GOVERNMENT OF CANADA
DEPARTMENT OF ENERGY
MINES AND RESOURCES

BRITISH COLUMBIA HYDROMETRIC NETWORK STUDY

VOLUME I OF II

APRIL 1969

T. Ingledow & Associates Limited
Consulting Engineers

T. Ingledow & Associates Limited · Consulting Engineers
1112 West Pender Street, Vancouver 1, Canada · Phone 683-2411 · Cable: Ticonsult

April 30, 1969

Mr. G. H. Caldwell
Chief, Water Survey of Canada
Inland Waters Branch
Department of Energy, Mines and Resources
588 Booth Street
Ottawa, Ontario

Dear Sir:

British Columbia Hydrometric Network Study

We have pleasure in submitting herewith our report entitled "British Columbia Hydrometric Network Study" Volumes I and II, dated April 1969, in accordance with the agreement between the Minister of Energy, Mines and Resources and T. Ingledow & Associates Limited, dated October 30, 1968 as amended March 31, 1969.

We consider that this Report provides a sound plan for the early implementation of a regional hydrometric network in British Columbia, and stresses the need for future studies to ensure logical and orderly development of the network. We will be pleased to participate in such development.

Yours very truly,

R. J. Balfour
President

GOVERNMENT OF CANADA
DEPARTMENT OF ENERGY
MINES AND RESOURCES

BRITISH COLUMBIA
HYDROMETRIC NETWORK STUDY

VOLUME I OF II

April, 1969

T. Ingledow & Associates Limited
Consulting Engineers

CONTENTS

PREFACE

TERMINOLOGY

The following definitions are presented to clarify and explain the meaning of some important terms as they are used in the context of this report.

Hydrologic Cycle

The hydrologic cycle can be defined, in simple terms, as the continuous circulation of water from the earth's surface through the atmosphere and back to the land or to the oceans, directly or by surface or underground channels. The processes of the cycle include evaporation, precipitation, transpiration, infiltration, storage and runoff.

Hydrology

Hydrology in the broadest sense, is the science that is concerned with all the various phases of the hydrologic cycle, including a consideration of water quality, its chemical and physical properties and sediment load. In this report, the term hydrology is used in a more restricted sense to describe the occurrence, circulation and distribution of water with no concern for its quality or properties.

Meteorology

Meteorology is the science that is concerned with the atmospheric phase of the hydrologic cycle. More generally, in relation to hydrology, it is concerned with the states and the physical and dynamic processes of that part of the atmosphere within which water plays an important role.

Hydrometeorology

Hydrometeorology, as practiced in Canada, is a branch of meteorology that is concerned with the application of meteorology to hydrological problems. It is concerned with certain aspects of both the atmospheric and land phases of the hydrologic cycle with emphasis being placed on atmospheric processes and their inter-relationships with surface water phenomena.

Hydrometry

Hydrometry is the science of the measurement of water and is concerned not only with the quantity and movement of water but also with its quality and temperature, characteristics of ice on rivers and lakes, and sediment load. In this report the term hydrometric is restricted to mean the measurement of streamflow and water level of fresh water rivers and lakes.

Climatology

Climatology is the science that is concerned with the long-term manifestations of weather, that is, with the average and extreme variations of the atmosphere and its various meteorological elements. Climate is thus determined by meteorological processes.

Main Stream

A main stream is one which drains a catchment area of greater than about 400 square miles in mountainous regions and greater than about 1,000 square miles in relatively flat regions.

Major Stream

A major stream is one which has one or more main streams as tributaries.

Small Stream

A small stream is one which drains an area of less than 400 square miles.

Representative Basin

A representative basin is defined as a basin which has been selected for systematic sampling of small streams within a hydrologic zone and which, as far as possible, is typical of basins in the zone.

Bench-Mark Station

A bench-mark station is a permanent stream gauging station which is operated for an indefinite time period on a small basin which has not been affected by the works of man, to document natural hydrologic changes with time.

Long-Term Station

A long-term station is a stream gauging station which is operated continuously for a long period of time but not necessarily indefinitely. A period of about 50 years has been suggested as a possible duration.

Short-Term Station

A short-term station is a stream gauging station which is operated over a limited period of a few years until a suitable correlation is established with a long-term station.

Natural Regime Stream

A natural regime stream is one on which flows can be measured under natural conditions, undisturbed by the works of man.

Modified Regime Stream

A modified regime stream is one on which the natural flows have been modified or affected by the works of man.

CONTENTS

VOLUME I

CONTENTS

VOLUME II

LIST OF PLATES

LIST OF PLATES (Cont'd)

LIST OF PLATES (Cont'd)

LIST OF TABLES IN APPENDICES

LIST OF TABLES IN APPENDICES (Cont'd)

SECTION 1

SECTION 1

INTRODUCTION

1.01 GENERAL

The fresh water resources of British Columbia are becoming increasingly valuable, and the compilation of a complete inventory of such resources is urgently required, as an important factor in the development of the Province.

The evolution of a water policy requires a reasonably accurate knowledge of the streamflow characteristics of the region under consideration. The data gathering systems which have been established by the Water Survey of Canada have necessarily tended to be in response to project demands and for water management purposes, and do not constitute a regional network of stations which will adequately sample streamflow patterns over the entire Province.

The study of British Columbia described herein was carried out in a period of six months. This study and a concurrent study in Ontario, contribute to the initial stage of long-range planning of the national hydrometric survey and therefore constitute an important step towards the formulation of a national water policy.

It has been demonstrated by the study that there is a lack of suitable data in British Columbia to make an adequate inventory of the water resources. A plan for a first stage regional hydrometric network involving a minimum number of additional stations has been formulated in the report. Coordination of the hydrometric and meteorological networks will be important, in the development of a comprehensive regional plan, and a study has been recommended to demonstrate potential economic advantages of closely coordinated networks. The limited time available did not afford sufficient opportunity to coordinate the study with the Provincial Water Resources Service and the Federal Meteorological Branch, but in future studies it will be important to phase the development and refinement of the regional hydrometric network, with the planning of meteorological and snow course networks. The future participation of the provincial agency will be essential to define the priorities for network development and implementation.

A future important aspect in the ultimate development of the plan for the regional network is an assessment of the existing network of stream gauging stations, to determine which stations can usefully be included in the regional network. It was recognized early in the study that it was not possible to do this in the time available, and it has been recommended in the report that a separate comprehensive study should be undertaken to determine which existing stations should be assigned to the regional hydrometric network.

Recommendations for the further studies and programs are given in Section 3, Summary of Recommendations.

1.02 TERMS OF REFERENCE

The basic terms of reference were as follows:

(a) An assessment of all of the various techniques of delineating within scientifically acceptable limits and on the basis of available hydrometric data, the areas of hydrologic homogeneity throughout the entire Province of British Columbia with specific recommendations governing the application of such techniques geographically.

(b) On receipt of approval of the Engineer to the techniques recommended by the Consultant in paragraph (a) above, the Consultant then to carry out as many as possible of the actual computations with the best available hydrometric data to be supplied by the Engineer.

(c) The work outlined above in paragraphs (a) and (b) is also to comprehend the Consultant carrying out an assessment and recommending accordingly, respecting those additional hydrometric metering stations that are needed throughout the Province of British Columbia in order to ensure that the entire Province is, and will be, afforded adequate hydrometric data gathering coverage.

(d) All new computer programmes and data files developed specifically for this study (as defined above in paragraphs (a) to (c) inclusive) will, to the maximum practicable extent, be designed and documented, wherever practicable, in such a way as to make possible the use of these programmes by outside users on generally available computing services employing standard FORTRAN computer programming language.

1.03 ACKNOWLEDGEMENTS

The study was conducted in close cooperation with the Water Survey of Canada through Mr. H. T. Ramsden, District Engineer, and the Vancouver Network Planning Group which was under the direction of Mr. W. Q. Chin, in order to ensure that full advantage was taken of available expertise.

Also, the consultative services of Mr. S. O. Russell, Assistant Professor at the University of British Columbia, were retained through the courtesy of the University of British Columbia, Civil Engineering Department, Water Resources Group.

The general program for the study was coordinated with the Shawinigan Engineering Company (who have conducted a concurrent study of the Province of Ontario) to ensure as far as possible, uniformity of technical approach and consistency of basic assumptions.

It is considered that the close cooperation with the Water Survey of Canada, and the University of British Columbia has been extremely valuable and demonstrates the practicability of implementing the recommendations of the Science Council of Canada for increased cooperation between the private section, the Government and the universities.

During the course of the study, the Water Survey of Canada sponsored a visit to the offices of the United States Geological Survey in Washington, D. C. and a visit to the hydrological centres of several European countries. The resulting discussions provided valuable background information for the study.

SECTION 2

SECTION 2

SUMMARY OF REPORT

2.01 GENERAL

Scientific planning of a hydrometric network on the scale presently envisaged is a relatively new concept which has only become a practical possibility in recent years with the advent of the computer.

This report presents a plan for the initial phase of hydrometric network planning and implementation, and is therefore considered to represent a major step forward. However, network design is an evolutionary process and continuing appraisal of network concepts, goals and performance will be required. The report is therefore regarded as being only the initial phase of a continuing planning and study program.

The studies described herein have been directed primarily towards the design of a first stage regional hydrometric network which will ultimately provide the data necessary for basic water resource inventory and planning purposes. As such, the regional network is distinguished from the project network which is operated to suit specific project design and operation needs and for water management purposes. Consideration of measurement of water quality, water temperature and sediment load have been beyond the scope of this report.

As of December, 1968, there were over 500 stream gauging stations in continuous operation in British Columbia and most of these stations were installed in response to project needs. The results of the study indicate that at least 300 additional stations are required to provide an adequate base coverage for the regional network. An immediate start on the implementation of the regional network has been recommended to provide the information upon which a comprehensive inventory of the water resources of the Province can be based.

2.02 ASSESSMENT OF TECHNIQUES

A primary objective of the study was the assessment of techniques for delineating zones of hydrologic homogeneity in British Columbia.

A distinction has been made between "physically" and "statistically" homogeneous zones, the former being zones of reasonably uniform topography and climate and the latter being zones within which hydrologic information can be generalized by computational methods. The two types of zones do not necessarily coincide and in fact a statistically homogeneous zone may encompass several physically homogeneous zones.

In general, there is no simple method by which zones of hydrologic homogeneity can be automatically outlined. Nevertheless, there are analytical techniques available for regionalizing hydrologic information which, if there are sufficient meteorologic, streamflow and physiographic data, can be used to delineate "statistical" hydrologic zone boundaries. The various methods for analyzing and regionalizing floods, low flows and the volume and pattern of streamflow are described in Section 4. Promising available techniques, described in Sub-section 2.04, have been tested in pilot areas to assess their potential and their applicability to British Columbia.

It would appear from the assessment of currently available techniques that the most general and immediately applicable approach to regionalizing streamflow characteristics is to relate streamflow to the physiographic and climatic characteristics that cause its variation using a multiple regression type of analysis. For the future, it is considered that two of the more promising techniques for regionalizing data are the computerized grid square regression method and the hydrologic modelling approaches. Stochastic methods for synthetic generation of streamflow data also have considerable potential for regional analyses. However, this technique is still in an early stage of development.

Although the definition of "statistically" homogeneous zones requires the use of the analytical techniques described above, the "physically" homogeneous zones can be delineated on a more qualitative basis as described in the following sub-section.

2.03 HYDROLOGIC ZONES

Large areas of the Province are sparsely gauged; therefore, there is insufficient data available for the general application of analytical techniques to delineate zones of hydrologic homogeneity by statistical methods.

It was possible, however, as described in Section 5, to delineate a set of 29 "physically" homogeneous hydrologic zones despite the limited amount of streamflow data. The hydrologic zones indicated in the report have been based on a detailed study of physiography, climate and generalized runoff and other pertinent data. Because of the dominant influence of topography on the hydrologic regimes of the Province, the probable boundaries of these zones can be relatively well defined in many areas. It is considered that the 29 zones which have been delineated form a useful and flexible framework for network design purposes.

2.04 PILOT STUDIES

The pilot studies, described in Sections 6, 7 and 8, were carried out to assess three of the more promising available techniques for delineating hydrologic zones.

In the South Thompson River basin, a pilot regression study was carried out using the computerized grid square system which utilizes both meteorologic and hydrometric data for estimating mean annual runoff in sparsely gauged areas. This technique was developed by the Shawinigan Engineering Company. The results of the study were very encouraging indicating that this method has promise for more general application in the Province. Further testing is required to refine and develop the technique.

In the East Kootenay basin area, a pilot regression study has been carried out relating mean annual, flood, low and mean monthly flows to physiographic parameters using the basin as the unit of analysis. In general, it is considered that the study has demonstrated the feasibility of establishing such relationships. However, the results of the studies were inconclusive as far as the accurate estimation of the streamflow from the developed regression equations is concerned. The fact that the derived equations do not adequately regionalize the observed streamflow data is partly due to the shortage of data which could be used in the analysis, and perhaps also to the fact that insufficient time was available to incorporate some additional important physiographic and climatic parameters.

Additional studies were carried out for the East Kootenay and Similkameen areas to evaluate the technique of correlation of monthly streamflow values. This technique has possible application for assessing the hydrologic homogeneity of an area and for evaluating the length of record needed to establish an acceptable correlation of data from a short-term station with observations at a long-term station. The results of these correlation studies appear promising but further testing in other areas of the Province is required.

2.05 NETWORK DESIGN

The prime objective of the present assignment has been to formulate a plan to enable the early implementation in British Columbia of a first stage regional hydrometric network. Following a review of available information on network planning, certain design concepts considered appropriate for British Columbia were selected. Specific proposals for the application of these concepts are presented in Section 9. The proposed network plan is presented as a first approximation to a scientifically designed network in order to illustrate the design concepts in concrete terms.

The developed regional network should eventually contain several categories of streamflow gauging stations (as described in Section 9). The present study, however, outlines only a base network of long-term stream gauging stations, with suggestions concerning secondary networks to provide important supplementary information. Whenever possible, consideration has been given to the incorporation of existing stations into the base network. However, a thorough appraisal of these existing stations will be required to assess their adaptability for this purpose. The existing network appears to provide adequate coverage of the larger rivers, but there is a definite need for information on smaller streams, especially at middle and higher elevations. The existing network is unbalanced geographically, with the majority of stations being located in the more heavily populated southern half of the Province. The purpose of the planned regional network is to provide adequate and reasonably uniform hydrometric coverage of the entire Province.

It is not practicable to measure every stream in the Province, and gauging must therefore be done on a sampling basis. Network design thus seeks a proper balance between point measurement and areal analysis. For regional or areal analyses to be successful, the network must be closely related to the physical factors which influence hydrology. Herein lies the value of the hydrologic zones as an integral part of network design. These zones delineate areas of physiographic and hydrologic similarity, and by strategically placing stations within each zone, it should be possible to provide an adequate sampling of most physiographic and climatic variations in the Province with a minimum number of stations. Once sufficient data from a network planned on this basis becomes available, regionalizing techniques such as those investigated during this study can be used to estimate areal variations of streamflow and thus to furnish information for ungauged areas.

In summary, the design of the proposed first stage base network has been based on the use of appropriate design concepts in conjunction with the framework of hydrologic zones developed during the present study. The detailed application of these concepts has been carried out to establish a plan for implementing a regional hydrometric network. The results of the studies have shown the need for at least 300 additional hydrometric stations to establish an adequate base network.

2.06 CONCLUSIONS

The present study has been a pilot project aimed at formulating the necessary plan for the implementation of a regional network and to provide guidelines for future work. The proposed network must be regarded as a first stage base network which can be modified in the course of detailed study of the proposed sites and in the light of a continuing appraisal of network requirements.

It is anticipated that several years will be required to implement a network along the lines proposed in this report and during this period, studies and research should continue to develop better computational and measuring techniques. A concurrent program for analyzing and processing data would result in a logical and orderly development of the network.

Since streamflow represents only one phase of the hydrologic cycle, extensive use of precipitation and snow course data forms an essential part of scientific hydrometric network design. Knowledge of meteorologic events is required for such purposes as regionalization, extension or reconstitution of streamflow records and for the rational delineation of hydrologic zones and the most efficient placement of regional hydrometric stations. It is therefore important that, in the future, steps be taken to ensure close coordination of hydrometric and meteorologic network planning and implementation.

SECTION 3

SECTION 3

SUMMARY OF RECOMMENDATIONS

3.01 ADDITIONAL HYDROMETRIC STATIONS

It is recommended that priority be given to the plan outlined herein, to establish a first-stage base network of long-term continuous recording stream gauging stations. A minimum of 300 additional hydrometric stations will be needed to implement the base network. These stations are urgently required to ensure the evolution of an adequate inventory of the fresh water resources of British Columbia.

