Identification	Source Variable	Communality	% of Variance
1	Stream network size Variate	N_1	0.97835	97.84
2	Intensity of Dissection Variate	D_d	0.83161	83.16
3	Shape Variate	R_c	0.89308	89.31
4	Relief Variate	h	0.86447	86.45

A further examination of the pattern of the percentage of explained common variance reveals the over-riding importance of stream network size variate, with N_1 having an h^2 of 0.97835. The interpretation is that the four components commonly accounted for 97.84% of the total variance in the number of first-order streams. The complement of the communality for N_1 (that is, $1 - h^2_{N_1} = 1 - 0.97835$) is 0.02165. This implies that only a negligible 2.17% of variance in N_1 is not accounted for by the four components. It is also important to note that N_1 has a factorial complexity of one. This was made clearer by the varimax rotation which maximized the loading of N_1 on one component which is Component One. As much as 96.83% out of 97.84% of the common variance in the number of first-order streams is accounted for by Component One alone, leaving the other components (that is Two, Three and Four) to share the remaining 1.01%.

The four components explained 83.16% of variance in the total drainage density, out of which 79.31% was accounted for by Component Two alone, as Components One, Three and Four share the remaining 3.85%. As much as 16.84% of variance in D_d was left unaccounted for by the four components. 89.31% of the variance in circularity ratio was accounted for by the four components leaving out 10.69% unexplained (in PCA, the proportion of variance not explained by the significant components is procedurally accounted for by the other components).

It should be observed that the proportion of common variance generally decreases from the diagnostic variable of the first component to that of the last one. This is evidenced by a general decrease in the communality values of the component-defining variables. This general empirical observation was not completely upheld or conformed with in the present investigation (Table 10). The communality of D_d of Component Two should have been greater than that of R_c of Component Three. However, this deviation is not too surprising as it could have emanated from the "devil's own variable" itself (since $D_d = \sum L/A_d$). In the same vein, A_d, which plays a notable role in the determination of D_d not only correlates negatively with it (r = -0.46, Table 4), but also has a factorial complexity exceeding unity, since it loads moderately high on more than one component in the varimax-rotated principal component matrix (Table 6). Also, operator variance in relation to the identification and exact delineation of stream channels could to some extent, account for the variance in the total drainage density.

The utility of the communality index is not limited to the diagnostic variables, for on the other extreme, it also reveals the variables with very low values of h^2 of which much of the variance is not accounted for by the significant components. Hypsometric integral and bifurcation ratio recorded very low communality values (0.68587 and 0.72738 respectively). The four components failed to explain as much as 31.41% and 27.26% of variance in HI and R_{b2} respectively. Explanation for the high proportion of unexplained variance in these cases derives from a combination of operator and unique variance which cannot be fully circumvented.

Operator variance stems from the fact that in any experimental investigation, the experimenter is part of the experiment. Inevitably, some variance may creep into the analysis either through the shortcomings of measuring parameters or through some variations that derive from the experimenter's subjective psychological disposition. Unique variance is a normal error term intrinsic to the issue under investigation which gives an idea of the degree of accuracy that could only be expected from the statistic applied. Drainage network analysts are aware of limitations introduced by the unique and operator variance. For instance, it has been maintained that:

> "the most difficult problem is to determine correctly the number of streams of first order, especially in large basins, for which the congruity of cartographic documents with the terrain must be ascertained".
> (Zavoianu, 1985, p. 48).

However, the contour crenulation technique applied in this work mitigated the influence of the above limitation, otherwise, the proportion of variance not accounted for by the four components could have been more than the values calculated.

The h^2 for hypsometric integral is notably low (0.68587). This is a clear indication that the morphometric analysis has not adequately taken care of the third dimension (or relief) of the basin morphology. This highlights the inadequacy of using essentially two-dimensional morphometric techniques to analyse three-dimensional solid geometry. This inadequacy will be remedied by recourse to hypsometric analysis (demonstrated in Chapter 5).

CHAPTER 5

HYPSOMETRIC ANALYSIS

The need to make up for the limitation of analysing a three-dimensional figure with two-dimensional techniques necessitated the choice of hypsometric analysis. The differential elevation of our study area is pronounced enough as to validate the operational and fundamental basis of such a technique. The morphometric analysis of Chapter 4 left much of the variance in some relief-related variables (particularly, HI) unexplained (Section 4.3) hence stressing the need for the use of a proper complementary technique of analysis to highlight the import of these variables. In order to satisfy the above need, this chapter concentrates on the application of some highly quantitative techniques to relief through hypsometric analysis. The application yielded relevant indices which further elucidated both basin solid and surface geometry.

5.1 The Concept of Hypsometry:

The idea of relief as differential elevation was further amplified to mean "the totality of landforms in a given drainage basin (Zavoianu, 1985, p. 22). Landform characteristics are viewed as a function of not only the evolutionary process but also of the interaction between external and internal factors. The genesis of the substructure is largely accounted for by tectonic activities that operated in the distant past. External processes relentlessly modify the landscape over time and consequently, landform assemblages at a particular time are evolutionary complexes. The cumulative imprints of surficial processes, to a great extent, determine the shape of landforms.

Relief is closely related to a drainage basin's potential energy which decreases gradually with erosion. At the drainage basin level, the cumulative effect of erosional agents gives an indication of the changes in drainage basin form over time. The rate of flow of matter and energy in the drainage basin can be inferred from a detailed morphometric analysis of the basin's surface geometry. Such a morphometric exercise, involving detailed mathematical analyses of basin configuration, is what Clarke (1966, p. 237) referred to as "hypsometry", defined as "the measurement of the interrelationship of area and altitude".

The technique of hypsometric analysis was popularized in drainage basin studies by the early works of Langbein

(1947) and Strahler (1952b). Later, the technique was elaborated, refined and empirically demonstrated by Coleman (1954), Clarke and Orrell (1958), Clarke (1966) and Eyles (1971). Hypsometric analysis gives rise to three main curves, which are: the area-height-, absolute hypsometric- and percentage hypsometric curves (Monkhouse and Wilkinson, 1971) and the application of this technique has been variously reviewed by Evans (1972), Mark (1975) and Zavoianu (1985).

Hypsometric analysis subsumes a group of techniques for highlighting the relationship between the vertical and areal attributes of the landscape. The results are conventionally presented graphically and the patterns of distribution of the attributes are statistically analysed. The shapes of the resulting curves are given geomorphological interpretation and can be further analysed using the mathematical technique of integration.

For a group of areas, the frequency of altitudinal distribution could be plotted against the corresponding areas to yield an altimetric frequency histogram. When altitudes are plotted against basin areas lying above the various altitudes, the result is a hypsometric curve. The plotting can be accomplished by using absolute altitude and areal values to produce an absolute hypsometric curve. But, more commonly, the exercise is carried out using relative values, in which case, cumulative relative height (h/H) is plotted against cumulative relative area (a/A).

The height of a given contour is defined by'h'; 'H' is the basin relief; 'a' is the areal extent of a given height and 'A' is the total basin area. When relative values are used, the result is called a percentage hypsometric curve. This method uses dimensionless values making it possible to compare the hypsometric curves of different drainage basins.

Finally, the third major type of curve that results from hypsometric analysis is the area-height curve. In this case, each chosen height is plotted against the percentage of the corresponding area.

The usefulness of hypsometric analysis derives from the fact that, in hydrological and erosion investigations, the shapes of the resulting curves can be an indication of the geomorphological evolution of the drainage basin (Langbein, 1947; Strahler, 1952b; Schumm, 1956). The evolution as seen at a particular time indicates the volume of solid materials already removed from the basin. it has been argued that the curves do not contain much information about certain relief features, such as slope discontinuities, platforms and scarps which are not at the same altitude throughout the basin area (Zavoianu, 1985). But, at the empirical level, hypsometric analysis is an objective method for the derivation of useful information on the solid geometry of the drainage basin, notwithstanding the extreme laboriousness and tedium involved. The procedure for this exercise, as well as the results and implications are demonstrated in Sections 5.2 and 5.3.

5.2 Empirical Demonstration:

The delimitation of sub-basins was consistently guided by contour patterns. There are various ways of accurately determining the planimetric areas on topographical maps and Gardiner (1981) noted that these methods range from the use of planimeter, dots and squares to the use of a digitizer aided by a computer.

While advancing the techniques of hypsometric analysis, Haan and Johnson (1966) developed the grid-square method. One variant of this method is based on the use of a net of points distributed uniformly and with a certain density on a tracing paper. The tracing paper (having the dots) is super-imposed on the outline of the area to be measured. Depending on the scale of the map, a conversion factor is applied to the resulting dot-density and from this application, the area is derived. In addition to the result comparing favourably with that obtained through the use of a planimeter, the grid-square method has an additional advantage of reducing computation time by four to ten times (Zavoianu, 1985).

In our present work, the grid-square method was used for areal calculations from the base maps and so the areal data used for the area-height analysis were calculated through this method. The topographical maps used in this work (Appendix E) had contours numbered in feet. It was found convenient to divide the relief of the study area into six classes using a vertical interval of 76.2m (that is, 250 feet). This is why a vertical interval of 76.2m was used to divide the basins into altitude classes and the geometrical figures that fell under these classes formed the outlines whose areas were to be measured. As already noted in Section 2.4, squared transparent overlays (1cm^2 equivalent to 0.25km^2 on the ground) were super-imposed on the various outlines. In each basin, these outlines represent the proportions of the basin that fall within the 76.2m height intervals specified in the first column of Tabble 11. The squares were then counted and those not completely enclosed by the outline were accordingly approximated. The scale of the map was applied to the value to derive the area of the figure. The detailed results of the area-height analysis for each of the 27 basins are presented in Appendix K. For a more meaningful morphological interpretation for the whole of the Aboine basin, these results had to be aggregated, and this aggregation led to the synthesis of Table 11.

The frequencies of the altitude classes in the 27 sub-basins, together with the corresponding total area for each of the classes are shown in Table 11. The data in the second and third columns were used to construct an altimetric frequency histogram shown in Figure 12. Also, altitude was plotted against basin area. In this case, the areal extent of each class interval was related to the total basin area to arrive at the percentage coverage. The midpoints of the various class intervals were finally plotted against their corresponding percentage areal coverages. The result of this exercise is graphically shown in Figure 13.

TABLE 11: Area-height analysis for the Aboine basin

Heights (in metres)	Frequencies out of 27 basins	Total area (km^2) in each class	% of total Drainage area
381.0 < 457.2	1	1.43	0.07
304.8 < 381.0	1	2.87	0.14
228.6 < 304.8	2	3.98	0.19
152.4 < 228.6	11	47.55	2.24
76.2 < 152.4	23	891.10	41.97
< 76.2	22	1176.20	55.40
		$A_d = 2123.13km^2$	100.01

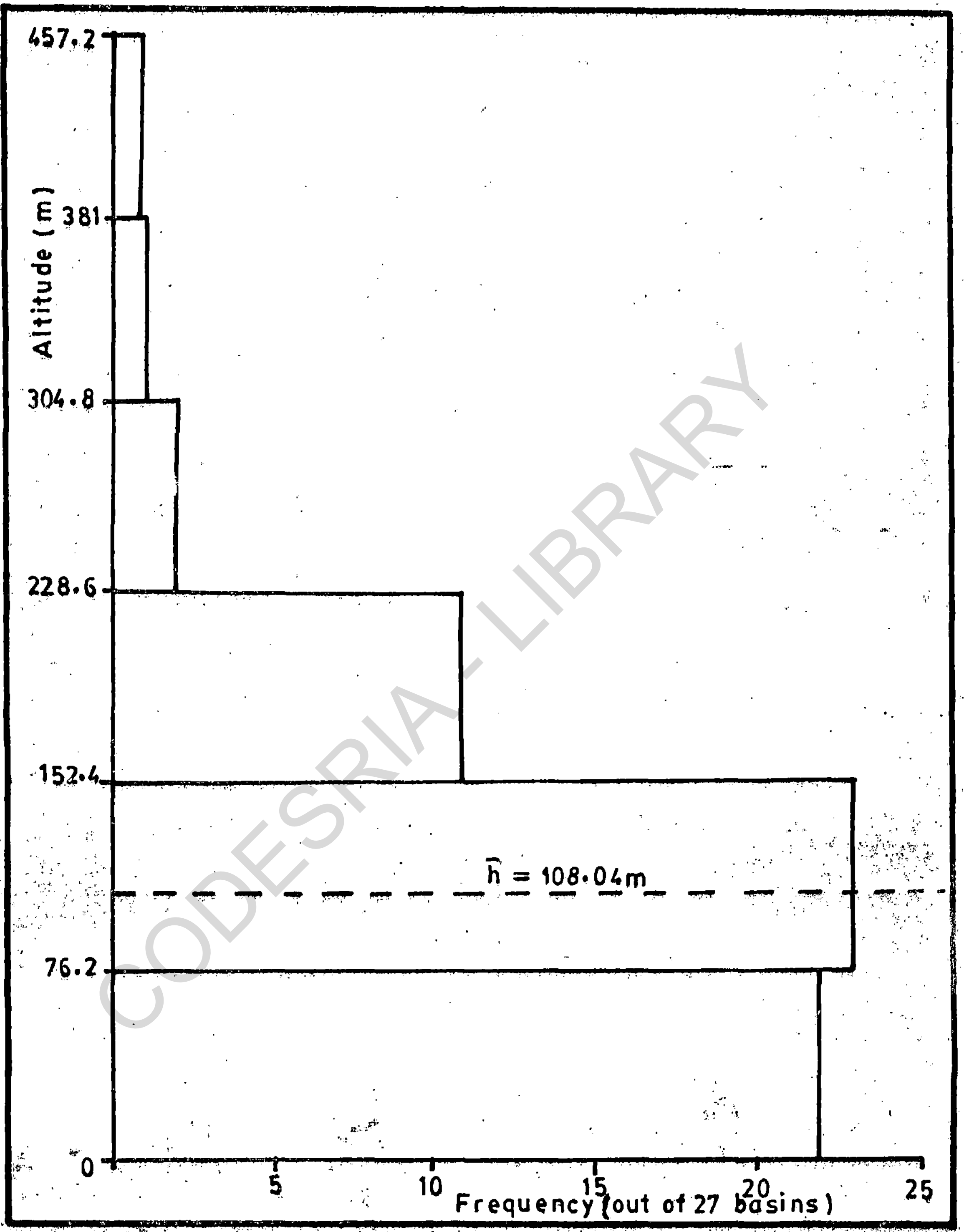

FIGURE 12: AN ALTIMETRIC FREQUENCY HISTOGRAM FOR THE ABOINE FOURTH-ORDER BASINS.