3.02 FUTURE STUDIES

The present report is only the first phase of what must be a continuing program of hydrometric network planning and development if the necessary information is to be provided to ensure optimum utilization and successful development of the water resources of British Columbia. Specific recommendations for additional studies are listed below:

(1) There is a definite requirement for a thorough appraisal of the historical records of existing hydrometric stations:

(a) to classify the purpose of each station and to determine which stations are suitable for inclusion in the regional base network.

(b) to assess the need for, and advisability of reconstructing the records of flows which have been modified by diversions and storages.

(c) to assess the accuracy of historical data and recommend the steps to be taken to upgrade data.

A program of data adjustment based on the findings of (b) and (c) above should then be considered.

(2) Further studies should be carried out to develop a systematic plan for a secondary hydrometric network which will provide back-up information for the first stage base network. In particular, the additional types of stations envisaged are

peak flow, low flow and short-term continuous recording stations which will collect the additional data needed for defining regional streamflow characteristics to desired degrees of accuracy.

(3) The importance of coordinating the hydrometric and meteorologic networks in developing the regional plan has been stressed in this report. It is further recommended that a study be carried out to demonstrate the potential economic advantages of coordinated networks.

(4) It is recommended that a province-wide inventory of existing and potential water uses be compiled. Detailed knowledge of water use will be of value in assigning priorities for network implementation and for assessing future network requirements, particularly for secondary network stations.

(5) It is recommended that further pilot studies be carried out to assess and develop promising conputational techniques for regionalizing streamflow data. In particular, continued study of the computerized grid square regression method will be required to test this technique in other areas of the Province, and also increased attention should be given to development, under British Columbia conditions, of the hydrologic modelling techniques described in Section 4.

(6) It is recommended that studies be undertaken to establish criteria or guidelines for accuracy standards for the collection of hydrometric data in British Columbia.

3.03 FURTHER RECOMMENDATIONS

(1) It is recommended that the present program of streamflow data collection and publication by the Water Survey of Canada be expanded to include the processing and analysis of the data and publication of the results. The results should include information on the frequency characteristics of the various streamflow categories.

(2) It is recommended that increased attention be given to the coordination and promotion of the research and development of streamflow instrumentation and measurement techniques, to further the effective and rapid development of the regional network.

(3) It is recommended that consideration be given to the development of a computerized grid data file for British Columbia.

SECTION 4

SECTION 4

ASSESSMENT OF TECHNIQUES

4.01 GENERAL

The primary aim of a regional hydrologic network is to provide information on streamflow for the planning and design of water resource projects. Requirements for information cannot be anticipated in detail and even if they could it would not be feasible to operate a gauging station at every site on every stream in the Province where information might be required. Hence, to a considerable extent, stream gauging must be looked upon as a sampling process which must be supplemented by analytical methods of generalization. If the whole data collection program is to be effective, the stream gauging network must be compatible with the analytical techniques to be used for generalizing the information.

In the study described herein emphasis has been placed on the delineation of hydrologically homogeneous zones since generalization techniques can usually only be applied within such homogeneous zones. In Section 5 a distinction has been made between "physically homogeneous zones" and "statistically homogeneous zones," the former being defined as areas within which all parts have a generally uniform topography, geology and vegatative cover and subject to similar climatic variations, and the latter being defined as areas within which it is possible to relate streamflow characteristics to physiographic or climatic parameters by means of a set of equations or a computational model.

It will be appreciated from the above considerations, that the stream gauging or "sampling" network, the generalization techniques and the outlines of the zones within which information can be generalized are all closely interrelated and must be keyed to one another. In this section various techniques for generalizing hydrologic information are considered together with their implications for design of stream gauging networks. Consideration of techniques has not been limited to methods currently in use and an attempt has been made to identify promising trends of development. Analytical techniques are developing rapidly and it would be most unfortunate if the network were "locked in" to a technique which might become obsolete in later years. It is believed that the concepts of network design as outlined in this report are sufficiently flexible that the proposed network not only can accommodate itself to new analytical techniques, but also can provide information which will assist in the development and testing of new techniques.

4.02 TYPE OF INFORMATION REQUIRED

Hydrometric data are required for many purposes such as design and operation of reservoirs for water supply, flood control and hydro-electric power production, design and operation of irrigation systems, pollution control, bridge and culvert design. However, as pointed out in the previous section, the primary aim of a regional network is to provide information for planning and design purposes, for which information on the following streamflow characteristics is required:

(a) floods - generally instantaneous or short period (such as one day) average rates of discharge, except for design floods for major projects where the shapes of the flood hydrographs are important.

(b) low flows - relatively short period (one to 30 day) average rates of discharge.

(c) volume of flow and its variability - quantities of water available in various periods of time and patterns of discharge.

Techniques for regionalizing data on the above three flow characteristics are considered separately herein since different techniques may be appropriate for each characteristic.

Data on sediment load, water quality and ground water, are outside the scope of the present study and hence have not been considered in this report. However, during the evolution of the hydrometric network, the need for this additional data will have to be assessed and provision should be made in the network design for obtaining all necessary data.

In the following discussion frequent reference is made to "correlation." For example: correlation between various categories of streamflow such as flood peaks and physiographic parameters such as mean basin elevation. Unless otherwise stated, the term "correlation" implies multiple linear regression either between the variables themselves or their logarithms. Other correlation techniques are available but regression methods are almost universally used in hydrology since available data is rarely adequate for the application of more sophisticated techniques.

4.03 TECHNIQUES FOR ANALYSIS OF FLOOD DATA

4.03.01 General

Data on floods are required for the design of new water resources projects and occasionally for analysis of existing ones. Floods for design purposes can be broken down into two categories as follows:

(a) Design floods for relatively minor structures such as small bridges and culverts, for which return periods in the order of 50 to 100 years are of interest and in general the magnitude only of the peak flood is of concern since there is usually no storage available to reduce the flood peak.

(b) Design floods for major structures where the consequences of failure would be catastrophic; for such projects floods with much longer return periods are of concern. Also to be considered are the "maximum probable" floods to which no realistic return period can be assigned. Normally with major projects some storage is available to reduce the peak of the flood in which case the volume of the flood and the shape of the flood hydrograph are also important.

There are different data requirements for the above two categories of floods and hence each will be considered separately.

4.03.02 Peak Floods with Return Periods in the Order of 50 to 100 Years

When adequate data are available, peak flows with return periods of about two to three times the length of the period of record can be satisfactorily estimated by one of the standard frequency methods such as log normal, Gumbel, Hazen or Pearson. Several methods are often tried and the one with the "best fit" is adlopted. However, for return periods several times the length of the period of record, the particular method chosen seems to make little difference and as described in Sub-section 4.03.06, it has been concluded in the U. S. A., following a recent study, that all agencies should standardize on one particular distribution.

Unit hydrographs can also be used together with a rainstorm of the desired probability of occurrence to estimate the required design flood. The unit hydrograph represents the response of the basin in question to 1 inch of excess rainfall (over and above "losses" such as infiltration) falling in unit time. Unit hydrographs are assumed to be linear, i.e. 2-inches of excess rainfall in the same time would produce a hydrograph with ordinates exactly twice as large as the unit hydrograph, and hence it is an easy matter to compute the flood resulting from any particular rainfall excess if the unit hydrograph is known. (The assumption of linearity is convenient and for practical purposes it is generally sufficiently accurate.)

Unit hydrographs can only be derived from actual flood records and preferably from accurate concurrent records of both discharge and rainfall over the drainage basin. These latter conditions are rarely fulfilled in British Columbia. However, the unit hydrograph is a convenient tool and has received considerable attention from hydrologists for regionalizing and other purposes; hence the concept is discussed briefly in the following:

4.03.03 <u>Regionalizing Unit Hydrographs</u>

After the unit hydrograph came into general use in the late 1930's, it was soon realized that sufficient records would probably never be available to make it possible to derive unit hydrographs for all sites where design floods would be required. An early attempt to extend the applicability of unit hydrographs was made by Snyder in the form of dimensionless hydrographs ("Synthetic Unit Graphs" by F. F. Snyder, Trans. Am. Geophys. Union, Volume 19, Part 1, 1938) and this method is still in use today. Many other attempts have been made to characterize unit hydrographs by a few parameters such as height of peak and time of concentration, and since the advent of computers attempts have been made to correlate these parameters with parameters describing the physiographic characteristics of the drainage basin. A typical modern example of this type of analysis in the U. S. A. is given in the paper "Design Hydrographs for Pennsylvania Watersheds" by J. E. McSparran, Journal of Hydraulics Division, July, 1968, published by the American Society of Civil Engineers.

In England Nash characterized unit hydrographs by their statistical moments and then correlated functions of the moments with physiographic parameters such as mean basin elevation and slope ("A Unit Hydrograph Study with Particular Reference to British Catchments" by J. E. Nash, Proc. Institute of Civil Engineers, Great Britain, November, 1960). Subsequently, attempts were made to estimate peak flood - frequency relations from unit hydrographs and rainfall duration - frequency curves, but apparently the attempt was not entirely successful (as reported in Chapter 6 "Applied Flood Hydrology" by J. E. Nash of "River Engineering and Water Conservation Works" edited by R. B. Thorn). As a result of this experience, Nash abandoned the attempt to regionalize peak flood data by separately regionalizing unit hydrographs and rainfall frequency curves and then combining the two. He concluded that regional flood frequency analyses as described in Sub-section 4.03.05 were much more useful.

4.03.04 <u>U. S. Geological Survey Method of Regionalizing Flood Peak Data</u>

A good example of the type of regional flood frequency study made for many parts of the U. S. A. is given in the report issued by the U. S. Geological Survey "Magnitude and Frequency of Floods in the U. S., Part 12, Pacific Slope Basins in Washington and Upper Columbia" by Bodhaine and Thomas.

Although the techniques used in the report are now slightly out of date, the report brings out the following interesting points which have a bearing on the present study:

(a) It provides, in one convenient volume, recorded data on all significant floods in the State of Washington.

(b) It presents an analysis of the data and includes graphs and charts which permit estimation of peak floods with any desired return period up to 100 years for any drainage basin (gauged or ungauged) in the State of Washington.

The steps used in the analysis of the data are listed below:

(1) Peak Flood data were adjusted to a base period.

(2) Frequency curves were plotted for each station.

(3) Tentative hydrologic zones were selected and for all stations within each zone the mean of the ratio of the 10 year flood to the annual flood was computed. Using this mean ratio for the group and the mean annual flood at each station, the magnitude of the expected 10 year flood at each station was calculated and the corresponding return period was obtained from the

frequency curve for that station. The return periods thus found were plotted on a confidence limit graph and when no more than 1 in 20 points fell outside the limits, the area was considered homogeneous. Eight such homogeneous zones were outlined for the State of Washington.

(4) For each homogeneous zone dimensionless average frequency curves were constructed showing values of the ratios of flood to mean annual flood against the corresponding return period.

(5) Corrections were made for the size of drainage basins and adjustment curves were prepared.

(6) Since all floods were now referenced to mean annual floods, these were correlated with physiographic parameters to permit estimation for ungauged basins. The best equations were found to be of the form:

$$Q = 0.638A^{0.889}R^{1.135}L^{-0.037}G$$ for the upper Columbia Basin

$$Q = 1.58A^{0.928}R^{0.696}L^{-0.099}G$$ for Pacific Slope Basins

where:

Q = mean annual flood in cfs
A = drainage area in sq. miles
R = average annual runoff in inches
L = area of lakes in percent of drainage area
G = geographical factor

The geographical factor "G" was obtained from the residuals and a map was prepared showing values of G for the State of Washington.

The above method has been described in some detail because it represents a reasonably successful application of regional hydrologic analysis and is of particular interest because of the proximity and similarity of the study area to British Columbia. The method also has the advantage that, although it made full use of the skill and experience of the hydrologist, it also included a reasonably objective test of hydrologic homogeneity, which was actually used in finalizing the hydrologic zones. However, this type of analysis is somewhat out of date and presumably will not be repeated. Instead, efforts by the U. S. Geological Survey are now being concentrated on directly correlating flood peaks with parameters describing the physiographic characteristics of the drainage basins. Separate equations are derived for floods with various return periods such as mean annual, 5 year, and 10 year.

4.03.05 Regional Flood Studies in Great Britain

As mentioned earlier, Nash has come to the conclusion that flood data can best be regionalized by first fitting a standard frequency distribution to the peak flood data and then correlating the flood frequency parameters with physiographic parameters. He suggests a double exponential frequency distribution (similar to Gumbel's) which can be characterized by the mean and the coefficient of variation of annual peak floods. He proposed the following estimating equations for Great Britain:

$$\bar{Y} = 0.009A^{0.85}R^{2.2}$$

$$Vy = 219R^{-0.5}$$

) when mean annual rainfall is known

$$\bar{Y} = 0.074A^{0.75}.S$$

$$Vy = 178S^{-0.25}$$

) when rainfall is not known

where,

$\bar{Y}$ = mean annual flood in cfs
Vy = coefficient of variation of annual floods
A = drainage area in sq. miles
S = drainage basin slope in parts per 10,000
R = mean annual rainfall in inches

4.03.06 Trend of Modern Practice in Regionalizing Peak Flood Data

As described in Sub-section 4.03.04, the U. S. Geological Survey are now correlating peak floods with various return periods directly with physiographic parameters. However, other agencies in the U. S. A. are first fitting flood frequency data to standard frequency distributions and then correlating the statistical characteristics of the frequency distributions with physiographic parameters as Nash had done in Great Britain.

It would seem therefore that as far as moderate floods are concerned, modern practice in both Britain and the U. S. A. is leaning towards regional flood analyses which make use of standard distributions to characterize the distribution by a few parameters which are then correlated with physiographic parameters. This technique would also seem to be the most promising for British Columbia.

The next question that arises is: which of the many possible frequency distributions should be used? Opinions are divided on which is most suitable but there seems to be fairly general agreement that the advantages of standardization would outweigh any local advantages which any particular distribution might have. A comprehensive study of flood frequency methods was made by the "Work Group on Flow-frequency Methods" of the Hydrology Committee of the U. S. Water Resources Council and it was concluded that the most generally applicable frequency distribution was the Log Pearson Type III and the group recommended its general adoption. The reasons for recommending selection of this particular distribution are given in the paper "Uniform Flood Frequency Estimating Methods for Federal Agencies" by M. A. Benson, Water Resources Research, October, 1968. It is suggested therefore that this same distribution should also be used in British Columbia in order to stay within the mainstream of North American practice.

4.03.07 Application to British Columbia

The method, described in Sub-section 4.03.06 for regionalizing peak flood data can only be applied if there is sufficient data available. A regional analysis of flood data has been attempted in the East Kootenay region as described in Section 7 and although this is one of the most intensively gauged areas in British Columbia, the results of the rather exhaustive studies have indicated that there are inadequate data. Elsewhere in British Columbia there are much less data available especially on small basins, and the conclusion is that much more flood data is required before meaningful regional analyses can be made. The minimum requirement is in the order of 30 medium to long-term stations for each "statistically homogeneous" zone. However, for flood estimating purposes, it is only necessary to measure one or perhaps two peak flows per year and consequently it would seem well worthwhile to devise simple methods to measure peak floods. Assuming that such methods can be devised, then measurements could be taken at many points where highways cross streams, giving a wide coverage of streams representing all sizes of drainage basins and thus providing some of the important data required for meaningful statistical analyses.

A possible way to obtain data on peak flows would be to design culverts to feed back useful information for use in the design of the next generation of highways. As another example of potentially helpful techniques, it may be possible to compute discharges from peak water levels recorded by crest gauges, and knowledge of cross sections at a few points on medium to large streams. (The calculations are of the iterative type which would have been too tedious for calculation before the advent of computers.) On small streams discharges could perhaps be computed from peak water levels and knowledge of the geometry of culverts or by constructing simple weirs.

4.04 LARGE FLOODS

4.04.01 General

For estimating design floods for important structures, frequency methods are useful only for indicating orders of magnitude and it becomes necessary to use either unit hydrograph techniques for rain floods or simulation (modelling) for floods which result from snow melt to assist in the derivation of design floods.

In either case, the normal procedure is to first develop a method for computing runoff from meteorological data: then "maximize" the meteorological variables such as storm rainfall or, in the case of snowmelt floods, snow accumulation and temperatures during the melt season; and finally to compute the runoff resulting from the extreme meteorological events using the computational technique already developed.

Techniques for maximizing meteorological events are outside the scope of this report but methods of computing rain floods from meteorological data are considered in Sub-section 4.04.02 and simulation of floods due to snowmelt is considered in Sub-section 4.10.02.