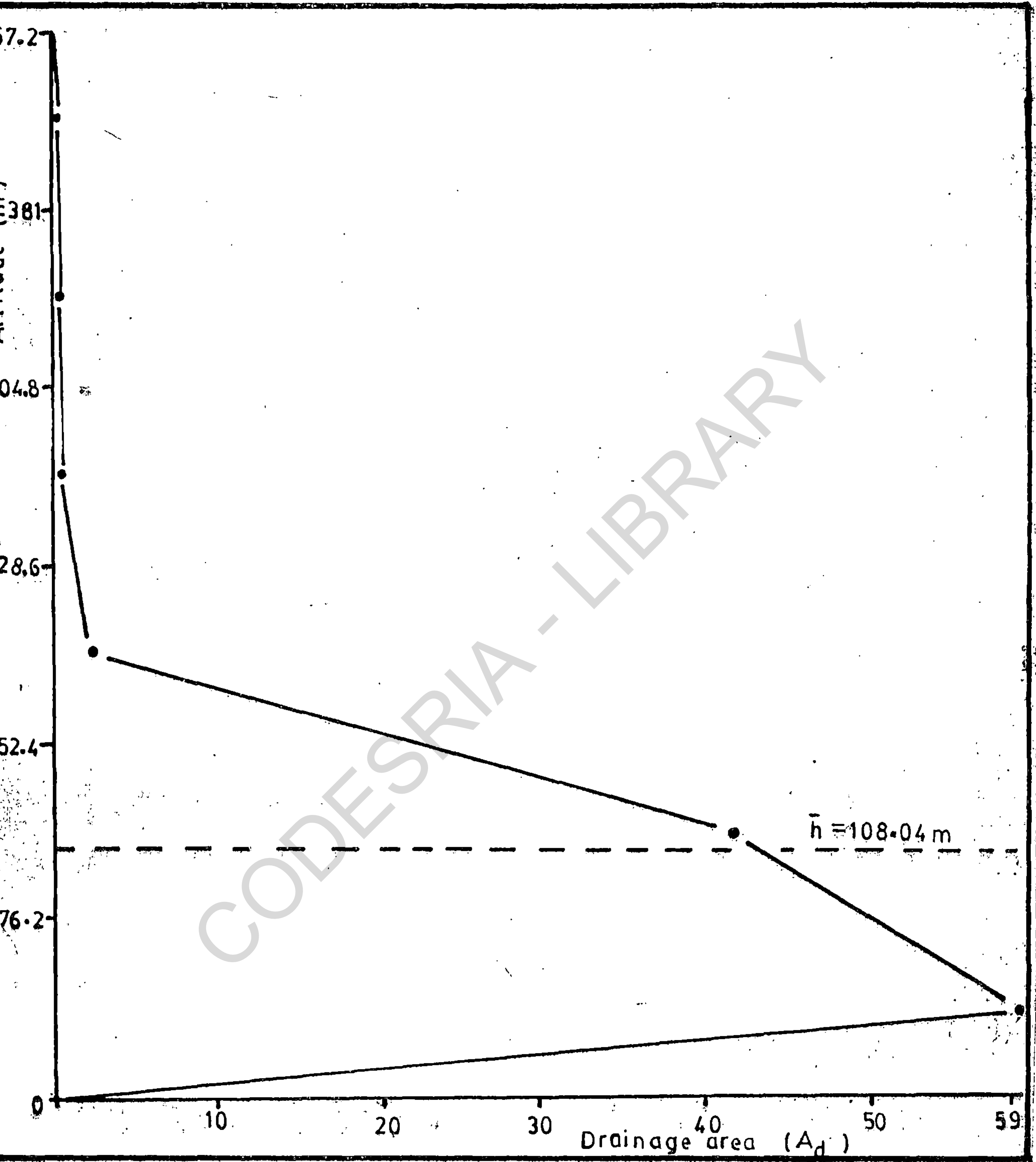

FIGURE 13: AN AREA-HEIGHT CURVE FOR THE ABOINE FOURTH-ORDER BASINS.

The six rows of columns three and four in Table 11 show the partial areas 'a_i'. The percentages (p), on the abscissa of Figure 13 were derived using the following equation:

$$P = 100\ a / \sum_{i=1}^{6} a_i \qquad (19)$$

where 'a' stands for each of the partial areas as defined by the altitude classes, while $\sum a_i$ is the total area of the basin.

In simple terms, Figure 13 is a direct plotting of the altitudinal increments against the partial areas. But from a geomorphological point of view, the most important curve that results from hypsometric analysis is the hypsometric curve, which is the plotting of cumulative basin altitude against cumulative basin area, either in absolute or in relative terms. In order to derive a hypsometric curve of absolute units, cumulative altitude values are plotted against their corresponding cumulative areal values. An absolute hypsometric curve is useful in the analysis of the solid geometry of one particular basin *per se*.

Absolute areal and altitude values are used to derive the absolute hypsometric curve. Such curves vary in shape, primarily due to variations in areas of different basins. Since the basins are not of equal sizes, a cursory look at the curve may not give a quick indication of the solid geometry of the basins. This limitation of the absolute hypsometric curve stresses the need for standardization. Such a standardization will provide an index of basin solid geometry irrespective of basin sizes and units of measurement. The standardization of areal and height values makes it possible for the resulting hypsometric curve to be easily compared with such curves derived for other basins. When areal and height values are in relative terms (that is standardized), the resulting relative or percentage hypsometric curves offer the basis for the comparisons of drainage basin solid geometry.

Irrespective of basin shapes and sizes, standardization makes the percentage hypsometric curve preferrable for comparability among several basins. As already noted in Section 5.1, the percentage hypsometric curve is arrived at by plotting the ratio of cumulative height to basin relief (h/H) against the ratio of cumulative area to total basin area (a/A). Conventionally, the plotting is accomplished in such a way that, on the ordinate, cumulative heights increase from 0.00 for the highest point in the basin to 1.00 for the local base level, while on the abscissa, cumulative areal values increase from nearly 0.00 embracing the least of the basin area to 1.00 embracing the whole basin area. This exercise was empirically demonstrated for the Aboine basin and the result is graphically presented in Figure 14.

5.3 Interpretation of Hypsometric Curve:

As a graphical representation of the solid geometry of the topography, hypsometric curve is a good index of available relief. The curve, as a reflection of the static relief, summarizes the erosional history of the landscape being depicted. Multiple possibilities of interpretation are offered by hypsometric analysis especially in relating the form of the hypsometric curve to the geomorphological evolution of the drainage basin (Strahler, 1952b; Schumm, 1956; Zavoianu 1985). The curve of the static topographical surface as derived at a particular time, is a function

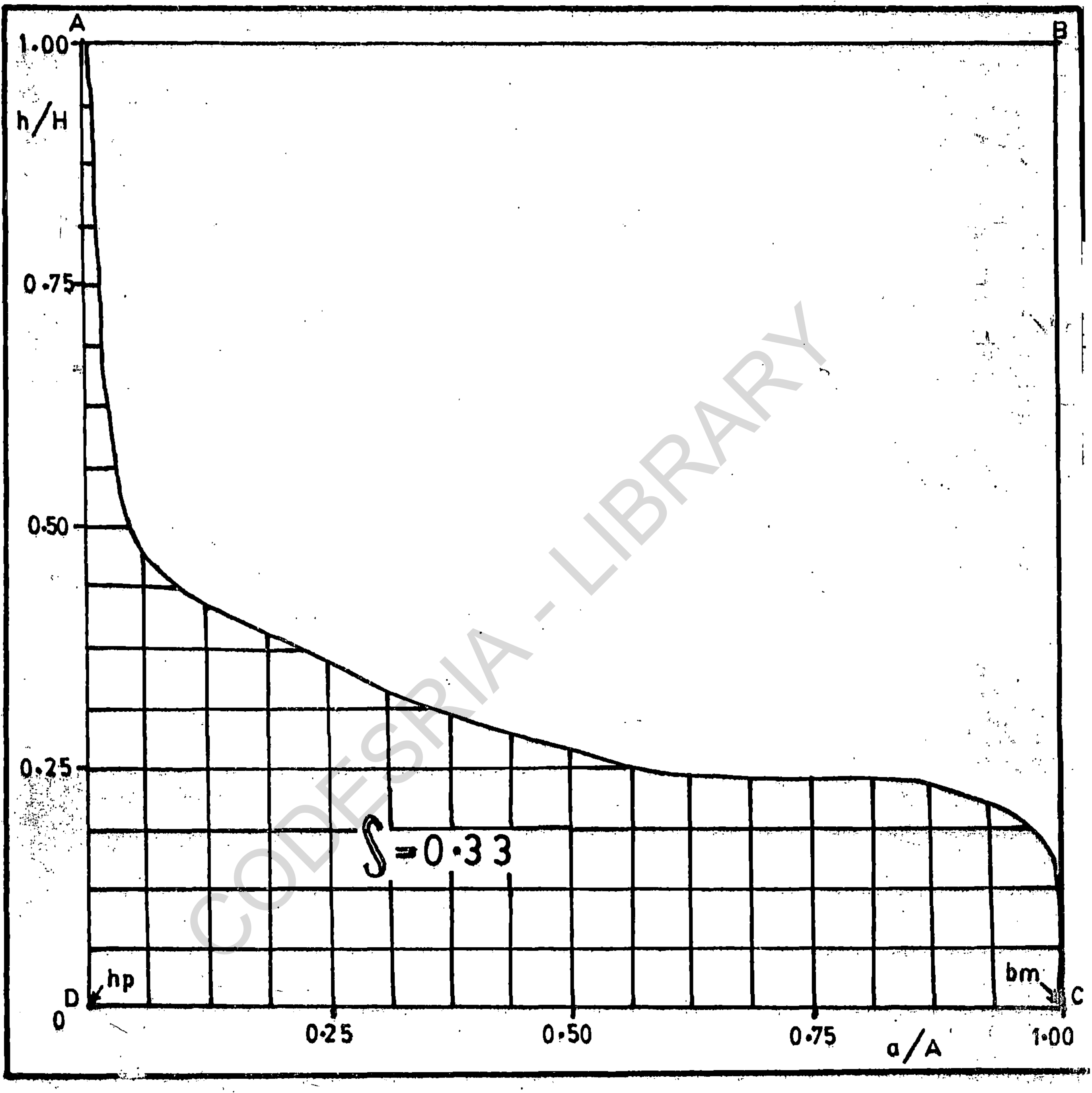

FIGURE 14: A PERCENTAGE HYPSOMETRIC CURVE OF DIMENSIONLESS VALUES FOR THE ABOINE FOURTH-ORDER BASINS.

of the dynamic geomorphological processes that relentlessly modify the landscape. In simple terms, what remains of the landscape is a reflection of how much of the topographic material that has been removed by the modifying agents. The hypsometric curve graphically defines the remnant landscape at a given time (that is, at the time of the aerial survey from which the topographical map used for the hypsometric analysis was made).

Qualitatively, in the classical Davisian terminologies, a convex hypsometric curve depicts youthfulness, with much solid material yet to be eroded by the dissecting rivers. Conversely, a concave curve implies senility, with comparatively less solid material liable to erosion. Midway between the two extremes, a curve which is neither convex nor concave simply shows maturity (Strahler, 1957). The curve for the Aboine basin (Figure 14) is concave showing that much of the topographic material has been removed by erosion, and this confirms the altimetric frequency distribution of Figure 12 which is positively skewed ($S_k = 0.20$) since it has relatively more values below the mean height ($\bar{h} = 108{\cdot}04$m).

In order to validate the inference, the qualitative interpretation of the hypsometric curve has to be buttressed with some quantitative facts. That is why hypsometric analysis has to be brought to its logical conclusion through the application of mathematical tool of integration. With the percentage hypsometric curve of dimensionless values, integration (whether mathematically or graphically executed) leads to the derivation of an index known as the Hypsometric Integral (HI). This index not only indicates the volume of topographic surface relative to that already removed by erosional agents but also serves as a useful measure for inter-basin comparison (Chorley and Morley, 1959; Eyles, 1971). This is a major reason why the percentage hypsometric curve of dimensionless values from which the HI is derived, is preferred to the hypsometric curve of absolute values. From the foregoing, the best single index quantitatively derived from the hypsometric analysis is the HI. Algebraically, the HI is expressed as:

$$\int_{hp}^{m} = A_C/A_R \qquad (20)$$

where the highest point (hp) in the

basin is the lower limit, and the basin mouth (bm) is the upper limit, A_C is the area under the hypsometric curve, while A_R is the total area of the rectangle defined by the maximum dimensions of the abscissa and the ordinate in Figure 14.

Thus, A_C gives an indication of the volume enclosed by the topographic surface (equivalent to the curve) and the horizontal plane passing through the basin mouth (equivalent to the abscissa). The ratio of A_C to A_R simply defines the HI, and the application of equation (20) to the Aboine basin (Figure 14) led to the derivation of $\int = 0.33$. Similarly, in Romania, Zavoianu (1985) arrived at $\int = 0.245$ for the Ialomita Basin, $\int = 0.56$ for the Staneasca basin, and $\int = 0.55$ for the Trepteanca basin. In another analysis, Clarke (1966) derived $\int = 0.43$ for the topography of Guernsey of Channel Islands and $\int = 0.44$ for Gozo in Malta.

The hypsometric integral shows the available solid mass, but the "complement" of the HI is equally important.

This complement shows the volume of material removed by erosion and is termed the Erosion Integral (EI). Clarke (1966) referred to the EI as the "inverse" of HI, but this designation is rather a misnomer. This is because, mathematically, the HI^{-1} (that is, the inverse of HI) does not define the ratio of the area above the hypsometric curve to the total area of the rectangle delimited by the dimensions of the ordinate and abscissa of Figure 14. The HI^{-1} _per se_ cannot give an indication of the volume of material removed by erosion and so should not be equated with the complement of HI. The sum of both the HI and its complement equates the total area circumscribed by the full dimensions of the rectangle in Figure 14. In erosion studies, the complement of the HI is of more practical relevance than its "inverse" which is a mere mathematical function. The initial volume of land mass is geometrically defined by the product of the coordinates, which is the rectangular figure. The difference between the original landmass and the volume, which is the area under the hypsometric curve corresponds to the erosion integral. In other words:

$$EI = (A_R - A_C)/A_R \qquad (21)$$

where EI is the Erosion Integral,

A_R and A_C are as defined in equation (20).

The erosion integral calculated for the Aboine basin is 0.67 (that is, 1-HI or 1-0.33). Both the HI and EI have wide geomorphological implications in terms of interpretation. In a geological work, Simpson (1954) adduced evidence to support a claim that after the Tertiary uplift which gave rise to the Okigwe-Abakaliki Anticlinorium, much of south-eastern Nigeria had been planated at least once before the current geomorphic cycle. Thus, the whole region, including our study area, was virtually level due to the post-Tertiary planation. This post-Tertiary surface approximates AB of Figure 14. This shows that among the fourth-order basins of the Aboine network, as much as 67.00% of the topographic mass has been removed by erosion as indicated by the EI which is 0.67. On the other hand, only 33.00% of the original solid mass is left as indicated by the HI which is 0.33. The above hypsometric indices are indicative of pronounced erosional activities in the Aboine basin.

The existence of relatively more numerous compact Aboine networks (and fewer elongated ones) identified in Section 3.3.4 was confirmed by both the shape variate of Section 4.2.3 and the hypsometric indices under consideration. In compact basins, floods travel more rapidly with greater capacities to erode and transport materials, with the result that the volume of topographic mass is greatly reduced in more compact basins. The severity of fluvial erosion observed during the field work also confirms the compact nature of most of the Aboine fourth-order basins and the low hypsometric integral quantitatively derived in this work.