4.04.02 Unit Hydrographs

As mentioned earlier, a unit hydrograph, the modelling technique normally used for rain floods, can usually only be derived from concurrent records of discharge and rainfall over the drainage basins, but these requirements are met in very few locations in British Columbia. Consequently, it becomes necessary to use artificial unit hydrographs such as those suggested by Snyder, but in using these it would be most desirable to have some actual unit hydrographs against which to check their validity. As part of a program of hydrologic research on the watersheds of the mountains immediately north of Burrard Inlet, near Vancouver, British Columbia, a project headed by Dr. W. W. Jeffrey of the University of British Columbia in cooperation with the Greater Vancouver Water District is being undertaken to intensively instrument several drainage basins in order to assess the effect of runoff of watershed changes such as changes in forest cover. As a by-product, this program should provide sufficient data to permit the derivation of several representative unit hydrographs.

It is believed that this program could be usefully supplemented with a program to measure streamflow and precipitation on a representative basin on Vancouver Island, the only other area in British Columbia where rain floods are likely to be more severe than snowmelt floods.

4.05 SUMMARY OF TECHNIQUES FOR REGIONALIZING FLOOD DATA

A knowledge of the magnitude and probability of occurrence of peak floods up to floods with a 1 percent probability of occurrence (100 year return period) is adequate for most purposes, and for floods of this magnitude, one of the more promising techniques for analysing basic data and providing regional information is as follows:

(1) Compute the statistical characteristics of the data, i.e. mean, coefficient of variation and coefficient of skew for each station assuming a Log Pearson Type III distribution.

(2) Correlate these statistical characteristics with parameters which characterize the drainage basin - such as area, mean elevation, slope.

At the present time flood data in British Columbia are inadequate and it is believed that a considerable effort should be devoted to developing simple techniques for measuring peak flood discharges and then using the techniques to rapidly extend the coverage of peak flood stations.

Unit hydrographs are required to estimate design floods due to rain, for use in the design of major structures, but at the present sufficient data are not available to permit derivation of unit hydrographs in British Columbia. A program for instrumenting basins in the lower Fraser Valley is already underway and it is suggested that following experience with these basins for a few years consideration should be given to instrumenting similar basins on Vancouver Island to provide reliable data for "calibration" of dimensionless unit hydrographs for design purposes. Simulation or modelling techniques for floods due to snowmelt are required, but consideration of these techniques has been postponed until Sub-section 4.10.

4.06 ANALYSIS OF LOW FLOW DATA

In British Columbia the lowest flows normally occur in winter during the freeze up period. Data on low flows are likely to become increasingly important as pollution and the need for its dilution increase with the development of the Province. Data on low flows during summer are important to any "run of the river" water resource scheme, for example some irrigation schemes.

Techniques for regionalizing frequency data on low flows (for example, one day low flow, seven day average low flow) are similar to those for regionalizing peak flood data as described in Sub-section 4.07. This type of analysis has been carried out by the Water Survey of Canada for droughts in the East Kootenay area. However, low flows are heavily dependent on the local geology and it is usually necessary to make at least spot measurements on every stream to check the applicability of the regional equations to that particular stream. It is recommended therefore that during periods of low flow, spot measurements of discharge be made on as many streams as possible.

For other than frequency data, summer low flow data are essentially no different from other flow data, and hence the regionalizing techniques discussed in the following sections should be applicable to low flows. Again, however, spot measurements during drought periods would be helpful in indicating the influence of local geology.

Data on stream flow during winter are difficult and expensive to obtain but on the other hand such flows are relatively constant during winter and it would seem to be simpler to "regionalize" low flow data than most other types of flow data. Unfortunately, adequate data are not available for such analysis and it is believed that the first essential is to develop better and simpler techniques for estimating streamflow in winter. Again, as with peak flows, there would seem to be a requirement for a research and development program to develop better discharge measuring techniques and a research program to develop better methods to extract the maximum information from such measurements. An example of an attempt to use temperature data to supplement winter discharge measurements is given in the paper "Effects of Temperature on Winter Runoff," by W. D. Simons, Western Snow Conference, 1967. Similar studies would seem to be very appropriate for Canada and fully in line with the thinking of the Science Council on research particularly applicable to Canada. Therefore, for present purposes, it is only possible to point out the problem of lack of data on winter flows and suggest a determined program of research and development in this area.

4.07 TECHNIQUES FOR ANALYSING AND REGIONALIZING DATA ON VOLUME AND PATTERN OF STREAMFLOW

4.07.01 General

The basic reason for measuring streamflow is to obtain information on the rates and pattern of discharge likely to occur in the future. Apart from some possible scientific interest in flows which have occurred in the past, there is little point in collecting such data if it cannot be used to predict conditions in the future. Since streamflow varies from hour to hour, day to day, season to season, and year to year, the longer the period of records, the greater is the degree of confidence that the recorded flows are representative of long term conditions and that, at some time during the period of record, flows have approached the possible extremes for that particular station; in other words, the longer the sample, the more representative it is considered to be. However, a 50 year period is considered adequate for most purposes.

4.07.02 Correlating Short Term Records with Long Term Records

Since funds for stream gauging are normally in short supply, an obvious first step is to set up temporary stations in the vicinity of stations with long term records and correlate the short term records with the long term records in order to transfer some of the reliability of the long term station to the short term record, thus hopefully obtaining the most of the advantages of two long term records without incurring the full cost. This is the base and roving station concept believed to have been originally put forward by Langbein.

The most obvious way of correlating records from one station with those from another is by graphical correlation or linear regression of annual and monthly flows at the two stations for the overlap period. Then the graphs or equations can be used to extend the short term records. The main shortcoming of this method is the need for a fairly long overlap period if the correlations are to be meaningful. In an attempt to overcome the need for the relatively long overlap period, Langbein developed a method of transforming the monthly flow data which permitted the use of all the data simultaneously in developing the correlation instead of just two sets for one month at a time.

Since this method appeared to be immediately applicable to British Columbia, and since it is the type of relatively simple technique which appeared suitable for use during the early phase of development of a new regional network, considerable effort has been devoted to trial and assessment of the technique. The studies, which are described in some detail in Section 8, indicate that the method is a useful one for extending short term records when there is a long term station in the vicinity.

4.07.03 Regionalizing Frequency Data

Although the Langbein technique is widely used and it appears to be applicable to British Columbia for purposes of extending short term records, it is inherently limited in that by itself it cannot be used for estimating streamflow in ungauged basins, the ultimate aim of any regionalizing technique. Following the reaoning outlined in Subsections 4.02 to 4.04 on regionalizing flood data, it would seem that similar techniques would be appropriate for streamflow data. For example, frequency analyses could be made if say, monthly flows and again, assuming a standard frequency distribution such as Log Pearson Type III, each monthly flow frequency could be characterized by its mean, coefficient of variation and coefficient of skew, which in turn could be correlated with physiographic parameters characterizing the drainage basins. It is thought that the mean is generally the most variable flow characteristic from place to place, while the coefficient of skew hardly varies at all over wide areas. When all the equations have been determined, frequency characteristics can be computed for any ungauged basin from which the flow frequency distribution can be obtained and from this the flow, with any desired probability of occurrence, can be estimated.

The method used by the Water Survey of Canada for the frequency analyses of drought flows in the East Kootenay area affords an excellent example of this type of analysis, but although this approach may appear promising, it has two main drawbacks; the first is the large number of relatively long term stations required for meaningful correlations (about 30 stations per zone, each with at least 20 years of records); and the second is the difficulty of characterizing the streamflow pattern by one or two parameters.

If it could be established with more certainty that the coefficient of variation was less variable than the mean runoff and that the coefficient of skew was still less variable, as is sometimes assumed, then the coefficient of skew could be assumed constant over an entire area, the coefficient of variation could be estimated from relatively few stations, and the areal variation of the mean runoff could be estimated from a few base stations supplemented by and correlated with short term roving stations, thus reducing the number of long term stations required.

Unfortunately, not enough is known at this time about the areal variation of the coefficients of variation and skew to be sure that the need for a large number of long term stations within a particular zone can be overcome by having a few base stations supplemented with roving stations. The technique of correlating streamflow frequency components with physiographic parameters has been tried using the available data in the East Kootenay Area but as described in Section 7, the results were inconclusive.

The second difficulty, that of finding a few parameters to characterize the streamflow pattern, arises because quite often the pattern or sequence of flow is extremely important, especially where storage is involved. For planning a reservoir on an ungauged stream, even quite well defined frequency curves of monthly runoff and droughts are not particularly helpful since they cannot give information on the sequence of flow, i.e. how the flow varies from time to time. Some attempts have been made by Yevjevich to characterize flow patterns by the amount of storage required to maintain various constant rates of discharge, but even if successful these would be of limited usefulness since the amount of storage required to maintain constant rates of discharge is not usually the only information required. However, it is not necessary to pursue this approach since a more promising technique for dealing with sequences of flows is afforded by stochastic or synthetic hydrology which is described in Sub-section 4.08.

4.08 STOCHASTIC HYDROLOGY

4.08.01 General

Stochastic hydrology was largely developed by Thomas and Fiering and first reported in 1962. Basically it involves analysis of existing records of discharge, usually performed on monthly flows, to separate out random and non-random components, following which, new random components (with the correct frequency characteristics) are generated by computer and re-combined with the non-random components to give asequence of synthetic flows which, if the analysis has been performed correctly, should have the same chance of occurrence as those in the existing record. A great advantage of the method is that very long sequences of flows can be generated from which, as an example, the probabilities that various amounts of storage will be adequate to sustain a given discharge can be estimated with greater precision than would be possible from the much shorter sequence of actual recorded flows.

Following the original work by Thomas and Fiering, considerable effort has been, and is being, made on similar techniques (for example, Young and Pisano), but as yet no generally recognized superior method has been publicized. A useful summary of the state of the art is given by Matalas.

4.08.02 Regionalizing Stochastic Hydrology Coefficients

The statistical parameters derived for the generation of synthetic streamflow sequences at gauged sites can themselves be correlated with physiographic parameters and, from the resulting equations, suitable parameters can be estimated for ungauged basins. Sequences of flows can be synthesized, using these parameters, for any basin and such sequences should have all the characteristics of natural flows with the additional advantage that "records" of any length could be created. Benson and Matalas give an example of this type of analysis for the Potomac River Basin. This technique which involves derivation of the necessary parameters from existing streamflow records, extension of the parameters by regional equations and finally synthesis of flow sequence from any basin within the same hydrologic zone, appears extremely promising and if successful would seem to offer the "ultimate" in regionalizing techniques. However, the technique is still subject to some difficulties. The first results from the need for extensive data to permit derivation of the necessary synthesizing parameters, e.g. serial correlation coefficients between flows in successive months, for which about the same amount of data would be required as for the frequency characteristics discussed in Sub-section 4.07.02; and the second arises from some as yet unresolved problems with synthetic hydrology, particularly as it applies to Canada.

4.08.03 Some Deficiencies in Stochastic Hydrology

One of the unresolved problems with stochastic hydrology arises when trying to simultaneously generate flows at two or more sites. Flows at each site can be generated separately but the problem of generating synthetic flows at two or more sites and still maintaining the natural cross correlation between the flows has not yet been solved. Another present drawback to synthetic hydrology in Canada results from the seasonal nature of the flow and the fact that flow always increases rapidly in spring. At the changeover from low flows to high flows at the spring freshet, the effect of serial correlation is very small and the random component of the flow is large; consequently the normal effect of persistency from one year to the next is lost in the synthetic sequence as a result of which the synthetic records become less representative of natural conditions. Harms and Campbell have attempted to overcome the lack of continuity from year to year by first generating a sequence of yearly flows; then generating a separate sequence of monthly flows; and finally adjusting the monthly flows to ensure that in each 12 month period the total added up to the previously generated annual flow. This approach appears promising and worth exploring. An interesting variant to this approach and one which might be more applicable to British Columbia where most runoff originates from snowmelt might be to separately synthesize values of the snowpack water equivalent just before the melt season and the net evaporation (i.e. evaporation less rainfall) during the melt season and then combine the two to obtain estimates of summer runoff (a very large proportion of the annual runoff in British Columbia.) As far as is known, little work has been done along these lines, although as described in Sub-section 4.03 Nash tried such an approach with rain floods, but without much success; however, there the problem was more complicated. Similar ideas have been put forward by Solomon and Banks, for the derivation of design floods (Discussion on "The Philosophy of Estimating Spillway Design Flood." Engineering Institute of Canada Journal, January, 1969) and they would seem to be worth pursuing, especially since the technique outlined in the following section offers the possibility of separately estimating annual precipitation, evaporation and runoff for gauged and ungauged basins.

4.09 ESTIMATING MEAN ANNUAL FLOWS BY THE GRID SQUARE APPROACH

A new approach to the estimation of runoff is that put forward by the Shawinigan Engineering Company, in which precipitation, temperature and runoff data are all used to estimate annual runoff at any point over a wide area. Many publications have stressed the desirability of using all available information but apart from very detailed simulation models such as in the Stanford Model (Crawford and Linsley), which reputedly was very costly to develop, few successful attempts have been made to use all available data.

The grid square approach would therefore seem to represent a step forward in the efficient use of all available hydrologic data. In this approach, which is described in more detail in Section 6, the study area is broken up into a large number of squares, of the order of 10 kilometers per side, and physiographic parameters are determined for each square; regression equations are derived for estimating precipitation and temperature at any point within the area from available meteorological data; precipitation and evaporation are then estimated for each square, the two are subtracted to obtain runoff in each square and the runoff from all the squares in a given drainage basin is summed to obtain an estimate of the runoff for the entire basin; the computed runoff is then compared with recorded runoff and if it disagrees, runoff from each square is adjusted to give the correct total; a new estimate is made of the precipitation and evaporation; and a new equation is then derived to relate precipitation to physiographic parameters; and the whole procedure is repeated until computed and recorded runoff agree as closely as is practicable.

This method has been tested as described in Section 6 and found to work satisfactorily in a rugged area in British Columbia for which there were reasonably adequate records of precipitation, temperature and streamflow. Obviously the method is open to detailed development to tailor it for use in areas with different types of terrain, for example, different sizes of squares and different physiographic parameters could be tried. Basically, however, the method appears to be sound and applicable to British Columbia, assuming the availability of sufficient data. Attempts have also been made in the present study to expand the method to make use of data from snow courses but results have been inconclusive. However, snow course data is presently being used for the preparation of forecasts of the volume of runoff in British Columbia and hence it would seem that in British Columbia snow course data ought to be able to contribute significantly to the grid square method.

To date the grid square method has only been applied to mean annual flows but there would seem to be no reason why it could not also be applied to the annual flows in particular years. In some areas there may be difficulties with glaciers which may cause a carry over effect from one year to the next, but such areas are a relatively small percentage of the total and hence are unlikely to affect the accuracy of the method in many areas.

One important component of the grid square approach is the estimation of annual evaporation and for this Turc's formula has been used. Attempts to verify the applicability of Turc's formula to British Columbia have been made but it was not possible to find sufficient data in various areas to make a thorough check on the applicability of the formula. If the method is to be developed, it would seem to be desirable to select and instrument one or two areas where the formula could be checked for general use in British Columbia.

The grid square method offers an efficient method for estimating first of all the mean annual runoff from any basin within the study area, which information will be extremely valuable for inventory purposes; and secondly it would seem to offer a method of estimating the annual runoff in particular years, and not only the annual runoff but also the total precipitation and evaporation, which information can probably be used for synthesizing a series of annual flows at any required location as suggested in Sub-section 4.08.

Another great advantage of the grid square method is that it provides an extremely simple method of storing data on the physiographic characteristics of an area. For example, data on the squares in a basin could be aggregated to provide "lumped" physiographic parameters for entire basins for use in regression equations such as those suggested in Sub-sections 4.04 and 4.06.

As described above, the grid square method offers an efficient method of storing data, estimating mean annual flows and, hopefully, flows in individual years. At present, there seems to be no way of extending it for estimating the pattern of flow within any individual year, the type of information which is vital, say, for reservoir design. Possible techniques for estimating the pattern of flow are described in the following:

4.10 SEASONAL PATTERN OF FLOW

4.10.01 General

In British Columbia most of the flow originates as snowmelt and hence the pattern of discharge is affected to a large degree by the depth of snow which accumulates and the rate at which it melts. In basins at low elevations most of the runoff occurs early in the season, whereas those at higher elevations have their peak runoff at a later date. It was hoped that attempts could be made to correlate the average pattern of flow in various basins with physiographic parameters such as drainage basin area and mean elevation of basin, but in the time available little could be accomplished. It had also been hoped to follow up this particular study with attempts to correlate the flow in individual summer months (flow in each month expressed as a percentage of the runoff which had not yet appeared, i.e. snow which had not yet melted), with departures of temperature from the mean at index stations within or near the basin in question. The hope was that if such a study had been successful, it would be possible to simulate the pattern of flow in any particular year given the temperature at the index station and the total volume of annual runoff. This particular study was intended as a supplement to the grid square study in that the grid square study could provide a method for estimating annual flows and this particular study should provide a method for breaking down annual flows into monthly flows so that the pattern could be used for design purposes or for tying in an incomplete record into a longer term record. For example, a record of two months discharge at a station would be essentially valueless by itself, but if it were known that flow in those particular months represented say 25 percent of the annual flow and that the particular annual flow represented say 90 percent of the long term flow, then the record would be of a much greater value.

At this stage, all that can be said about the technique suggested here is that it could not be tried in the time available, but it offers some promise and probably should be tried in future.

The approach outlined in the above paragraphs in effect represents a very crude form of modelling, i.e. attempting to reproduce hydrographs from meteorological data; it is crude in that it is attempting to reproduce hydrograph patterns on a monthly basis instead of say a daily basis and that it takes no account of the time between melting of the snow and appearance of the snowmelt as runoff in the stream at the gauge in question. Perhaps it would be better to try starting with a more detailed modelling approach and if a successful technique could be developed then it could be approximated on a monthly basis. Modelling techniques are considered in the following.

4.10.02 <u>Modelling</u>

There have been many attempts at modelling runoff from meteorological data but most of these have been concerned with runoff resulting from rainfall whereas in British Columbia most of the runoff originates as snowmelt. However, some attempts have also been made at simulation of runoff from snowmelt. Modelling techniques involve first of all estimation of the amount of snowmelt and then routing of the melt into the river channel. Runoff from snowmelt has been simulated with reasonable success in the course of the derivation of design floods for the Peace River project and the Columbia River Treaty projects. The technique used for the Peace River simulation was essentially similar to that outlined in the U. S. Corps of Engineers Manual "Runoff from Snowmelt" and was reported by Davies and Rockwood. The technique used on the Columbia River projects was similar but somewhat simpler; it is described in the report "Progress Report on the Mica Project," 1962, Vol. 9 by Caseco Consultants Ltd.

Simulation techniques involve the use of various constants and these are normally estimated from past records and in many cases a trial and error procedure is the most efficient method of deriving the necessary constants. As described above, reasonably successful simulations were made of runoff on both the Peace and Columbia rivers indicating that the constants must have been at least reasonably accurate. However, both these studies were made several years ago and now with new larger computers, more powerful methods are available for determining the necessary constants. An example of the new powerful type of technique available for "closing in" on constants for simulation is given by Beard, who describes an optimization technique developed in the Hydrologic Engineering Section of the U. S. Corps of Engineers in Sacramento. This technique is relatively simple but with it, or other similar techniques, it should be possible to develop simulation models for parts of British Columbia where adequate data are available.

However, modelling is a fairly time consuming process and one requiring considerable skill and patience, and, although its promise was recognized, it was not considered appropriate for a short term study. Nevertheless, it is considered that increased attention should be given to the development of modelling techniques. Eventually, hydrologic models could complement the grid square approach and stochastic techniques in that meteorologic data could be synthesized much more readily than streamflow data; the grid square approach could be used for estimating annual volumes of runoff and the modelling approach could be used to determine the pattern of runoff within a particular year. Such a comprehensive approach is a long way off, but in the meantime the process of developing a computational model usually provides considerable insight into the physical processes involved and as such could produce much useful knowledge about the hydrologic regime in parts of British Columbia.

4.10.03 Summary of Techniques for Regionalizing Data on Volume and Pattern of Streamflow

At this stage it is perhaps worth reviewing the trend of thought on techniques dealing with volume and patterns of streamflow. Various regionalizing techniques have been considered starting with simple correlations between flow records at adjacent stations, leading through more sophisticated techniques and ending on a somewhat visionary note. In general, as techniques become more sophisticated, they offer the promise of being able to extract more information from a given amount of basic data (or alternatively, the same information from less data), but at the same time the techniques themselves are progressively less well defined as the boundaries of present day hydrologic knowledge are approached. Thus, the more sophisticated the technique, the greater the need for research and development to adapt it for use in British Columbia but at the same time, the greater the potential for economizing on basic data collection. It follows that network planning should involve a judicious mixture of basic data gathering with research and analysis; too much of one or the other could result in either "frozen" attitudes and techniques which would necessarily be simple and relatively inefficient or at the other extreme in a pure research institution which would produce insufficient "hard" facts.

4.11 SUMMARY OF ASSESSMENT

Summarizing the above description of techniques for regionalizing hydrologic information, the conclusions are:

(a) For peak flood data the frequency characteristics of the floods at each station should be derived on the assumption of a Log Pearson Type III frequency distribution and these characteristics should be correlated with physiographic parameters of the drainage basins. Since this will require a considerable amount of data, somewhere in the order of at least 30 stations per statistical zone, and since only one or two peak flow measurements are required per year, it is believed that considerable effort should be devoted to developing simple methods of estimating peak flows, and it is suggrsted that it would be worthwhile coordinating this effort with the Department of Highways, one of the main users of this type of information.

(b) Data on the frequencies of droughts can be treated similarly as to that on flood peaks as described in Sub-section 4.03.04 but since low flows are very dependent on local geology, spot measurements should be made during drought periods to provide firm data on base flows.

(c) Winter low flows are difficult to measure but it is believed they do not vary much from year to year. However, data are so scarce that it is considered that first priority should be given to the development of better and simpler techniques for the measurement of flows in winter.

(d) For estimating volume and pattern of runoff it is considered that the Langbein technique of correlating short term records with base station records is immediately useful. However, the longer term future is believed to lie with the stochastic methods, not the present day methods but methods specially adapted to British Columbia. The most promising method is thought to be the separate synthesis of annual flows, either directly or by subtracting evaporation from precipitation, and monthly flows. The grid square method seems to offer the greatest promise for the estimation of annual flows and a modelling technique would seem to be most promising for estimating the pattern of flow within any particular year.

At the moment, with the exception of the Langbein technique, none of the above techniques listed under Sub-section 4.11 (d) above are immediately applicable to British Columbia. It would seem therefore that research and development into the more promising techniques should continue. In particular it is believed that work on the grid square approach should continue under fairly high priority in order to best adapt the method to British Columbia, i.e. find the optimum size of squares, the most descriptive physiographic parameters, etc. Once this has been done, then data for the whole Province could be coded on a grid square basis from which data on any basin could readily be extracted for further studies. The grid square approach would seem to be very valuable, at the very least as a method of storing data.

Research and development on modelling techniques should also continue. Modelling techniques will give an insight into physical behaviour of runoff and can be used for determining the pattern of flows. Also, the modelling technique can be used for the derivation of design floods for major structures, should such be required.

With the speed at which hydrology is developing, continuing research and development into techniques for analyzing data is an integral part of a hydrologic data gathering program. Techniques are continually being developed, but usually such techniques are not immediately transferable to other areas. In order to make the best use of new techniques, it is considered essential to maintain a pool of skilled hydrologists in British Columbia continually analysing, interpolating, extrapolating and researching the hydrology of British Columbia.

4.12 IMPLICATIONS FOR NETWORK DESIGN

The techniques for regionalizing streamflow data, which are considered to have the greatest long-term potential, are the regression study using a computerized grid square and the modelling techniques. Since both methods require meteorological input, a comprehensive approach to data collection is considered most important. It is therefore recommended that the planning of meteorologic, snow-survey and hydrometric networks be closely coordinated.

In addition to the general need for coordination between the various types of hydrological data gathering networks, it is considered worthwhile to establish test or research basins in order to provide reliable data for checking the various aspects of the grid square and modelling techniques. Some general suggestions for research type basins are presented in Section 9.

In general, for the application of modelling techniques, data is required from streams with natural flow regimes or streams for which modifications to actual flow conditions can be accounted for. In particular, it was suggested in Sub-section 4.08 that stockastic techniques offer great promise for the future. However, to apply these techniques, it is essential to be able to separate out long-term trends in streamflow data which have been subjected to modifications, such as an increast in water diversions for irrigation purposes. Considerable effort will be required to account for diversions or other interference with natural flow conditions if data from modified regime streams is to be useful for application of stochastic and even other techniques.

The importance of regionalizing techniques as an integral part of the network design and planning has been stressed. It can be seen, therefore, that a regional hydrometric network must be compatible with these techniques. In particular, at least during the early stages of development, a proposed network should be sufficiently flexible so as to be able to adapt itself to new techniques or, in turn, provide the data necessary for the development of these techniques.

Section 4 had dealt almost exclusively with techniques for regionalizing streamflow data. Although such techniques may ultimately be used to delineate hydrologically homogeneous zones, no specific methods which could be applied immediately for this purpose have been mentioned. The main reason is that there are no known analytic techniques for automatically outlining hydrologic zones. In addition, even if there were, there is insufficient data available in most of British Columbia to apply such techniques. Moreover, to some extent, the zones will be dependent on the computational system adopted and it will only be possible to accurately outline given "statistical" zone boundaries after a system has been selected, assuming adequate data is available. Hence, for this study, the general application of techniques outlined in this section for design of hydrometric network has not been pursued.

In spite of the limited amount of available hydrometric data, however, it is still possible to delineate a flexible set of meaningful hydrologic zones for British Columbia where topography plays a dominant role in determining hydrologic variations. The zones presented in this report have thus been outlined on the basis of a detailed study of physiographic, climatic, streamflow and other pertinent information and are thus classed as "physically" rather than "statistically" homogeneous zones. The actual selection of the zones is described in Section 5.

SECTION 5

SECTION 5

HYDROLOGIC ZONES

5.01 DEFINITION

The assessment and application of techniques for delineating zones of hydrologic homogeneity is an important objective of the study and it is therefore necessary to distinguish between two working definitions of hydrologic homogeneity. In this study, hydrologic zones have been termed either "physically homogeneous" or "statistically homogeneous."

(a) Physically Homogeneous Zone

A "physically homogeneous zone" is defined as an area within which all parts have a generally uniform topography, geology and vegetative cover and are subject to similar climatic variations. The water yields in the various parts of the zone need not be uniform but the hydrograph characteristics of runoff must be sufficiently similar so that it will be possible to reconstruct, to an acceptable degree of accuracy, the actual flows at any given point from observed flows at another point, once a correlation between the flows at the two points is established.

(b) Statistically Homogeneous Zone

A "statistically homogeneous zone" is defined as an area within which it is possible to relate, to an acceptable degree of accuracy, the frequency characteristics (mean, coefficient of variation and coefficient of skewness) of any component of the streamflow hydrograph (such as annual runoff, peak flow, low flow) to physiographic and climatic parameters by means of a set of equations or a "computational model." The topography, geology, vegetation and precipitation intensity need not be similar providing that the significant parameters which affect the runoff characteristics can be assigned numerical values and used successfully in the computational model to explain variations from point to point within the zone.

5.02 DELINEATION OF ZONES

As indicated in Section 4, there are no knwon techniques for automatically outlining hydrologic zones, and techniques for regionalizing data which do exist require adequate data before they can be realistically applied. In British Columbia which has a relatively sparse network of hydrometric and meteorologic stations, it would be difficult to use statistical techniques for evaluating hydrologic zone boundaries in all but a very few areas. Moreover, the pilot regression study in the East Kootenay area (described in Section 7) has indicated that, even in the more intensively gauged area of British Columbia, the available data is generally inadequate for successful application or development of regionalizing techniques. The implications of the results of the pilot studies for delineation of hydrologic zones are discussed in Sub-section 5.09.

On the other hand, topography plays a very important role in the climatic and hydrologic regimes of the Province and it is still possible to delineate probable boundaries for the physically homogeneous zones as defined above chiefly on the basis of a study of physiographic, climatic and streamflow patterns. River basins within zones defined in this manner could be expected to be subject to similar climatic and hence hydrologic variations. However, until the boundaries of these zones can be checked by statistical or mathematical techniques, it is unrealistic to assign to them the term homogeneous either in the physical or statistical sense. Thus, the zones which have been developed during the course of the present study and which are presented in this report will be referred to simply as hydrologic zones.

It follows from the second definition of hydrologic homogeneity that the delineation of boundaries for the statistically homogeneous zones will have to await the results of future studies which in turn will be dependent upon the availability of data. It will be important to keep in mind that these boundaries will probably vary with the runoff characteristics being examined and also with the sophistication of the computational model.

Plate 1 presents a map of British Columbia showing the 29 Hydrologic Zones which have been delineated as a result of the investigations carried out during the course of this study.

These zones have been selected on the basis of the information described in the following pages. To summarize, the first and perhaps most important step was the division of the Province into physiographic zones as based on a study of topographic maps. Secondly, the climatic zones were delineated after a detailed study of climatic maps, principally maps of precipitation and temperature patterns plus maps of climatic regions as defined by other investigators and of climatic data such as index precipitation graphs. Thirdly, maps showing patterns of mean annual, peak and low streamflows were developed as part of the study program.

A simultaneous comparison of these three fundamental factors plus a consideration of geologic, vegetative and soil characteristics led to the selection of the Hydrologic Zones. Wherever possible, the zone boundaries have been drawn to follow drainage basin limits. This procedure was followed in order to facilitate network planning and to produce a practical unit for analysis and a workable unit for a program of network development and implementation.

A detailed discussion of the individual hydrologic zones is given in Sub-section 5.08 following the outline of background information on physiography, climate and streamflow. In addition, Table I-0 in Appendix I presents a list of the approximate areas of each of the 29 zones.

5.03 PHYSIOGRAPHY

5.03.01 General

The following information has been extracted from the British Columbia Atlas of Resources (1956) and presents a general picture of the areas occupied by the more important physiographic features of the Province.

5.03.02 Land and Water Coverage

(a) The total area of British Columbia is approximately 366,000 square miles.

(b) Rock and Barren: 124.2 million acres - approximately 54 percent of British Columbia, consisting of alpine barren, snowfields, glaciers.

(c) Forest Land: 90.5 million acres - approximately 39 percent of British Columbia.

(d) Arable and Grazing: 10 million acres - approaching 5 percent of British Columbia.

(e) Water: 4.5 million acres - about 2 percent of British Columbia consisting of fresh water lakes and rivers (excludes swamps).

5.03.03 (a) Major Rivers

The following river data refers to that part of the watershed lying within British Columbia.

Name	Area Square Miles	Length Miles
Fraser	89,310	850
Liard	55,374	300
Peace	49,595	175
Columbia	39,770	466
Skeena	21,038	360
Stikine	19,445	335
Nass	8,046	235

(b) Lakes

Nechako reservoir	340 (approximate flooded area only)
Atlin (in B. C.)	217
Babine	186
Kootenay	158
Stuart	139
Okanagan	136
Shuswap	123
Takla	102
Quesnel	100
Francois	91

5.04 TOPOGRAPHY

5.04.01 General

British Columbia is essentially a mountainous province. It forms part of that great group of mountain systems known as the American Cordillera which extends in an unbroken line along the western margins of the two American continents.

Three basic units comprise the Cordillera in British Columbia (see Plate 2) - a Coastal System comprised of a northward trending group of mainland and insular mountains; an Interior System of scattered plateaus and mountains in the central portion of the Province; and an Eastern System of northwestward trending mountains. The northeast corner of British Columbia extends beyond the Cordillera to include a small portion of the Great Plains.

5.04.02 The Coastal System

The Coastal System forms a belt of mountainous country which averages about 200 miles wide and extends for about 1,000 miles from the 49th to the 60th parallel. It may be divided longitudinally into three parts - Coast Mountains, an Outer Mountain Area, and a Coastal Trough lying between them.

The Coast Mountains are exceedingly rugged. They are deeply indented by a maze of fiord channels and are broken at intervals by great canyon type valleys such as those of the Fraser, Stikine and Skeena Rivers. In the south the highest peaks reach elevations of 8,000 to 9,000 feet; around Chilko Lake, between about latitude 50.5° and 52° north, they exceed 10,000 feet. Further north, near Eutsuk and Whitesail Lakes, the maximum height is 7,500 feet. North of 55° latitude, peaks again reach elevations between 8,000 and 10,000 feet and are covered by extensive glaciers and snowfields. Mount Waddington is the highest peak with an elevation of 13,260 feet.

5.04.03 The Interior System

(a) Southern Plateau Area (South and Central Interior)

The Southern Plateau is only 30 to 40 miles wide in the south and broadens northward to about 200 miles between the great bend of the Fraser River and the Coast Mountains. The surface is essentially a rolling upland mantled with glacial deposits and deeply incised by the major rivers. The plateau is high in the south, standing between 4,000 and 6,000 feet, but elevations decrease northward to between 2,000 and 4,000 feet in the vicinity of the Nechako River. In many places, isolated mountains or small ranges of mountains, some of which are volcanic in origin, form prominent features on the upland surface.