The EI is a very useful palaeogeomorphological index in that it gives an indication of the rate at which denudational processes have operated over time. The usual qualitative and descriptive studies on planation surfaces can now be corroborated quantitatively through hypsometric analysis that culminates in the derivation of the erosion integral. The hypsometric indices (HI and EI) can serve as useful adjuncts to the reconstruction of palaeo-surfaces. These indices are not only useful in palaeogeomorphology and geochronology, but can also form the basis for temporal analysis involving relatively shorter time spans. For example, the hypsometric integral (say HI_{1965}) calculated in the present work reflects the topographic surface as at the early 1960s per se when most of the aerial coverages were carried out. If an aerial photo-coverage carried out in the 1990s gives rise to another series of topographical maps, then such map series can be used to derive another hypsometric integral (say HI_{1995}). The difference between the two HIs will directly reflect the extent of topographic transformation (whether lowering or accretion) over the intervening period (30 years in this hypothetical case).

Having complementarily utilized topological, morphometric and hypsometric analyses (Chapters 3, 4 and 5 respectively), the implications of the results are presented in Chapter 6 in order to bring the work to a completion.

CHAPTER 6

CONCLUSION

Before drawing a curtain over this work, it is pertinent to recapitulate the major issues that emerged and highlight both the theoretical and practical implications of these results.

6.1 Findings and Implications:

Characteristically, this work has a high theoretical resolution. Scientific knowledge is always conceived, engendered and nurtured purely at the theoretical level before being empirically demonstrated for practical application. The erection of valid theoretical constructs basic to applied work requires enormous intellectual effort and analysis. The success of environmental (applied) programmes aimed at an optimum, balanced use of our natural resources, to a great extent, depends on the dialectical articulation of pure, factual and functional information.

This investigation has yielded pure hydromorphological details which are fundamental to practical development of the hydrological and agricultural potentials of the

Aboine river basin. There is no doubt that our findings are valid for the enetire Aboine networks developed on the Cross River Plains and underlain by a virtually homogeneous geological sub-structure (shale). This is irrespective of the fact that some fourth-order networks of the Ikwo headwaters (Figure 3) were not studied. There is no compelling reason to suggest that the Ikwo network would radically depart from the general pattern of the entire Aboine sub-networks. Geological uniformity and super-imposed drainage pattern characterized the Aboine basin. A survey of over 95% of the Aboine fourth-order sub-basins upholds the unity concept making the conclusions valid for the whole basin.

Along the diameters, the preponderance of trans-links (55.11%) over cis-links (44.89%) is an indication that the Aboine dendritic network is free of structural control. The drainage pattern confirms the geological uniformity of the area as well as the geological superstructure of deeply weathered regolith. The regolith forms the topographic mass which the dissecting rivers traverse. Highlighting the relationship between these rivers and the material on which they flow was a major focus of our fluvial investigation. The strong causal influence of the area's humid tropical climate on the regolith was also noted, particularly with respect to the red-yellow ferralsols that characterize the area. Topographic details can be combined with the Köppen's A_f climatic type experienced in the area to derive fundamental data necessary for general land use planning and ecological conservation. The highly friable nature of the soils of the Shale underscores the susceptibility of most of the Aboine headwater zones to intense dissection. The knowledge of this lithological vulnerability to active erosion can be utilized to design programmes to stabilize the slope through aforestation and erection of concrete structures. Agricultural land use policies can also be designed to ensure that fluvial erosion along stream channels is not accelerated by the land use.

The E-index which was statistically found to be positively skewed (0.67) shows that majority of the basins are compact and only few are elongated. The fourth-order networks of the Aboine basin have links totalling 2,639 super-imposed over an area of 2,123km². Both the compact nature of most of the basins and the numerous links are of much hydromorphological significance. Floods concentrate more quickly in the compact basins (unlike in the elongated ones) and have greater potentials to erode. This is important especially in relation to agriculture and other activities capable of intensifying fluvial erosion. The areas's 1,600-2,500mm of mean annual rainfall (with the driest month having $\geq$29mm) favours both root crops and tree-crops. However, numerous links that traverse the area could be of great hydrological implications for irrigation especially with respect to the production of grain crops (such as rice) which need plenty of water and some species of beans.

Against the backdrop of process-form analysis, the work underscored the introduction of dynamism and trend to the static forms. It was established and demonstrated that the degree of operation of the causative processes can be reasonably inferred from the configuration of the forms, which was in turn, deduced through geomorphometry. The scientific analysis of geomorphometric properties revealed the surface morphology and gave an indication of the trend of topographical evolution under the action of the modifying processes. In the Aboine basin, it was empirically deduced that this evolution is degradational and the fluvial processes are actively lowering the basin surface. This basic knowledge about the inexorability of the processes as well as their susceptibility to accentuation by human interference is necessary in order to control landscape evolution. It is possible to exert this control by cautiously executing various land use activities which otherwise intensify the transforming processes. Hence, the methodological articulation of the theoretical knowledge of landscape dynamics provides a convenient basis for applied work. The demonstration of the relevance of the fundamental ideas is unique about the findings of our investigation.

This work methodologically and didactically demonstrated the application and refinement of multivariate statistical tools. With the aid of Principal Components Analysis, the chronic issue of proliferation of geomorphometric parameters was meaningfully and objectively addressed. Using the fourth-order basins as our spatial framework, the eigenvalues for four principal components accounted for 88.04% of the total variance among 15 morphometric variables. Operationally, drawing the work to a logical terminus, the communality index revealed that N_1, D_d, R_c and $\underline{h}$ are the diagnostic variables underlying the four components respectively. This exercise is a contribution towards the search for an objective method of eliminating redundant variables while isolating the diagnostic ones. This application represents an advancement of the efforts at grapling with the multiplicity of variables through the use of Multivariate techniques as already discussed in Sections 2.5 and 4.1.

Our morphometric work with the fourth-order basins (instead of the conventional third-order basins so far used in Nigeria) gave rise to interesting discoveries. The over-riding predominance of Stream Network Size Variate as the most important component accounting for the lineal characteristics of the morphometric variables is particularly noticeable. The component-defining variable - the number of first-order stream segments (N_1)

positively and significantly correlated with drainage area ($r = 0.75$). This observation strengthens our thesis that the scale of analysis is a factor in the determination of diagnostic variables. This is a challenging revelation in relation to the choice of basin order on which morphometric analysis is to be carried out.

Uniquely, this investigation is also an empirical demonstration of how morphometry could be complemented with hypsometry. The various mathematical computations necessitated by the area-height analysis yielded relevant graphs summarizing much of the basin solid geometry. The hypsometric curve of dimensionless values was used to algebraically derive a unique and ultimate index - the hypsometric integral, $\int = 0.33$. The implications are obviously wide. The resulting curve which is concave and buttressed by the low value of the integral shows that much fluvial erosion has taken place in the Aboine basin. The volume of topographic material available for lowering by the denudational agents is now virtually low.

This finding is corroborated by the result of erosion integral (EI = 0.67) which is a complementary index to the hypsometric integral. The observed incidence of erosional activities along the channel-way and in the headwater zones is capable of complicating and thereby, worsening the implications of the values of the EI and HI calculated in this work. This trend stresses the need for consciously stabilizing the slope. Land uses capable of accentuating erosional processes also need to be executed with caution. Hypsometric indices were calculated for the Aboine basin. The present work quantitatively derived the volume of topographic mass enclosed between the highest peaks and the network outlets of the fourth-order basins. Also, the volume of topographic mass removed by fluvial erosion since the post-Tertiary period was hypsometrically derived for the Aboine basin. The results of our pioneering effort not only provide a base for temporal work in the Aboine basin but also serve as indices for comparison with other basins. Sequel to the implications of the above findings is the disclosure of some research themes that should be pursued by future investigators.

6.2 Issues for Further Exploration:

In addition to advancing the research frontiers of the discipline, this work epistemologically opened up some challenging research vistas that could be very viable for further exploration.