(b) Northern Plateau Area (North Interior)

The Northern Plateau Area is an extension of a great belt of plateau country spreading through the Yukon Territory and Alaska and reaching southeastward to the headwaters of the

Stikine River in the vicinity of latitude 57° north. The degree of dissection by streams is less advanced than in the southern plateau and extensive plateau surfaces stand as tablelands, separated by the broad, deep valleys of the major rivers.

The fairly uniform ranges of the Skeena, Omineca and Cassiar Mountains dominate the remainder of the northern interior.

5.04.04 The Eastern System

(a) Rocky Mountains

The Rocky Mountains form the most eastern part of the Cordillera in British Columbia. In the vicinity of the Peace River, summit elevations are moderate, averaging 4,000 to 6,000 feet but in the north and to the south, along the inter-provincial boundary with Alberta, they are high and rugged, with peaks exceeding 10,000 feet. Mount Robson is the highest of these with an elevation of 12,972 feet.

The Rocky Mountains slope abruptly to the Rocky Mountain Trench, a great trough which lies between 2,000 and 4,000 feet in elevation and extends almost the entire length of the Province. The Trench is occupied by parts of three great river systems: the Columbia River, the Fraser River, and the Peace and Liard Rivers draining to the MacKenzie River.

(b) Columbia Mountains

The Columbia Mountains, located in southeastern British Columbia, are very rugged and exhibit the usual shapes associated with alpine glaciation. Large areas lie above 6,000 feet and there are several peaks above 10,000 feet. Mount Sir Wilfred Laurier is the highest peak with an elevation of 11,750 feet.

5.04.05 Geology

The geology of British Columbia is extremely complex, and a detailed description will not be attempted. Map 932A published by the Geological Survey at a scale of 20 miles to the inch provides an overall picture of the geology of British Columbia. A simplified version of this map appears in the British Columbia Resources Atlas.

Briefly, the Coast Mountains are composed of great masses of intrusive rocks, principally granite.

The Interior Plateau is composed mostly of volcanic rocks although there are extensive areas of metamorphosed and sedimentary rocks. The whole region has been heavily glaciated, and legacies of the ice age, such as uneven layers of till, lake silts, ridges of gravel, and scoured bedrock knolls, are in evidence everywhere. The plateau is considerably dissected.

Considerable areas of the Columbia Mountains consist of batholithic intrusive rocks in addition to highly metamorphosed sedimentary rocks.

The Rocky Mountains are composed almost entirely of stratified sedimentary rocks.

The northeast interior plains area at the northeast corner of the Province is composed mainly of sedimentary sandstones and shales.

Most of the valleys in the Province are underlain by glacial deposits. The southern portion of the Rocky Mountain Trench with a valley floor from one to three miles wide is composed of deep layers of glacial till.

5.04.06 Soils

The soils of British Columbia are as varied as its terrain and are closely connected to the climatic and vegetative complexes. They include brown grasslands soils developed under less than 10 inches annual precipitation and strongly leached soils developed under dense forest and 150 inches of precipitation. The British Columbia Resources Atlas contains a generalized soil map of the Province. This information on soils is mainly useful insofar as it reflects or confirms the climatic zone boundaries.

5.04.07 Vegetation

Vegetation in general is a direct reflection of climatic and altitudinal variations as demonstrated by the map of Biotic Regions included in the British Columbia Resources Atlas.

Fairly dense forest covers the coastal and eastern mountains. The tree line is about 4,500 feet in the Coast Mountains but extends to between 5,000 and 7,500 feet in Columbia and Rocky Mountains. Alpine vegetation grows above the tree line. In the higher mountain ranges, perennial snow caps the higher peaks. In the Interior Plateau south of about latitude 55° north, dry forest predominates with grassland up to about 3,000 feet elevation with mixed open forest and grassland at higher elevations. North of latitude 55°, the interior region is mostly covered by Boreal Forest.

The Northeast Interior Plains gives way to the open grassland or parkland vegetation of the plains.

5.05 CLIMATE

5.05.01 General

In a mountainous region such as British Columbia, the climatic factors which are directly connected with hydrology are precipitation and temperature and important variations occur vertically as well as horizontally. As a natural consequence of the lower temperatures experienced in a mountain climate, practically all precipitation during the winter falls in the form of snow. The accumulation of winter snow is acted upon by rapidly rising spring temperatures to produce the annual spring runoff. Runoff produced from snowmelt represents a major portion of the total annual runoff in most areas of the Province. The major factors influencing climate are:

(a) the proximity of the Pacific Ocean to the west of the Province,

(b) the location of the Province directly in the path of the westerly winds which prevail in the middle latitudes,

(c) the movement and positioning of the air masses,

(d) the physiography of the Canadian Cordillera.

5.05.02 Atmospheric Controls

Two of the most important atmospheric controls are the location of a semi-permanent anti-cyclone over the northeastern Pacific Ocean and the semi-permanent low pressure area in the vicinity of the Aleutian Islands. During the late spring the Pacific High migrates northward, diverting the storm track to higher and higher latitudes. It reaches its maximum development in July and August and then recedes southward permitting more numerous and more active disturbances to batter the coast at increasingly lower latitudes. This produces a very wet winter season, particularly along the Coastal Mountains. The Aleutian low favours generation of low pressure areas which drift eastward over British Columbia on a path which is generally determined by the location of the Pacific high pressure area.

In the winter, continental Arctic air occasionally spills over the Rocky Mountain barrier and moves southwesterly across a large portion of the Province to produce the coldest winter temperatures. The summer climate in the interior of the Province is often influenced by invasions of hot, dry continental tropical air from the arid western plains of the U. S. A.

5.05.03 Influence of Topography

The mountainous character of British Columbia is one of the predominant factors causing precipitation and affects distribution, intensity and whether it falls in the form of snow or rain. The nature of the country, whether steep, bare rock, or forest covered rolling plateau, affects the quantity of runoff and altitude, because of its relation to temperature, determines the principal feature of basin runoff, namely spring floods derived from melting snow.

5.05.04 Precipitation

The precipitation in British Columbia is influenced by three important topographical features:

(a) the Coast Mountains which form a bastion against the westerly moisture laden winds and the wall which prevents the dissipation of cold air from its northerly source,

(b) the Eastern Mountains which present a second face to the westerlies and form a rampart which delays the spread of continental polar air,

(c) the Interior Plateau which is situated in the lee of the Coast Mountains.

Plate 4 shows the isohyetal lines of mean annual precipitation for British Columbia. This map has been developed using all available sources of information including a Canada land inventory map which has not yet been published. It was checked against the 10 year average runoff data which has been produced by this study to verify precipitation values in the high yield areas and in more northern areas.

In general, the moist westerly winds from the Pacific Ocean are forced upwards over the western slopes of the Coastal Mountains producing extremely heavy precipitation which exceeds 150 inches over many areas of the higher peaks. East of the Coast Mountains the air descends to the Interior Plateau, is compressed and clouds are dissipated. In the southern interior precipitation amounts decrease to under 20 inches. The main effect of the Coast Mountains in the interior, therefore, is to create an extensive rain shadow over the Interior Plateau which extends eastwards to the Eastern Mountains. These mountains again induce a marked increase in precipitation up to an annual maximum of over 60 inches in the higher parts of the Cariboo Mountains and in the Selkirk Mountains. The Rocky Mountain Trench in the southern portion of the Province lies in a rain shadow of the higher Columbia Mountains and precipitation decreases to less than 20 inches in the Trench Valley itself. As the air is lifted over the Rocky Mountains, precipitation increases to over 40 inches in the south and over 60 inches between latitudes 51° north and 56° north. Over the northern interior of the Province the Coast Mountains still present an effective barrier but precipitation is more uniform and slightly higher than in the south.

In his report on a Synoptic Climatology for Parts of the Western Cordillera, E. R. Walker concluded that over the province of British Columbia a major portion of the precipitation occurred with a westerly or south-westerly circulation. He also concluded that, in general terms, in summer the level of maximum precipitation is probably about 6,000 feet on the southern coast of British Columbia. In the southern interior summer precipitation reaches a maximum at 7,000 feet. On the northern British Columbia coast the summer level of maximum precipitation is perhaps 4,000 feet. In the northern interior the altitude of maximum summer precipitation is 6,000 feet. In the winter the levels are estimated at 4,000 feet in coastal regions and 5,000 feet in the interior of the Province. Over the season, the altitudes above sea level of maximum precipitation might be 4,000 feet in coastal regions and 6,000 feet over the interior. There should be a north-south gradient with lower heights in the north. These values are highly idealized and local variations are to be expected.

5.05.05 Temperature

Temperature in combination with precipitation is a major climatic factor which affects the hydrology of the Province particularly in connection with spring runoff and summer evaporation. The temperature in a general fashion depends on altitude and latitude. Latitude, however, is not an effective control of temperature in British Columbia as a whole, although considerable latitudinal extent results from the significant variation in day length. Altitude, on the other hand, is a much more significant control and the rate of change of temperature with increasing altitude has a climatological value of great importance in British Columbia. Unfortunately, it is frequently not adequate to assume the standard lapse rate of about 3.3° F per thousand feet since the pronounced concave form of many valleys and basins may lead to inversions of sufficient permanence to influence the climatological characteristics.

The principal air masses which influence the Province are the maritime and continental arctic, the maritime polar and the continental tropical air masses. Arctic air originates over ice covered arctic regions. The Maritime arctic air which follows a short trajectory over open water, normally occupies much of the Province in the winter, but the dry continental variety on occasion overrides the Rocky Mountain barrier to the east and invades the interior plateau and occasionally the coast. Maritime polar air, although it has the same source as arctic air, is distinctly warmer and moister than the arctic air since it penetrates further south and has a longer trajectory and sojourn over the Pacific Ocean. In winter Maritime polar air is comparatively mild and humid. Continental tropical air comes from the hot arid deserts of the western U. S. A. This typically hot and dry air mass sometimes invades the south of British Columbia in summer and produces the hottest spells of weather.

The moderating influence of the ocean is greatest in mid-winter and mid-summer. Mild winters extend far up the coast but rapidly become more severe as the land mass is penetrated. In the summer temperatures along the coast are relatively cooler than in the interior with its hot dry climate.

5.06 CLIMATIC ZONES

5.06.01 General

The chief physiographic features of British Columbia have a general northwest-southeast trend, approximately at right angles to the prevailing warm, moisture-laden westerly winds. The resulting distinct climatic regions form the basis for a discussion of variations in climate within the Province. Plate 3 presents the Climatic Zones selected after comparison with those drawn by Kendrew and Kerr (1965) and Powell (1965) plus a detailed examination of climatic maps of precipitation and temperature variations (Canada Land Inventory maps) and index precipitation graphs.

Plate 9 presents selected index precipitation graphs representative of the precipitation patterns in the various climatic zones. These index precipitation graphs were developed from mean precipitation values for the 253 stations published in the Meteorological Branch Circular CDS No. 8-65. This circular presents monthly and annual normals of rainfall, snowfall and total precipitation for all stations with an appreciable length of record in the Province over the period 1931 - 1960. As these graphs were used to depict precipitation distribution patterns rather than absolute values, this readily available information is of sufficient accuracy for this purpose. The index precipitation graphs show the ratios of monthly to annual precipitation as a percentage. There are only five stations available for Zones VII, IX and X in the northern part of the Province so no valid comparisons are possible. However, the graphs which seem most appropriate have been selected for demonstration. Index precipitation graph data for the 253 stations examined are shown in Table I-1 of Appendix I.

5.06.02 Zone I: Littoral

The outstanding features of the Littoral region with its marine climate include the very heavy precipitation with a winter half year maximum and a small annual range of temperature along the coast, and increasing extremes of temperature at higher elevations in the mountains.

The index precipitation graphs for Stewart, Bella Coola, 52° 23' north, 126° 36' west and Vancouver show the winter maximum advancing from October in the north to December in the south in accordance with the fall retreat of the Pacific High and the southward migration of the storm track. The spring and summer seasons are relatively dry.

5.06.03 Zone II: Southwest Interior

The Southwest Interior region has a continental climate and includes the driest and hottest parts of the Province (see also the description of

Zone V). Lying in the rain shadow of the Coast Mountains, annual precipitation is generally less than 20 inches and in the particularly well protected Thompson Valley in the Kamloops-Ashcroft-Merritt loop, less than 10 inches. The index precipitation graph for Kamloops is representative of most of the area, showing the relatively even distribution between winter and summer with a minimum in the spring. The marked monthly variations are typical of low precipitation totals. The June peak is apparently related to an abrupt change in position in July of the Pacific anticyclone and is noticeable over most of the southern interior.

Long hours of summer sunshine, combined with hot air from the interior of the States of Washington and Oregon in the U. S. A., lead to high summer temperatures, especially in the confined valleys. The combination of high temperatures and low precipitation creates semi-arid conditions which require irrigation for most types of agriculture. The annual temperature range is greater than on the coast.

5.06.04 Zone III: Southeast Wet Interior

The Southeast Interior region has been sub-divided into two sections labelled with the relative terms wet and dry. The Southeast Wet Interior is composed of the Columbia Mountain System with its high mountain ranges and assortment of relatively large lakes such as the Quesnel, Shuswap, Arrow, and Kootenay Lakes. It is a region of high annual precipitation with marked differences in climatic characteristics between valley and mountain locations.

The valleys are generally drier than the mountains, and this difference increases towards the south of the region where valley conditions border on semi-arid. Similarly, summer heat and length of frostless season are greatest in the south valleys and least towards the north. The high annual precipitation and heavy snowfalls are the most distinctive feature of the mountains.

The index precipitation graph for Revelstoke is typical of the annual distribution over most of the zone. The winter half-year maximum is greater in the mountains than in the valleys but the spring minimum and June peak are common to both areas.

5.06 05 Zone IV: Southeast Dry Interior

The Southeast Dry Interior region is characterized by the Rocky Mountain Trench which, lying in the lee of the Columbia Mountains, receives a low annual precipitation decreasing to less than 20 inches in the southern half. Precipitation increases again up the western slopes of the Rocky Mountains to over 40 inches in the south and 60 inches in the north.

The index precipitation graph for Cranbrook is representative of conditions in the Trench. The winter and summer distribution is perhaps more evenly balanced than in Zone III but the pattern is quite similar.

The climate tends to be a little more continental in temperature than further west.

5.06 06 Zone V: Central Interior West

The climate of the Central Interior West region is similar in many respects to that of the Southwest Interior (Zone II). It has been separated mainly because the climate and topography are more uniform than in the south.

Most of the zone lies in the rain shadow of the coast mountains. Annual precipitation averages generally less than 20 inches and in the lower Chilcotin and Fraser river valleys, less than 10 inches.

The index precipitation graph for Quesnel is fairly typical of the distribution pattern in the zone. Summer and winter precipitation are more or less evenly distributed with summer precipitation being more variable as would be expected.

Summers are short and much cooler than in the south since the tropical air from the U. S. A. rarely makes its way into the North.

5.06.07 Zone VI: Central Interior East

The Central Interior East region is in some ways really an extension of Zone III. It is characterized by a much higher precipitation than the central interior plateau to the west, with values exceeding 50 inches over the mountains in the southern and eastern parts of the zone.

The index precipitation graph for McBride (53^{o} 18' north, 120^{o} 10' west) portrays the pattern in the Rocky Mountain Trench. The winter precipitation is slightly greater than the summer precipitation and the monthly variation is much less marked than that over the central plateau.

The climate is more continental than in the western part of Zone V.

5.06.08 Zone VII: North Interior

The North Interior region constitutes a very large area with very little climatic data. Generally, the winters are long and cold and the summers, short and cool.

The precipitation would appear to be fairly evenly distributed over the area with a local maximum on the west slope of the Rocky Mountains which form the eastern boundary of the zone.

The index precipitation graph for Germansen Landing (55° 47' north, 124° 42' west) probably gives a reasonable picture of the annual distribution over the zone. Winter and summer precipitation is more or less evenly distributed and the spring minimum is typical of the interior of the Province.

5.06.09 Zone VIII: Northeast Interior

The Northeast Interior region covers the interior plains which are separated from the rest of the Province by the Rocky Mountains. Although in similar latitudes to zones to the west, it has more extreme temperature conditions owing to this effective protection from maritime influences. The winters are the coldest in the Province but the summers are reasonably hot.

Annual precipitation is generally less than 20 inches to the east of the Rocky Mountain foothills. The index precipitation graph for Fort St. John is typical, showing a very even distribution from September to May with a pronounced summer maximum. The winters are relatively dry because of the low moisture content of the arctic air which covers the zone during this period.

5.06.10 Zone IX: Yukon Plateau

The Yukon Plateau region is composed of the extension of the Yukon Plateau into northwestern British Columbia. It lies directly in the rain shadow of the coast mountains and its central portion receives less than 15 inches precipitation in some areas.

The index precipitation graph for Atlin, the only station within the zone, shows a high winter precipitation characteristic of the coast zone. On the other hand, a relatively high percentage of the annual precipitation occurs in the summer, a feature more characteristic of interior regions.

5.06.11 Zone X: Liard Plain

The Liard Plain region which extends into the Yukon, has a much more continental climate than that of Zone IX immediately to the west.

The index precipitation graph for Smith River (59° 54' north, 126° 26' west) indicates that the climate of this zone is much more similar to that experienced in the northeast plains (Zone VIII) where there is a pronounced summer peak of precipitation.

Topographically, this zone is distinct from Zone VII to the south.

5.07 RUNOFF DISTRIBUTION

5.07.01 General

In order to evaluate the distribution patterns of runoff over the Province with respect to annual, peak and low flows, maps of these three streamflow components were prepared. The data upon which these maps are based are included in Appendix I in Tables I-2, I-3, I-4 and I-5.

It will be seen that the distribution of both peak and low flows corresponds very closely with the pattern of mean annual flows. This phenomenon is not too surprising and emphasizes the overriding influence of topography on precipitation, temperature and thus on all phases of runoff. It may thus be possible to sample average, peak and low flows with the same basic network, admitting, of course, the importance of supplementary measurements of peak flows and low flows.

5.07.02 Annual Runoff

Plate 5 shows the distribution of mean annual runoff in inches in British Columbia representative of the 10 year period from October 1956 to September 1966. This 10 year period was chosen in order to use the maximum number of stations possible and still have a reasonably good picture of average flows. Hydrometric records from a total of 109 stations were used in the analysis. In addition, streamflow data was obtained by subtraction of flows between stations where possible. All existing stations with eight or more years of record in the 10 year period were included. These records were adjusted to the base period using standard techniques.

To obtain a more detailed pattern of the areal variations in annual flow, particularly on the coast, in the central interior and in northern British Columbia, average runoff values for the water year 1965 - 1966 were computed for all available stations. In general, the pattern of annual flow values for the 1965-66 water year compares quite closely with the 10 year mean flow map. For this reason, a map for the 1965-66 flows has not been included in the report. Instead, the 10 year mean runoff map has been modified in those areas, particularly on the coast and in the central interior, where it appears fairly certain that the 1965-66 values are representative of the 10 year means. Most of the coastal area is ungauged and the ungauged areas have been left blank on the map in Plate 5.

5.07.03 Peak Runoff

The highest mean daily flow at the peak of the 1964 spring-summer runoff was used to study the variation of flood flows across the Province. In most of the medium and larger sized basins, the flood peak occurs from snowmelt alone or from a combination of snowmelt and rainfall. In some of the smaller basins, peak flows may be produced by rainfall after all snow has melted.

Plate 6 presents the pattern of peak flows in cfs per square mile for the small and medium size basins. Data for downstream stations on the larger rivers is not included on the map since the object of the map is to portray local patterns and large river stations integrate the runoff from too large an area to be meaningful.

5.07.04 March Runoff

The mean flow for the month of March, 1964, was chosen to depict the low flow regime of the Province. Runoff during March is usually at a minimum and should be most representative of the groundwater contribution to streamflow.

Plate 7 presents the pattern of March 1964 flows in cfs per square mile for the small and medium size basins.

5.08 DESCRIPTION OF HYDROLOGIC ZONES

5.08.01 General

As described earlier in Section 5.02, the Hydrologic Zones outlined on Plate 1 adhere in many respects to the definition of physical homogeneity. A comparison of Plate 1 with the physiographic zone map shown on Plate 2 and the climatic zone map shown on Plate 3 clearly indicate this point. The runoff maps shown in Plates 5, 6 and 7 reflect strongly the physiographic variations but have provided valuable information for a further breakdown of zones in areas of apparent topographic uniformity. The available information on vegetation and soil patterns is very general. These two elements are so closely related to topographic and climatic variations that information concerning their distribution is in many ways of marginal use in delineating hydrologic zone boundaries. However, the vegetation and soil patterns lend support to the climatic zone boundaries. Information on geology is quite difficult to incorporate into the delineation of hydrologic zones. In addition to the complexity of geologic variations in British Columbia, the problem of assessing the hydrologic or water bearing properties of the different types of rock has not been resolved.

A consideration of geologic patterns in British Columbia is perhaps more pertinent to the selection of representative basins and research basins, particularly with respect to low flows.

Topographic maps of the individual hydrologic zones at the scale of 16 miles to the inch are presented in Plates 81 to 116. Zone 2 is shown on Plate 82 at a larger scale, 8 miles to the inch, because of its relatively small size. In some cases, the larger zones which will not fit onto a single sheet have been divided into two or three sections in order to adhere to a single map scale.

In order to portray typical runoff patterns, representative index hydrographs for each zone are also shown in Plates 81 to 116. Most of these index hydrographs were developed from the same 10 year runoff records used to produce the mean annual runoff map shown on plate 5. The ratios of monthly average, low and high runoff to mean annual runoff as a percentage for the 10 year period are presented. For several zones, less than 10 years data was available for streams within the zone. In this case, only the graphs for average flows are shown to at least indicate the general runoff patterns. Index hydrograph data for the average monthly runoff at the 124 stations examined are shown in Table I-6 of Appendix I.

The effect on precipitation and runoff of the almost perpendicular orientation of the northwest-southeast trending mountain chains to the westerly atmospheric circulation which produces a large percentage of the annual precipitation is clearly reflected in the selection of the hydrologic zones. In general, the zone pattern parallels the mountain structure orientation and zone boundaries tend to follow major topographical boundaries.

A detailed description of the zone pattern and of the individual zones is contained in the following sections.

5.08.02. Coastal Area

(a) General

The coastal area which includes the offshore islands is characterized by rugged inaccessible mountains with a high precipitation and correspondingly high runoff. The eastern boundary follows the divide of the Coast Mountains which effectively isolates the interior of the Province from the maritime influence of the Pacific Ocean. There are two distinct runoff regimes in this area. In the first regime, streams draining low elevations have runoff which is in phase with the precipitation, which means that runoff has a winter maximum and a summer minimum. In the second regime higher elevation streams have distribution patterns typical of snowmelt regimes where flow during the winter is relatively low and there is a late spring and summer snowmelt runoff peak.

(b) Zone 1: Vancouver Island

The Vancouver Island zone comprises the natural physiographic units of Vancouver Island (see Plate 81). The island is characterized by a ridge of mountains along its axis in which some of the peaks rise from sea level to over 7,000 feet. The island has been divided into two sub-zones separating streams flowing to the east coast from those flowing westward to the Pacific Ocean. Most of the streams drain relatively small areas and have very high yield which exceeds 100 inches in many basins. Runoff at the lower elevations is depicted by the index hydrograph for the Sarita River in the Southwest corner of the Island. It is generally in phase with precipitation indicating that most of the precipitation at lower levels occurs as rain throughout the winter.

(c) Zone 2: The Lower Fraser Valley

The Lower Fraser Valley zone, separated because of its unique characteristics, is made up of the flat alluvial plain of the Fraser River (see Plate 82). South of the Fraser River streams are small and meandering. Precipitation amounts increase northwards and eastwards along the valley and runoff is generally in phase with the precipitation as indicated by the index hydrograph for Mahood Creek where there is a winter maximum and summer minimum. Streams flowing into the Fraser from the north drain the mountainous area and the hydrographs have entirely different characteristics from those of streams south of the Fraser.

(d) Zone 3: Coastal Mountains

The Coastal Mountains region extends from north of the Lower Fraser Valley northward to the Portland Canal which forms the boundary between British Columbia and the Alaska Panhandle (see Plates 83, 84 and 85). This zone is characterized by the steep west-facing slopes of the Coast Mountains and its streams, which drain high elevations, are fed by permanent glaciers and have an extremely high yield exceeding 100 inches in many parts of the zone. Another characteristic of the coastal area is the maze of fiord channels which penetrate deeply into the Coast Mountains. As a result, on the western facing slopes of these mountains, most of the streams drain fairly small areas that are oriented in a general north-south or east-west direction as they flow into the fiord channels, rather than flowing directly into the Pacific Ocean. For purposes of presentation, this zone has been subdivided into three sections. Since most of the coastal zone is presently ungauged, it is not possible at this time to further subdivide the area into meaningful hydrological zones. However, the three subdivisions for this extensive zone are useful for the purposes of network planning.

(e) Zone 29: Queen Charlotte Islands

The Queen Charlotte Islands region forms a distinct zone on the basis of being a group of islands (see Plate 116). The relief is generally low except for a few isolated mountain peaks with elevation between 3,000 and 4,000 feet. These islands receive heavy precipitation because of their proximity to the Coastal Mountains.

(f) Zone 28: Northern Coast

The Northern Coast region might properly be considered as an extension of Zone 3 to the south but is isolated by the intervention of the Alaska Panhandle (see Plate 115). It is characterized by high glacier covered mountains deeply incised by the relatively low and broad valley of the Alsek River which drains into the Pacific Ocean.

5.08.03 Lee Slopes of the Coast Mountains

(a) General

A narrow band of zones lies along the lee slopes of the Coast Mountains. This region is characterized by sharp topographic, climatic and hydrologic changes. The western boundary of this area follows the Coast Mountains Divide. The eastern boundary in the south is fairly well defined by the rather abrupt change from the flat interior plateau to the steep east facing slopes of the Coast Mountains. In the north where the topographic divisions are less distinct, the eastern boundary is somewhat arbitrary and is based mainly on runoff and precipitation characteristics.

In the area south of latitude 54^{o} north, the elevations drop thousands of feet within a relatively short distance from the mountain divide to the plateau. Precipitation decreases from over 100 inches at the higher elevations to nearly 20 inches on the Interior Plateau. Runoff or yield shows a correspondingly sharp decrease with decrease in elevation and, with the exception of Zone 4, the index hydrograph is typical of a mountainous region with its pronounced late spring snowmelt peaks and low winter flow.

(b) Zone 4: Fraser Canyon

The Fraser Canyon region lies in the lee of the southern end of the Coast Mountains and extends from the Canada-U. S. A. border northward to just south of Lillooet (see Plate 86). Its chief characteristic is the narrow Fraser Canyon bounded on the east and on the west by steep sided mountains. The western boundary follows the divide of the Coast Mountains while the eastern boundary begins in the south by following the divide of the Cascade Mountains and continues along the divide of the ridge of mountains which parallel the Fraser River. This zone has been separated because of the unique effect produced by the lower end of the zone being open to the Fraser Valley, and as a result moist Pacific air is funnelled up the valley along the Fraser Canyon producing much higher amounts of precipitation than are observed further north. The northern boundary marks the approximate northern limit of the influence of this funnel effect. Except for the area south of Hope, the streams have a general east-west orientation, drain small basins, and are very steep. Runoff generally exceeds 40 inches and is particularly high in those streams draining from the Coast Mountains.

The index hydrograph for the Coquihalla River near Hope shows the influence of the funnelling effect of precipitation. The spring runoff peak is typical of the snowmelt regime but the relatively high winter precipitation which is more typical of river in the lower Fraser Valley in the coastal area should be noted.

(c) Zone 5: Cascade Mountains

The Cascade Mountains region comprises the northern extension of the Cascade Mountains, and would be extended down into the State of Washington in the U. S. A. (see Plate 86). It is characterized by low mountains with elevations between 4,000 and 8,000 feet and forms an area distinctive from the plateau to the east and the rugged mountains of Zone 4 to the west. The eastern border of this zone follows the general boundary between the plateau and the Cascade Mountains. The streams drain in a northward direction with yields from over 20 inches at the higher elevations to about 5 inches near the plateau. This variation in yield reflects the fact that the zone lies in the lee of the coastal divide. The index hydrograph for the Ashnola River which drains the eastern portion of the zone indicates marked snowmelt regime with a pronounced spring runoff peak and extremely low runoff during the summer and winter periods.

(d) Zone 16: Eastern Slopes - Coast Mountains

(i) General

The Eastern slopes - Coast Mountains region form a single hydrologic zone, climatically and in terms of runoff yield and distribution. However, this zone can be conveniently divided into 3 sub-sections (see Plates 98 and 99).

North of latitude 55° north the relief in the interior changes from a plateau to a rough low mountain type of terrain. As a result, the eastern boundary lines of the zones on the east side of the Coast Mountains are much less distinct than they are in the south and are based on precipitation and runoff characteristics much more than on topographic divisions. These northern zones contain some extremely rugged terrain.

(ii) Sub-Zone 16A

The streams in Sub-Zone 16A drain eastward and northward into the Fraser River system. It is a very rugged area with the sharpest elevation change occurring near the eastern boundary which marks the division between the plateau to the east and the mountain slopes to the west. As this zone lies in the lee of some of the highest mountain peaks in the coast range, yields are moderate decreasing rapidly from over 30 inches at higher elevations to near 5 inches on the boundary bordering the interior plateau.

(iii) Sub-Zone 16B

The Sub-Zone 16B has been delineated to separate the number of streams which drain westward to the Pacific Ocean rather than draining eastward into the Interior Plateau. The eastern boundary marks the sharp change from the plateau to the mountain slopes except in the very northern end where it crosses the Dean River. Most of this region, as for Sub-Zone 16A to the south, lies in the lee of the highest elevations in the Coast Mountains. Precipitation and runoff in the southern half of the sub-zone are similar to that in Sub-Zone 16A. In the northern half the runoff is slightly higher because moist air is funnelled up the Bella Coola and Dean River valleys to give high precipitation.

(iv) Sub-Zone 16C

Streams in the Sub-Zone 16C also drain eastward into the Interior Plateau. This Sub-Zone is distinctive from Sub-Zones 16A and 16B, since it includes much more of the plateau region and is therefore much less rugged. In addition, it is characterized by several major lakes, namely the Eutsuk, Ootsa and Morice Lakes. The Coast Mountains to the west of this zone are much lower than they are to the south with peak elevations in the neighbourhood of about 7,000 feet. Precipitation and thus runoff are much higher than in the two sub-zones to the south.

(e) Zone 17: Nass-Skeena River Basins

The Nass-Skeena River Basins region has been selected as a separate zone because of its unique characteristics (see Plate 100). The Nass and Skeena Rivers drain a large area of the interior and then cut through the Coast Mountains in steep narrow valleys as they pour into the Pacific Ocean.

Zone 17 contains the lower reaches of the Nass and Skeena Rivers. The western boundary falls along the Coast Mountain Divide while the eastern boundary in the south separates the Interior Plateau from the Lower Skeena Basin and in the north follows a ridge separating the northwest-southeast oriented upper part of the Skeena River. This zone then includes the eastern slopes of the Coast Mountains in the west, the broad lower valleys of the Nass and Skeena Rivers in the centre and the western slopes of the Skeena Mountains in the east. These two main river valleys open directly to the Pacific Ocean and moist Pacific air is able to penetrate into the interior and produce relatively high precipitation over the headwater area in the eastern part of the zone. A combination of this high precipitation over the Skeena Mountains and glacier fed streams on the lee slopes of the Coast Mountains results in a moderate to high runoff yield over the entire basin. The runoff distribution in this zone as depicted by the index hydrograph on Plate 100 shows a late spring peak characteristic of the late snowmelt regime and a fall October maximum more characteristic of the Maritimes Coastal area.

(f) Zone 25: Lee Slopes - Northern Boundary Ranges

The Lee Slopes - Northern Boundary Range area (see Plates 111 and 112) is an elongated zone which comprises an extremely rugged mountainous area capped by extensive permanent snowfields and glaciers. The western boundary lies along the border between British Columbia and Alaska. The eastern boundary was more difficult to define. It has been drawn to separate the Yukon Plateau to the east from the high yield rugged mountain territory of this zone. Except for the major river valleys of the Stikine and Iskut Rivers in the south, most of the region is drained by small high elevation, high yield glacier fed streams.

5.08.04 Interior

(a) General

The wide interior region of British Columbia situated between the Coastal and Eastern Mountain Systems divides conveniently into northern and southern sections at about latitude 55° north.

The south interior is composed of the dry plateau country which falls within the rain shadow of the Coast Mountains. Precipitation in the southern region is more or less equally divided between winter and summer. During the summer, precipitation amounts are more variable than in the mountainous regions and evaporation is extremely high. As a result of the dry conditions experienced in the southern interior annual yields are extremely low averaging less than 5 inches over most of the region. A typical index hydrograph for the area exhibits a relatively sharp spring runoff peak from snowmelt and indicates that winter and summer runoff is more variable and represents a higher proportion of the annual runoff than in mountainous regions.