The history of science reveals that paradigms experience a continuous refinement in the light of newly discovered facts. Four diagnostic variables were inductively found to significantly account for the variance in drainage basin morphometry. The four components left as much as 16.84% of variance in D_d unexplained. Though the devil's own variable might be contributory to this lapse, yet further enhancement of the techniques of identifying and delineating the first-order streams will definitely increase the accuracy of the cumulative stream length and thus the accuracy of the total drainage density. Further work can be carried out at an individual basin level in order to verify the exact basin delimitation and the accuracy of basin morphometric parameters such as the number and lengths of first-order streams. Such a purely field-based work will possibly reveal the source of errors and thereby explain why the four components accounted for a low percentage of variance in the total drainage density.

Methodologically, this work put forward a thesis founded on the premise that the scale of analysis is a factor in morphometric work. In other words, the basin order at which analysis is resolved can stifle or accentuate the contribution of source variables, and indirectly influence the combination of relevant variables. Most morphometric investigations in Nigeria have been resolved at the third-order basins. The Aboine network is of Strahler's eighth-order, and our analysis was only based on the fourth-order sub-basins, implying that future exploratory morphometric work can still be resolved at the other order levels. A wide horizon still exists for exploration and confirmation (or otherwise) of the influence of order-resolution on the isolation of diagnostic variables.

Currency in a virile discipline such as geomorphology is tested by the degree of enhancement of the epistemology as well as the analytical techniques. It is a sound principle that the landscape as it is could be studied with the processes that have operated over time in order to elucidate the ecological links among geomorphological phenomena. Much work can still be carried out in this direction especially to evaluate the contribution of anthropic factors in accelerating or modulating fluvial processes.

The empirical rigours of this work clearly betray a conspicuous lacuna. The genetic aspect of geomorphology which primarily extrapolates the trends of past and future landform developments has been stifled by methodological constraints and lack of basic information. Using the 1:50,000 topographical maps (of 1965), our hypsometric analysis yielded a hypsometric integral, $\int = 0.33$ which summarizes the static solid geometry of the Aboine drainage basin. This integral is a benchmark for genetic analysis. It is a stepping stone for both introspective and retrospective landform extrapolation.

Our hypsometric indices were derived from the 1965 maps. However, future analysts can use other more recent topographical maps (if they are available) to derive hypsometric indices that would reflect the cumulative effects of erosional processes that had acted in the Aboine basin since 1965. With the information on the volume of landmass eroded over a given period, it will be possible to predict the trend of landscape evolution over a particular time in the future, given the current processes at work.

This work appreciates that temporal topographical analysis will be given an impetus by the production of new medium- and large-scale topographical maps to be used in conjunction with the 1965 series. Then, with the input of the same amount of analytical rigours, Nigerian morphometric work carried out with large-scale topographical maps will enjoy the same status and recognition as those done in the United States of America and Britain.

6.3 Conclusion:

Scientific knowledge is always conceived, engendered and nurtured purely at the theoretical level before being empirically demonstrated for practical application. The present work was notably pre-occupied with the erection of valid theoretical constructs basic to applied work. It is when relevant concepts in fluvial geomorphology are well-articulated at the theoretical level that they can be translated into practical societal relevance. The present work attempted providing the theoretical foundation for the superstructure of applied geomorphology in the context of the drainage basin. Economic development programmes invariably involve a spatial transformation capable of accentuating fluvial processes.

The 2,639 links traversing 2,123km^2 could be of great hydromorphological implications for irrigation. Land use planning in the Aboine basin can greatly benefit from the resulting details about the inexorable processes as well as their susceptibility to accentuation by human interference. There is no substitute for a clear appreciation of the theoretical basis of drainage basin dynamics on the part of our river basin development authorities.

This work has demonstrated the application and refinement of multivariate statistical tools. In addition to advancing the research frontiers of fluvial geomorphology, the work epistemologically opened up some challenging research vistas that could be very viable for further exploration. The thesis founded on the premise that the scale of analysis is a factor in morphometric work, empirically deserves confirmation (or otherwise) by drainage basin analysts.

Basic topological, morphometric and hypsometric indices were derived from the Aboine basin. The didactic demonstration of the complementarity of these analytical techniques is in no way definitive, and so, no rigid and permanent status is implied. Our methodology is therefore open for further exploration, amplification and refinement with a view to enhancing the theoretical status of fluvial geomorphology.

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APPENDIX A: LIST OF VARIABLES

1 N_1 = Magnitude, number of stream sources.

2 $\sum_{i=1}^{n} L_1$ = Total length of first-order streams (Km).

3 $\bar{A}_1$ = $\sum_{i=1}^{n} A_1/N_1$ = Mean area of first-order basins (km^2).

4 R_{b2} = N_1/N_2 = Bifurcation ratio between the first- and second-order stream segments.

5 $\sum_{i=1}^{4} N$ = $N_1 + N_2 + N_3 + N_4$ = Total number of stream segments, from the first- to the fourth-order.

6 $\sum_{i=1}^{4} L$ = $L_1 + L_2 + L_3 + L_4$ = Total length of stream segments, from the first- to the fourth-order (Km).

7 $\bar{L}_s$ = $\sum_{i=1}^{4} L / \sum_{i=1}^{4} N$ = Mean stream length, from the first-order to the fourth-order (Km).

8 A_d = Drainage area, that is, at the fourth-order level (Km^2).

9 h = h.max-h.min. = Local relief (m).

10 D_d = $\sum_{i=1}^{4} L/A_d$ = Total drainage density at the fourth-order level (Km/Km^2).

11 R_e = $\frac{\text{Diameter of circle with same area as basin}}{\text{Basin length.}}$

= Elongation ratio.

12 R_c = $\frac{\text{Area of basin}}{\text{Area of circle with same perimeter as basin}}$

or $R_c = \frac{4\pi A_d}{P_b^2}$ = Circularity ratio.

13 d = Network diameter.

14 E = E-index.

15 HI = Hypsometric Integral.

APPENDIX B: AIR-PHOTO SOURCES FOR THE TOPOGRAPHICAL MAPS USED

[1] Shell B.P., Nov.-Dec., 1950.

[2] Aircraft Operating Company (Aerial Surveys) Ltd., March-April, 1959.

[3] Canadian Aero Service Ltd., Photogrammetric Engineers, Ottawa and Pathfinder Engineering Ltd., Vancouver, Dec., 1961.

[4] Fairey Air Surveys Ltd., April-May, 1962.

[5] Hunting Surveys Ltd., January and April, 1961; Dec., 1963.

APPENDIX C: ADMINISTRATIVE/THEMATIC MAPS USED

[1] Benue State of Nigeria (Administrative Divisions)
1:500,000 (including part of Kogi State).

[2] Administrative Map of Anambra State
1:250,000 (including Enugu State).

[3] Imo State, Administrative Map.
1:250,000 (including Abia State).

APPENDIX D: THE GEOLOGICAL MAPS USED (PUBLISHED IN 1957)

[1]	Nigeria	1:250,000 Geological Series, ENUGU Sheet 72.
[2]	Nigeria	1:250,000 Geological Series, OGOJA Sheet 73.
[3]	Nigeria	1:250,000 Geological Series, UMUAHIA Sheet 79.
[4]	Nigeria	1:250,000 Geological Series, OBAN HILLS Sheet 80.

APPENDIX E: 1:50,000 TOPOGRAPHICAL MAPS USED (PUBLISHED IN 1965)

[1] Nigeria 1:50,000, Sheet 288, Igumale SE, SW.

[2] Nigeria 1:50,000, Sheet 301, Udi SE.

[3] Nigeria 1:50,000, Sheet 302, Nkalagu NE, SE, SW, NW.

[4] Nigeria 1:50,000, Sheet 303, Abakaliki SW, NW.

[5] Nigeria 1:50,000, Sheet 313, Afikpo, NE, SE, SW, NW.

APPENDIX F: AIR-PHOTO SOURCES FOR THE GEOLOGICAL MAPS USED

[1] USAAF 1943.

[2] RAF 1949.

[3] Aircraft Operating Company of Africa, Johannesburg, 1950.

[4] Federal Survey Department 1952, 1953, 1954.

APPENDIX G: CALCULATION OF THE BASIN AREAS (A_1, A_2, A_3 and A_d or A_4) AND THE MEAN BASIN AREAS ($\bar{A}_u$) DRAINED BY THE VARIOUS BASIN ORDERS ($\bar{A}_u = \sum_{i=1}^{n} A_u/N_u$, where A_u is the total area drained by streams of a given order and N_u is the number of streams in that order)

Basins	A_1 (Km²)	$\bar{A}_1$ (Km²)	A_2 (Km²)	$\bar{A}_2$ (km²)	A_3 (Km²)	$\bar{A}_3$ (Km²)	A_4 (Km²)
1	42.25	1.28	47.25	5.25	79.25	39.63	85.75
2	46.50	0.74	58.00	3.41	97.75	24.44	105.50
3	34.50	0.60	47.50	3.39	65.88	21.96	80.63
4	48.25	0.75	50.50	2.81	39.25	13.08	109.00
5	19.00	0.41	30.75	2.20	11.75	3.92	47.75
6	84.50	0.56	114.25	3.17	161.75	20.22	227.50
7	18.25	0.42	29.00	2.64	24.00	12.00	34.00
8	14.00	0.24	18.00	1.29	20.75	5.19	30.00
9	9.50	0.22	11.50	0.96	12.25	4.08	16.75
10	25.00	0.31	37.75	1.64	35.00	7.00	58.50
11	7.00	0.29	9.75	1.22	10.75	5.38	20.25
12	16.75	0.48	24.25	2.69	25.75	8.58	52.00
13	9.00	0.50	16.00	3.20	17.75	8.88	26.75
14	50.75	0.46	64.75	2.49	46.00	7.67	104.25
15	11.50	0.68	54.50	10.90	36.00	18.00	85.00
16	22.50	0.83	25.50	4.25	34.00	17.00	40.00
17	33.50	0.93	38.00	4.22	21.75	7.25	66.00
18	17.00	1.06	18.50	3.08	15.25	7.63	23.00
19	14.00	0.56	22.25	4.45	27.50	13.75	28.00
20	35.25	0.90	77.75	7.78	107.50	53.75	113.75
21	61.50	0.92	94.50	4.97	84.75	21.19	133.00
22	57.50	1.13	53.25	4.10	95.75	31.92	121.50
23	113.00	1.07	133.75	4.95	248.75	62.19	299.25
24	69.00	1.50	93.75	6.25	116.25	58.13	123.25
25	13.75	0.40	12.75	1.82	34.75	17.38	38.25
26	10.50	0.44	15.00	1.67	21.75	10.88	39.00
27	6.25	0.35	6.50	0.93	11.00	5.50	14.50
$\sum_{i=1}^{27} A_u$	890.50		1205.25		1502.88		2123.13
	$\bar{A}_1 = 0.67$		$\bar{A}_2 = 3.41$		$\bar{A}_3 = 18.33$		$\bar{A}_4 = 78.63$

APPENDIX H: LOCATIONAL CHARACTERISTICS OF THE FOURTH-ORDER BASINS STUDIED

S/No	Basin Name	Basin Description, LGA and Towns	Topo-Sheets
1	Ashinu R. (I)	Okpowu LGA (Benue State), Isiuzo LGA, Eha Amufu (Enugu State)	Igumale S. E.
2	Ashinu R. (II)	N.E of Eha Amufu, Isiuzo LGA; North of Agila near Ibende, Igumale; Ador LGA of Benue State.	Igumale S. E.
3	Ugberi R.	Ishielu & Ohaukwu LGAs, Amananto, Okpotoagu	Nkalagu N. E.
4	Itumu R.	Ishielu, Ohaukwu & Ezza LGAs; Ohafia-Agba, Nkomofu	Nkalagu NE & SE
5	Aboine R. (I)	Onicha LGA (Abia State), Agbabor-Isu, Isu.	Nkalagu S. E.
6	Akaduru R	Ezza & Ohaukwu LGAs, Ogboji, Okposi, Amuda	Nkalagu NE&SE & Abakaliki NW&SW
7	Ikam R.	Ezza LGA; Umueze Nkwo, Aghara	Nkalagu SE & Abakaliki SW
8	Aboine R. (II)	Ezza LGA; Idembia	Nkalagu SE & Abakaliki SW
9	Aboine R. (III)	Onicha LGA; Ezza LGA; Enyibichiri	Nkalagu SE & Abakaliki SW
10	Aboine R. (IV)	Onicha LGA, Onicha Uburu Ezza LGA, Umudame	Nkalagu SE
11	Aboine R. (V)	Onicha LGA, Ezza LGA, Enyibichiri	Nkalagu SE & Abakaliki SW
12	Aboine R. (VI)	Ikwo LGA, Okputumo, Amodu, Ezekwe	Nkalagu SE & Abakaliki SW

S/ No	Basin Name	Basin Description, LGA and Towns	Topo-Sheets
13	Asu R. (I)	Ohozara LGA, Uburu, Asumgbom	Nkalagu SW & SE & Afikpo NW
14	Ata R.	Ohozara LGA; Okposi, Umuko, Obiozara	Nkalagu SE & Afikpo NE
15	Idimo R.	Afikpo LGA, Amiyima, Okporojo	Afikpo NE
16	Irohia R.	Ohafia LGA, Agbaja	Afikpo NW, NE & SE
17	Iyi Akwa R.	Ohafia LGA, Umunato Ama Ekpu	Afikpo NW, NE, SE & SW
18	Olum R.	Bende LGA, Okoko Item, Ameke, Amaeze	Afikpo NW & SW
19	Ide R.	Isuikwuato LGA (Abia State), Umuanya, Otampa	Afikpo SW & SE
20	Asu R. (II)	Awgu LGA, Mpu	Nkalagu SW & Afikpo NW
21	Ezia R.	Awgu LGA, Nenwentan, Awgu	Nkalagu SW & Udi SE
22	Asu R. (III)	Awgu LGA, Ohozara LGA, Oduma, Etu	Nkalagu SW
23	Asu R. (IV)	Nkanu LGA, Nara, Agbani	Nkalagu NW & SW
24	Asu R. (V)	Agbaraeze; Nkanu LGA, Ohozara LGA	Nkalagu SE, SW & NW
25	Ude R. (I)	Enugu N & Nkanu LGAs, Onuba, Ugboba-Ani	Igumale SW & Nkalagu NW
26	Ude R. (II)	Enugu N & Nkanu LGAs, Ndiaguowa, Owo	Igumale SW & Nkalagu NW
27	Ude R. (III)	Enugu N & Nkanu LGAs	Igumale SW

APPENDIX I: MORPHOMETRIC DATA GENERATED FROM THE ABOINE BASIN (AT THE SCALE OF 1:50,000, VARIABLES ARE AS LISTED IN APPENDIX A)