The north interior is a rough irregularly rolling upland with large areas exceeding 5,000 feet with isolated mountain peaks between 6,000 and 8,000 feet. Few of these peaks stand out conspicuously, either in height or shape. Precipitation over the northern interior is higher than in the south but annual totals are still relatively moderate since this area lies to the lee of the formidable Coast Mountains. In the extreme north the rough mountainous regions give way to the southern extension of the Yukon Plateau and the Liard Plains. Hydrometric as well as climatic records in northern British Columbia are extremely limited and most stations have only short period of record. Thus the index hydrographs shown on Plates for the related Hydrologic Zones portray only the average flow as calculated from the short periods of record and maximum and minimum variations are not indicated.

(b) Zone 6: Southwest Interior

The Southwest Interior region is essentially the same as Climatic Zone II. It comprises the southern portion of the Fraser Plateau which is characterized by gently undulating terrain with elevations varying between 4,000 and 6,000 feet (see Plate 87). The plateau has been carved into blocks by several glacial deepened valleys that descend as much as 2,500 to 3,000 feet below the upland surface. The region is dissected in the north by the Thompson River valley and in the east by the Okanagan River valley. Climatically, the region is characterized by relatively low precipitation and high summer evaporation. Consequently, runoff yields are very low, averaging less than 5 inches over almost the entire region. The index hydrograph of the Nicola River near Merritt is characteristic of most of the region which has a very low runoff for most of the year except for the spring peak created by runoff from snowmelt.

(c) Zone 15: Central Interior

The Central Interior region is characterized by a broad extensive plateau with elevations varying from 2,000 to 4,000 feet and some highlands between 4,000 and 6,000 feet in the central and southern part of the zone (see Plates 96 and 97). All streams in this area drain into the Fraser River which flows southward along the eastern edge of the zone. As this zone lies completely in the rain shadow of the Coast Mountains it has the lowest annual precipitation and yield of any area in the Province. The south-western portion is particularly dry. It should be noted that water from the Nechako River which drains the northwestern corner of the zone is diverted westward across the coast range to Kemano. A typical hydrograph for this region shows a pronounced spring snowmelt peak and a variable summer flow which reflects the variability of the summer precipitation in this zone.

(d) Zone 18: North Central Plateau

The North Central Plateau region comprises the northern end of the Interior Plateau (see Plate 101). This part of the plateau received a higher precipitation than the area to the south. This condition is caused by the uplifting of relatively moist air which is able to pass over the lower section of the Coast Mountains between latitudes 53° north and 55° north. The zone is characterized by several large lakes, including the Stewart, Takla and

Babine Lakes. The index hydrograph for the Stewart River shows the snowmelt runoff peak occurring in July. This is a result of the delaying effect on runoff of the Stewart Lake System.

(e) Zone 23: Omineca Mountains

The Omineca Mountains region delineated as Zone 23 and the North Central Uplands delineated as Zone 24, essentially form one more or less uniform topographic unit (see Plates 108, 109 and 110). The southern half of the western boundary of Zone 23 separates the mountainous area from the Central Plateau. The northern half of this boundary has been drawn mainly on the basis of drainage orientation considerations to separate east flowing from west flowing streams, the Findlay River being the one exception. The eastern boundary of Zone 23 is well defined and lies along the centre of the Rocky Mountain Trench. The smaller streams in this zone are generally oriented in an east-west direction and drain into the Peace River system with the exception of the extreme northern tip of the zone.

(f) Zone 24: North Central Uplands

The Northern Central Uplands region is similar in character to Zone 23 (see Plates 108, 109 and 110). The uplands are carved into blocks by a myriad of streams which seem to disregard normal topographic divides. This zone contains the headwaters of several major rivers, namely those of the Stikine, the Finlay and the Skeena Rivers. Average yield in both Zones 23 and 24 is in the order of 20 inches per year. A typical index hydrograph indicates a pronounced snowmelt peak in June and July with considerable variation in runoff pattern during the last 5 months of the year.

(g) Zone 26: Yukon Plateau

The Yukon Plateau region is reasonably well defined and is characterized by the relatively uniform terrain of the Yukon Plateau (see Plate 113). It lies in the rain shadow of the Coast Mountains and precipitation falls to less than 20 inches on the valley floors. Annual yield is correspondingly low in this plateau area compared with the surrounding regions. The eastern and southern boundaries mark the transition between the plateau and the surrounding mountains. The northern boundary is the border between the Yukon Territory and British Columbia. The index hydrograph for this zone is similar to those for Zones

23 and 24. The zone is also characterized in the northern half by drainage northward and several large lakes including Teslin and Talin Lakes and in the south by drainage of the headwaters of the Stikine River westward toward the Pacific Ocean.

(h) Zone 27: Liard Plain

The Liard Plain region is bounded on the north by the border between British Columbia and the Yukon Territory and is characterized by the Liard Plain at its centre surrounded by the Cassiar Mountains and Rocky Mountains to the west and south and by the Liard Plateau to the east (see Plate 114). The terrain slopes gradually from the southern perimeter where elevations exceed 7,000 feet to the central plain where elevation averages less than 3,000 feet. The zone is divided into two sections. In the eastern section streams draining from the Cassiar Mountains flow in a general northern direction whereas streams in the northeastern corner of the zone flow southward into the Liard River. Precipitation and runoff patterns in this zone are not too well defined. However, there are indications that, in general, runoff is lower than in the mountains to the south.

5.08.05 Columbia Mountains

(a) General

The Columbia Mountains region occupies a triangular area in the southeast of British Columbia with the apex near latitude 54^{o} north. This band of mountains forms a fairly broad zone which conveniently divides into two parts. The first division is the west-facing slopes which rise from the edge of the interior plateau to the divide of the Cariboo and Monashee Mountains. This area lies beyond the reach of the Coast Mountain rain shadow and both precipitation and runoff show an increase which corresponds with the increasing elevation. The second division is the central portion which is characterized by the higher elevations of these rugged mountains with high winter snowfall and many small permanent glaciers and snowfields. Streams draining this central mountainous area exhibit a very high annual yield and typical mountain snowmelt regime hydrograph with a pronounced summer maximum caused by the delayed melting of the high elevation snowfields.

(b) Zone 7: Southern Monashee Mountains

The Southern Monashee Mountains region includes the rugged highlands of the Southern Monashee Mountains with elevations varying between 2,000 and 8,000 feet (see Plate 88). It is characterized by several mountain ridges oriented in a north-south direction and divided by the fairly wide river valleys of the Kettle and Granby Rivers. The western boundary follows the divide separating the Okanagan and Kettle River Valleys. The eastern boundary has been drawn on the basis of topographic and runoff yield considerations. The northern boundary follows the natural divide between the Shuswap River which drains northward and the Kettle and Granby Rivers which drain southward. The runoff pattern reflects the increase in precipitation from the plateau to the west with yields varying from 5 inches in the western part of the zone to over 20 inches in the eastern and northern portions. The index hydrograph for the Kettle River is typical of the runoff pattern from the snowmelt regime in the low mountain area. It shows a pronounced spring snowmelt peak in May and June with a relatively low runoff during the rest of the year.

(c) Zone 11: South Thompson Area

The South Thompson Area region is characterized by the fact that it delineates only the upper drainage area of the South Thompson River. The basin is bowl shaped and opens directly onto the Thompson Plateau (see Plate 91). The western boundary of this zone delineates the topographic division between the Thompson Plateau and the foothills of the Monashee Mountains, and also separates the zone of very low yield to the west from the zone of increasing yield and increasing precipitation to the east. The eastern boundary of the zone is well defined and lies along the great divide of the Monashee Mountains. The northern boundary follows the divide between the Adams River and the North Thompson River and separates the more open south Thompson Valley from the more rugged and topographically uniform zone to the north. Elevations in the basin vary markedly dropping rapidly from the steep slopes of the Monashee Ridge where some peaks are over 8,000 feet elevation to the lower areas of the Shuswap Lakes where elevations are less than 2,000 feet. The runoff varies markedly in the basin, increasing from less than 10 inches per year near the plateau to over 50 inches per year along the ridge and the Monashee Mountains. The region is also characterized by several important lakes such as the Adams, Shuswap, Mabel and Sugar Lakes. The index hydrograph for the Shuswap River at Shuswap Falls shows the typical spring snowmelt peak of the Columbia Mountain region. It is interesting to note that the percentage of winter and autumn runoff is higher than that indicated by the index hydrograph for the Kettle River in the zone immediately to the south.

(d) Zone 13: Cariboo Mountains

The Cariboo Mountains region has a more uniform topographical variation than does Zone 11 to the south (see Plate 94).

From the western boundary, which separates the interior plateau from the Cariboo Mountain foothills, the terrain rises gradually over the western half of the zone and abruptly up the steep slopes of the Cariboo Mountains in the eastern half of the zone, and to the topographical divide. This zone is characterized by several lakes such as the Bowron, Quesnel, Horsefly, Hobson, Clearwater, Azure and Murtle Lakes. Steep high elevation streams draining the Cariboo Mountains have very high yields exceeding 50 inches per year. In the western half of the zone, yields decrease rapidly to near 5 inches per year along the western boundary. The hydrographs of streams draining the higher elevations are typical of a mountain snowmelt regime with a pronounced summer peak and a gradual decrease in runoff during the rest of the year.

(e) Zone 8: Kootenay Highlands

The Kootenay Highlands region is in effect an extension of Zone 10 to the north but has been separated because of significantly lower yield and lower average elevation (see Plate 88). It is characterized by uniform rugged highland with peak elevations varying between 6,000 and 8,000 feet. It is drained by the Kootenay and Slocan Rivers. The eastern boundary lies along the divide of the Purcell Mountains. Annual yields in this zone are moderate varying between about 25 and 40 inches. The runoff pattern is similar to that in Zone 7, as indicated by the index hydrograph for the Salmo River which is representative of the zone and indeed of most of the southern portion of the Columbia Mountains.

(f) Zone 10: Selkirk Mountains

The Selkirk Mountains region is characterized by uniformly steep rugged mountains which are drained by streams having a very high yield (see Plate 90). Most of the smaller streams in the northern two-thirds of the basin are fed by small permanent glaciers. The region is divided in the south by several ribbon like lakes, namely the Upper Arrow, Slocan, Duncan and Kootenay Lakes. Winter precipitation is high and most of it falls in the form of snow.

The index hydrograph for the Incommapleux River is typical of the smaller tributaries draining the very high elevations of the Columbia Mountains. Runoff during the winter is very low while runoff during the late spring and summer is high due to the delayed snowmelt.

(g) Zone 14: Upper Fraser River

The Upper Fraser River region covers the apex of the Columbia Mountain triangle (see Plate 95). It is characterized by northward flowing streams and a terrain which slopes northward from the tip of the Cariboo Mountains to the plateau at the great bend of the Fraser River. Both precipitation and runoff yield are moderately high in this zone. The index hydrograph for the Willow River shows a fairly sharp spring runoff peak followed by the variable runoff pattern during the summer indicating the variability of the precipitation which is more typical of the plateau area to the west.

5.08.06 Rocky Mountains - Western Slopes

(a) General

The Rocky Mountains - Western Slopes region comprises a narrow band of three zones. In the south a characteristic feature is the Rocky Mountain Trench which lies in the lee of the Columbia Mountains. The western boundary of the two southernmost zones has been drawn along the divide of the Purcell and Cariboo Mountains as well as the western slopes of the Rocky Mountains.

The main reason for including the east-facing slopes in the same zone as the west-facing slopes of the Rockies is that, due to spillover precipitation and the effects of permanent glaciers, the yield of the small streams draining the steep eastern slopes of the Columbia Mountains is equally as high as that on the western slopes of the Rocky Mountains. It is conceivable, however, that Zones 9 and 12 could be sub-divided along the Rocky Mountain Trench to form separate zones for the western slopes of the Rocky Mountains and the eastern slopes of the Columbia Mountains.

(b) Zone 9: East Kootenay Area

The East Kootenay Area region is characterized by the Rocky Mountain Trench bounded both east and west by steep mountain slopes (see Plate 89). The northern boundary of this zone is somewhat arbitrary and has been selected chiefly on the basis of yield. Over most of its length this zone lies in the rain shadow of the Columbia Mountain range and precipitation values are lower than those in the Rocky Mountain Trench area to the north. The zone is drained by the Columbia and Kootenay River systems with small tributaries having a general east-west orientation. These tributaries have high elevation drainage but only moderate yield since the zone lies in the lee of the Purcell Mountains. Small permanent glaciers feed some of the streams draining both the Purcell and Rocky Mountains in the northern half of the zone. The index hydrograph of the smaller mountain streams are typical of the mountainous area of southeastern British Columbia. The boundaries of Zone 9 are fairly well defined except for the northern boundary.

(c) Zone 12: Central Rocky Mountains

The Central Rocky Mountain region is similar to Zone 9 (see Plates 92 and 93), the basic difference being a much higher annual yield especially from small streams draining the eastern slopes of the Purcell and Cariboo Mountain ranges and from the upper reaches of the McGregor River system in the north. The western boundary follows along the divide of the Purcell and Columbia Mountain Ranges except in the extreme north where it cuts across the Fraser River and follows the base of the western slope of the Rocky Mountains. The eastern boundary lies along the divide of the Rocky Mountains. The northern boundary is arbitrary and it has been convenient to separate the flow to the Fraser River system from that to the Peace River system.

(d) Zone 22: Northern Rocky Mountains

The Northern Rocky Mountains region (see Plates 106 and 107) has eastern and western boundaries which are well defined and lie along the Rocky Mountain divide and the Rocky Mountain Trench respectively. The northern boundary has been drawn to separate streams flowing northward to the Liard River from streams flowing in a general eastward direction. This region is fairly uniform topographically with elevations varying from less than 3,000 feet in the trench to between 8,000 and 9,000 feet along the divide.

Annual precipitation and annual yields are only moderate. The runoff pattern is characteristic of northern mountain areas with very low winter runoff, a summer snowmelt peak and a gradual decrease from the summer peak to the end of the year.

5.08.07 Rocky Mountains - Eastern Slope

(a) Zone 21: Eastern Slopes

The Eastern Slopes region is narrow and elongated and lies along the entire portion of the eastern slope of the Rocky Mountains which are included in British Columbia (see Plates 104 and 105). The eastern boundary lies along the division between the Interior Plains and the Rocky Mountain foothills marking the end of the rapid decrease in elevation from the Rocky Mountain divide. The changes in topography, climate and hydrology of the eastern slopes of the Rocky Mountains are much less pronounced than those in the eastern slopes of the Coast Mountains. Precipitation and yield decrease from higher to lower elevation but the lack of information prohibits a definition of the pattern at this time.

5.08.08 Northeast Plains

(a) General

The Northeast Plains area east of the Rocky Mountains has been divided into two sections to separate the north and south flowing streams. The entire area is characterized by uniformly flat topography which has a low annual precipitation and consequently low annual yield. This area has a markedly different climate from the rest of British Columbia. The precipitation pattern exhibits a winter minimum and a pronounced summer maximum. The index hydrograph for the Sikanni Chief River shows a pronounced summer maximum caused chiefly by snowmelt and a fairly high runoff in August and September produced by the high summer precipitation.

(b) Zone 19: Albertan Plateau

The Albertan Plateau region has a relatively uniform relief with elevations varying between 2,000 and 3,000 feet (see Plate 102). Streams in this zone drain into the Peace River. The zone is bounded on the east by the border between Alberta and British Columbia.

(c) Zone 20: Fort Nelson Lowlands

The Fort Nelson Lowlands region is uniform in relief with elevations generally less than 2,000 feet (see Plate 103). The drainage of the major streams, the Fort Nelson and the Petitot Rivers, is northward with the exception of the headwaters of the Hay River which drain eastward from the eastern part of the zone.

5.09 ASSESSMENT OF PILOT STUDIES AS APPLIED TO ZONE DELINEATION

The results of the pilot studies carried out during the present assignment have certain promising implications for the delineation of hydrologic zone boundaries. A brief discussion of these implications is presented in the following paragraphs for each of the three pilot studies. It should be pointed out that these results were not available until the end of the study period and that time did not permit the incorporation of any of the possible changes mentioned.

(a) Pilot Regression Study, South Thompson River Basin

In the pilot regression study of the South Thompson River basin using the computerized grid square approach (see Section 6), the test area overlapped two hydrologic zones, covering part of the Interior Plateau and part of the western slopes of the Monashee Mountains. The fact that a successful regression equation was developed for this area supports the concept that a statistically homogeneous zone may encompass more than one physically homogeneous zone, at least for average annual runoff.

It is interesting to note that a number of the meteorological stations used for the study are located outside the area covered by the statistical equation developed. In addition, the topographic variations in Zone 13 to the north are somewhat similar to those in Zone 11 in that both zones lie along the general western slopes of the Columbia Mountain ranges. It is considered that these two points indicate that it should be possible to extend the grid square analysis northward and develop a regression equation which will be applicable over a much larger area. The result, in effect, would be the delineation of a statistically homogeneous zone which could conceivably encompass all of Zones 11 and 13 and bordering portions of Zones 6 and 15.