VARIABLES														
N_1	$\sum L_1$	$\bar{A}_1$	R_{b2}	$\sum N$	$\sum L$	$\bar{L}_s$	A_d	h	D_d	R_e	R_c	d	E	HI
33.00	55.50	1.28	3.67	45.00	94.75	2.11	85.75	68.58	1.11	0.50	0.40	21.00	6.58	0.203
62.00	71.50	0.74	3.65	84.00	135.50	1.61	105,50	68.58	1.28	0.77	0.56	21.00	7.31	0.172
58.00	57.25	0.60	4.14	76.00	119.25	1.57	80.63	106.68	1.48	0.56	0.49	28.00	10.18	0.398
64.00	86.50	0.75	3.56	86.00	161.50	1.88	109.00	106.68	1.48	0.56	0.51	28.00	9.45	0.500
46.00	39.70	0.41	3.29	64.00	74.50	1.16	47.75	64.01	1.56	0.82	0.70	17.00	6.12	0.344
150.00	149.75	0.56	4.17	195.00	293.25	1.50	227.50	106.68	1.29	0.58	0.45	44.00	13.38	0.422
43.00	32.90	0.42	3.91	57.00	65.30	1.15	34.00	85.34	1.92	0.56	0.42	25.00	7.84	0.433
58.00	36.00	0.24	4.14	77.00	64.75	0.85	30.00	70.10	2.16	0.61	0.65	23.00	6.87	0.500
44.00	26.40	0.22	3.67	60.00	42.35	0.71	16.75	54.86	2.53	0.75	0.80	20.00	5.99	0.500
82.00	64.50	0.31	3.57	111.00	117.00	1.05	58.50	83.82	2.00	0.65	0.54	32.00	12.97	0.438
24.00	17.90	0.29	3.00	35.00	36.15	1.03	20.25	54.86	1.79	0.56	0.51	11.00	4.00	0.500
35.00	32.70	0.48	3.89	48.00	70.10	1.46	52.00	54.86	1.35	0.77	0.57	13.00	4.55	0.500
18.00	19.30	0.50	3.60	26.00	38.35	1.48	26.75	54.86	1.43	0.61	0.38	10.00	3.34	0.172
110.00	97.00	0.46	4.23	143.00	181.50	1.27	104.25	79.25	1.74	0.59	0.49	36.00	12.05	0.360
17.00	15.00	0.68	3.40	25.00	49.30	1.97	85.00	67.06	0.58	0.69	0.51	9.00	2.84	0.188
27.00	29.20	0.83	4.50	36.00	52.35	1.45	40.00	160.02	1.31	0.47	0.34	17.00	5.37	0.422
36.00	49.30	0.93	4.00	49.00	91.25	1.86	66.00	160.02	1.38	0.64	0.51	15.00	4.54	0.391
16.00	14.40	1.06	2.67	25.00	28.00	1.12	23.00	160.63	1.22	0.64	0.55	7.00	2.48	0.438

APPENDIX I (Cont/d.)

Basins	VARIABLES														
	N_1	$\sum L_1$	$\bar{A}_1$	R_{b2}	$\sum N$	$\sum L$	$\bar{L}_s$	A_d	h	D_d	R_e	R_c	d	E	HI
19	25.00	22.60	0.56	5.00	33.00	40.00	1.21	28.00	163.68	1.43	0.56	0.47	12.00	3.45	0.563
20	39.00	58.75	0.90	3.90	52.00	117.20	2.25	113.75	109.73	1.03	0.52	0.46	19.00	5.74	0.125
21	67.00	100.50	0.92	3.53	91.00	187.20	2.06	133.00	312.42	1.41	0.70	0.67	19.00	6.89	0.223
22	51.00	74.45	1.13	3.92	68.00	138.05	2.03	121.50	109.73	1.14	0.56	0.53	26.00	7.51	0.180
23	106.00	153.35	1.07	3.93	138.00	316.55	2.29	299.25	256.34	1.06	0.67	0.61	30.00	10.53	0.281
24	46.00	64.60	1.50	3.07	64.00	123.60	1.93	123.25	36.58	1.00	0.56	0.45	17.00	5.00	0.203
25	34.00	31.70	0.40	4.86	44.00	59.30	1.35	38.25	140.21	1.55	0.55	0.51	16.00	5.87	0.289
26	24.00	24.25	0.44	2.67	36.00	50.75	1.41	39.00	124.97	1.30	0.67	0.67	12.00	1.61	0.133
27	18.00	15.40	0.35	2.57	28.00	25.70	0.92	14.50	56.39	1.77	0.64	0.62	11.00	3.65	0.125
$\bar{x}$	49.37	53.35	0.67	3.72	66.52	102.72	1.51	78.63	108.04	1.46	0.62	0.53	19.96	6.52	0.333
s	31.93	39.91	0.34	0.60	40.89	74.63	0.45	65.70	63.72	0.40	0.09	0.11	8.93	3.17	0.142

APPENDIX J: THE S.P.S.S. COMPUTER PROGRAMME USED FOR PRINCIPAL COMPONENT ANALYSIS

```
JOB                 LASER ENG, PH, 06 APRIL 1994

FILE NAME           UME LIS'

RUN NAME            FACTOR ANALYSIS

VARIABLE LIST       XN1, XL1, XMA1, RB2,

                    SUMN, SUML, XML, AD,

                    REL, DD, RE, RC, DI, EX, HI.

INPUT FORMAT        FREE FORMAT

INPUT MEDIUM        MAGNETIC TAPE

N OF CASES          27

FACTOR              VARIABLES = XN1 TO HI/
                    TYPE = PA1/
                    ROTATE = VARIMAX/

STATISTICS          ALL

READ INPUT DATA

FINISH
```

APPENDIX K: AREA-HEIGHT ANALYSIS FOR THE 27 SUB-BASINS OF THE ABOINE NETWORK

Heights/Basins	1	2	3	4	5	6
< 76.2m	-	-	17.00	46.00	35.50	150.50
76.2 < 152.4m	84.50	104.50	63.50	63.00	12.25	77.00
152.4 < 228.6m	1.25	1.00	0.13	-	-	-
228.6 < 304.8m	-	-	-	-	-	-
304.8 < 381m	-	-	-	-	-	-
381 < 457.2m	-	-	-	-	-	-
Total (Km²)	85.75	105.50	80.63	109.00	47.75	227.50

APPENDIX K continued

Heights/Basins	7	8	9	10	11	12
< 76.2m	27.00	30.00	16.75	46.75	20.25	52.00
76.2 < 152.4m	7.00	-	-	11.75	-	-
152.4 < 228.6m	-	-	-	-	-	-
228.6 < 304.8m	-	-	-	-	-	-
304.8 < 381m	-	-	-	-	-	-
381 < 457.2m	-	-	-	-	-	-
Total (Km²)	34.00	30.00	16.75	58.50	20.25	52.00

APPENDIX K continued

Heights/Basins	13	14	15	16	17	18
< 76.2m	26.25	88.75	84.75	12.75	22.25	6.75
76.2 < 152.4m	0.50	15.50	0.25	21.75	38.00	13.25
152.4 < 228.6m	-	-	-	5.50	5.75	3.00
228.6 < 304.8m	-	-	-	-	-	-
304.8 < 381m	-	-	-	-	-	-
381 < 457.2m	-	-	-	-	-	-
Total (Km²)	26.75	104.25	85.00	40.00	66.00	23.00

APPENDIX K continued

Heights/Basins	19	20	21	22	23	24
< 76.2m	0.75	105.00	40.70	110.50	120.25	115.75
76.2 < 152.4m	20.50	8.75	75.10	11.00	170.00	7.50
152.4 < 228.6m	6.75	-	9.17	-	8.75	-
228.6 < 304.8m	-	-	3.73	-	0.25	-
304.8 < 381m	-	-	2.87	-	-	-
381 < 457.2m	-	-	1.43	-	-	-
Total (Km²)	28.00	113.75	133.00	121.50	229.25	123.25

APPENDIX K continued

Heights/Basins	25	26	27
< 76.2m	-	-	-
76.2 < 152.4m	33.25	37.75	14.50
152.4 < 228.6m	5.00	1.25	-
228.6 < 304.8m	-	-	-
304.8 < 381m	-	-	-
381 < 457.2m	-	-	-
Total (Km²)	38.25	39.00	14.50