(b) Pilot Regression Study, East Kootenay Area

In the pilot regression study of the East Kootenay area (see Section 7), which comprises the southern portion of Zone 9, regression equations were developed for the various frequency components of streamflow but the results were basically inconclusive. In one case where substantial amounts of data derived from short term irrigation stations were used, it was possible to improve the regression equations by dividing the stations into two groups and developing two equations rather than one overall equation. One equation was applicable to small streams along the dry Rocky Mountain Trench straddling the Kootenay River while the other covered larger basins draining the higher elevation mountain slopes on both sides of the Kootenay River. The reason for this separation would appear to be attributable to the inadequacy of the available data and a lack of information concerning some of the climatic and physiographic factors rather than in the actual existence of two different zones.

(c) Correlation of Streamflow Records, Kootenay Area

The correlation studies carried out in the East Kootenay area and vicinity (see Section 8) appear promising insofar as possible definition of physically homogeneous hydrologic zones is concerned. The results indicate reasonably good correlation of streamflow records in an east-west direction along the Canada-U.S.A. border for streams in Zones 7, 8 and the southern part of Zone 9. This would seem to indicate probable similarities in climatic variations which could be the major factor in determining streamflow distribution patterns in these zones. In this case, the physiographic differences and the variation in runoff yields may be less significant than they were assumed to be in the delineation of the zones in this particular area. However, careful assessment is required, when using correlation studies to define the probable boundaries of the physically homogeneous zones, since good correlations may be obtained between widely separated rivers in entirely different physiographic regions, simply because of the time distribution or cyclicity of the streamflows. It is possible that much of Zones 7, 8 and the southern half of Zone 9 could be combined to form a single zone, but this would require verification by further study.

The correlation coefficients resulting from correlations between stations near the Canada-U. S. A. border with those to the north along the Rocky Mountain Trench show a significant decrease north of about latitude 50° north. This fact would appear to indicate that the division of the general Trench area into hydrologic zones may differ from that suggested in this report. This condition is not entirely unexpected; the arbitrary nature of the boundary between Zones 9 and 12 has already been pointed out in Sub-section 5.08.06. Since the topography is very similar along most of the Trench in Zone 12 and in the northern half of Zone 9, the climatic variations play an important role in differentiating the probable zones. However, more data will be required before a further breakdown or re-definition of zones can be carried out in subsequent studies.

SECTION 6

SECTION 6

PILOT REGRESSION STUDY
SOUTH THOMPSON RIVER BASIN

6.01 INTRODUCTION

The pilot regression study was carried out in the South Thompson River basin (see Plate 21) to test in British Columbia a promising new technique for estimating mean annual runoff in sparsely gauged areas. The application of this technique was developed by the Shawinigan Engineering Company Limited, in a study of the Province of Newfoundland, undertaken for the Atlantic Development Board in 1967.

The basis of the technique is to use a computerized grid square system to correlate firstly meteorologic and subsequently hydrologic data with selected physiographic parameters to estimate the distribution of the precipitation, temperature, evaporation and runoff for the selected region.

At present the technique is limited to estimating mean annual flow for sub-basins in the region, but as discussed in Section 4, there is good reason to believe that the method can be extended to estimate flows in individual years. The next step would be to develop modelling techniques to distribute the annual runoff volumes throughout the year. For the present pilot study the regression equation has been derived for the mean annual flow for the 10 year period 1956 - 1966.

The South Thompson River Basin area was selected as the pilot region, since it is one of the few areas in British Columbia where there is adequate meteorologic and hydrologic data to perform the regression analyses. The region overlaps two physiographic divisions, and encompasses most of Hydrologic Zone 11, (which covers part of the western slopes of the Columbia Mountain region) and part of Hydrologic Zone 6 (which covers the Interior Plateau region). It therefore offered the opportunity of checking the assumption that a regression equation could be established for a statistical homogenous zone which covers a number of physiographic regions.

The area of the South Thompson River Basin has been calculated at 6,350 square miles which is about 2 percent of the total estimated area of British Columbia of approximately 366,000 square miles.

6.02 DESCRIPTION OF THE METHOD

The method involves dividing the study area into a grid consisting of a series of uniform squares. Physiographic, hydrologic and meteorologic parameters are assigned to their respective squares. The characteristics of the overall area or drainage basins can be obtained by combining the characteristics of each square which lies wholly or partially within the boundaries.

The physiographic data for each square are extracted from available maps and climatological data for meteorological stations are available from published records. The grid system permits the storage and retrieval of basic data for future processing by means of simple computer operations. The procedure for the iterative computation to develop equations for mean annual runoff at any point within an area or basin is summarized as follows:

(1) Establish a preliminary relationship between mean annual precipitation at meteorological stations and the corresponding physiographic parameters by a standard linear multiple regression technique.

(2) Similarly, establish a relationship for mean annual temperature at meteorological stations.

(3) Compute evaporation as a function of precipitation and temperature (using a formula such as derived by Turc).

(4) Make an initial estimate of runoff for each square in the study area by estimating precipitation (Step 1), evaporation (Steps 2 and 3) and subtracting evaporation from precipitation.

(5) Compute the mean annual runoff for the drainage area above the streamflow gauging station by summing runoff of each square within the watershed.

(6) Compute for the overall drainage basin the ratio

$$K = \frac{\text{recorded mean annual runoff}}{\text{computed mean annual runoff}}$$

(7) Adjust the precipitation value for each square by the following formula:

$$\text{Precipitation (adjusted)} = K \times R_1 + E_1$$

Where R_1 represents runoff and E_1 represents evaporation obtained from the previous estimates.

(8) Using the adjusted value of precipitation for each square and the precipitation data at meteorological stations, establish a new correlation between precipitation and physiographic parameters with the meteorological station data given a weight ten times that given to the estimated precipitation in each square.

(9) Compute a second estimate of runoff for each square as in Step 4.

(10) Compute a new value of K by repeating Steps 5 and 6.

(11) Re-iterate steps 7, 8, 9, and 10 until a value of K as close to unity as practicable is obtained.

(12) Obtain the final regression equation between mean annual precipitation and physiographic parameters by repeating Steps 7 and 8.

(13) Correlate the final estimate of the runoff in each of the squares with the physiographic characteristics to establish a final equation relating runoff to physiographic parameters. At this stage, additional physiographic parameters such as area of lakes, which may be correlated with runoff, are introduced into the regression analysis.

6.03 SELECTION OF PILOT STUDY BASIN

In view of the short duration of the study and the large amount of data required to be extracted from maps, it was necessary to confine the study area to a relatively small region. The South Thompson River Basin, a tributary of the Fraser River, was the logical choice considering size, importance, hydrologic homogeneity and availability of both meteorological and streamflow data. The drainage basin is shown on Plate 21 and has a catchment area of approximately 6,350 square miles. The Water Survey of Canada stream gauging station at Monte Creek designated 8LE-69, provides a continuous 8 year record of streamflow.

6.04 THE GRID SYSTEM

The size of grid squares determines to a large extent the accuracy of the representation. A finer grid would give a more detailed assessment of topographic variations resulting in greater accuracy. On the other hand, a decrease in grid size would mean an increase in the total number of squares which would entail a sharp rise in cost of data extraction and processing.

The grid used in the Shawinigan Engineering Company study of Newfoundland has a 10 kilometer interval as marked on the 1:250,000 scale transverse mercator projection maps. The grid interval and map series were found to be satisfactory for the Newfoundland study and it was therefore adopted for the present study for uniformity and convenience. However, if the method were to be applied on a larger scale, it would first be advisable to study the optimum grid interval for different terrain types.

A difficulty arises due to the presence of discontinuity at every sixth meridian, and three such meridians intersect British Columbia, namely 120^{o}, 126^{o} and 132^{o}. The selected basin lies mostly to the east of 120^{o} meridian which intersects only the extreme southwestern corner. To simplify the study, the grid covering the basin was extended westward to include this portion of the basin. Application of the method to larger areas would involve an initial study to establish a procedure for bridging the meridian discontinuities.

The grid system covering the study area and the numbering system for the squares is shown on Plate 23. A total of 212 squares fall within or on the boundaries of the study basin.

6.05 PERTINENT DATA

6.05.01 Streamflow Data

A 10 year base period of 1956 - 1966 was chosen for the study on the basis of available streamflow records. Adequate streamflow records are available from four gauging stations in the pilot basin. The locations of these stations are shown on Plates 28A and 28B and data for the stations are as follows:

Station Designation	Station Name	Drainage Area Above Station (sq. miles)	Ten-Year Mean Flow (cfs)
8LC-3	Shuswap River near Lumby	776	1,800
8LC-19	Shuswap River at Mable Lake	1,560	2,890
8LD-1	Adams River near Squilax	1,156	2,560
8LE-69	South Thompson River near Monte Creek	6,350	10,700

The streamflow records for the South Thompson River near Monte Creek (8LE-69) and the Shuswap River at Mable Lake (8LC-19) were adjusted to the 10-year base period using 8 and 9 years of record respectively.

6.05.02 Meteorological Data

In the general area of the South Thompson River Basin 37 meteorological stations with acceptable precipitation records for the selected base period were utilized in the study. Only 15 of these stations are located within the pilot basin, while the remaining 22 are peripheral stations which presumably also reflect climatic conditions in the basin.

Adequate temperature data are available for 28 of the 37 stations used.

The locations of these stations are shown on Plate 22 and the 10 year mean values of precipitation and temperature at these stations are listed in Table II-1.

6.05.03 Mapping Information

The approximate area and physiographic features of the selected basin have been obtained from the following maps, produced or compiled by Surveys and Mapping Branch, Department of Mines and Technical Surveys, Government of Canada (the first two maps are of the World Aeronautic Chart Series):

Sheet No.	Scale	Area Covered
2215	1:1,000,000	Fraser River
2216	1:1,000,000	Kootenay River
82L	1: 250,000	Vernon
82M	1: 250,000	Seymour Arm
82D	1: 250,000	Canoe River
92I	1: 200,000	Ashcroft

6.06 PROCESSING OF METEOROLOGICAL DATA

Of the 37 meteorological stations used 21 had precipitation records for the complete ten year period, 1956 to 1966. The remaining 16 precipitation stations had periods of record varying from 4 to 9 years. Temperature data was observed at only 28 of the 37 meteorological stations examined, and of these only 14 had records for the complete ten year period.

For stations with missing monthly precipitation and temperature records, the missing values were estimated by the normal ratio method. For stations with short term records, the short term means were adjusted to the selected 10 year period utilizing the double-mass curve technique.

6.07 SELECTION OF PHYSIOGRAPHIC PARAMETERS

6.07.01 Definition of Parameters

The physiographic characteristics considered were:

(a) Elevation Parameter: The mean elevation of a square was obtained by averaging the elevations at the grid square corners, the centre and the intermediate 5 kilometer points.

(b) Land Slope Parameter: An index of average land slope of the grid square was considered using both of the following methods:

(i) Horton's Method - This method involves counting the number of contour lines crossing two perpendicular lines which pass through the centre of the square and are parallel to the sides.

(ii) Plane Fitting Method - This method has been used by the Shawinigan Engineering Company Limited in the Newfoundland study and involves computation of the plane of best fit through the grid square corners, the centre and intermediate points.

These methods are described in detail in Appendix VII. It is noteworthy that the average land slope values computed by these two methods differed considerably in many cases. For this reason, it was decided to include both sets of values in the preliminary regression analysis to examine their relative statistical significance and to select the more significant parameter for the final analysis.

(c) Distance Parameter: The distance from the centre of a square to a straight line drawn along the divide of the Coast Mountains, measured in a west-southwest direction, was adopted as an index since predominant wind direction for moisture inflow for the southern British Columbia lies in the southwest to west quadrant. The main topographic barrier, the Coast Mountains, Vancouver Island and the sea coast are approximately parallel to one another and are oriented in a northwest-southeast direction. The introduction of distance to the sea as an additional parameter would not have changed the statistical significance of the results obtained from the regressional analysis.

(d) Latitude Index: The latitude index was defined as the distance measured from a base line along the Canada - U. S. A. border to the centre of a grid square in the direction parallel to the Y-axis of the grid system.

(e) Barrier Height Parameter: The barrier height for a given barrier along a given line is defined as the difference between the highest elevation along this line and an average elevation for the base or bottom of the barrier on the leeward side. For each square a weighted average was calculated from values measured along five parallel lines evenly spaced over a width of 28.3 kilometers extending in a west-southwest direction and centered over the given square. The highest barrier between the square and the sea was used for this parameter.

(f) Shield Effect Parameter: As there are several possible barriers between the South Thompson River Basin and the sea, and the number of barriers differs for each square, the barrier heights along the same line were summed to reflect shield effect of the barriers. A definition sketch is given on Plate 25. The barriers considered are the Coast, Thompson, Okanagan and other local barriers, whichever are applicable.

6.07.02 Measurement of Parameters

The elevations at the grid square corners, the centre and intermediate points, the barrier heights, the land slope parameters by Horton's method, and the shield effect parameters were extracted manually for each square from the existing maps. The average elevation, the plane-fit land slope parameter, the distance parameter and the latitude index were calculated by the computer.

The physiographic data for a meteorological station were extracted from a 10 kilometer square which was centred over the corresponding station. In addition, the elevation at the meteorological station was used instead of the average elevation of the square.

A definition map for the distance parameter and latitude index is shown on Plate 24.

The determination of the barrier height parameter in a mountainous area, such as that encountered in British Columbia, requires a certain amount of subjective evaluation. The Coast Mountains, for example, do not have a single line of peaks but present a broad band of ranges of varying heights. In addition, the terrain to the lee of these mountains is not conveniently level but presents the deep Fraser River canyon followed by a fairly uneven or rugged stretch of country. Hence, the selection of mean elevation values for the top of this barrier and also the valley or terrain at its base (as indicated in Plate 25) is open to interpretation. In consideration of the variations possible in determining barrier heights, and especially in summing these values to obtain the barrier shield parameter, it would be expected that the possible statistical significance of these parameters could be reduced. In any case, it would be difficult to assess their significance in terms of the resulting regression equation. However, the potential importance of these parameters could not be ignored. They were thus evaluated as carefully as possible and included in the analysis so as to be able to assess their relative importance in the regression equations.

6.07.03 Selection of Parameters

Judgment is required when selecting the parameters since, if many parameters are chosen without proper consideration, the possibility of a chance correlation is greatly increased.

Examples of physiographic characteristics which have not been included in the present study are vegetative cover, geology and effect of glaciers. The vegetative cover and geology are fairly uniform for the study basin, and there are only a few small glaciers on the peaks along the ridge of the Monashee Mountains at the eastern boundary of the basin. It was predetermined that these parameters would not be included in the regression equation. However, for regression analyses to test larger statistical zones, these parameters and others such as index of overburden depth should be considered for inclusion.

As indicated in Section 5, the average elevation of maximum precipitation in the interior would be about 6,000 feet. Since this figure of 6,000 feet is idealized and the exact value in the area of study is really unknown, and in consideration of the nature of the grid square approach, no attempt was made to take this factor into account.

6.08 ESTIMATION OF TEMPERATURE DISTRIBUTION

Using data at the 28 meteorological stations, a correlation was established between the physiographic characteristics at each station and the corresponding mean annual temperature. The physiographic parameters included in the step-wise multiple regression analysis were station elevation, average land slope estimated by the two methods, distance to barrier, latitude index, barrier height and shield effect. The resulting regression equation is:

$$T = 52.1689 - 0.0318963E - 0.0142543L$$

where, T is mean annual temperature in $^{\circ}$F, E is station elevation in tens of feet, and L is latitude in kilometers.

The coefficient of correlation is 0.95 which, for the number of data and variables is significant at the one percent level. The standard error of estimate is 1.0° F. The coefficients of the variables included in the equation have the signs corresponding to their expected physical influence on the mean annual temperature.

The selected basin is situated in the interior of the Province and is well shielded from the marine influence of the Pacific Ocean by the Coast Mountains barrier. Hence, the distance and barrier shield parameters were not expected to have any influence on the temperature. An initial equation was developed relating temperature to elevation alone. This equation predicted an increase in temperature of $3.1^{O}F$ per 1,000 foot rise which agrees closely with the accepted standard lapse rate of $3.3^{O}F$.

The above regression equation was used with the grid physiographic data to estimate the distribution of mean annual temperature in the study area. The resulting isothermal lines are shown on Plate 27.

6.09 PRELIMINARY ESTIMATE OF PRECIPITATION DISTRIBUTION

A preliminary correlation was established between the mean annual precipitation at the 37 meteorological stations in the South Thompson River Basin area and the corresponding physiographic characteristics. The physiographic parameters included in the statistical analysis comprised station elevation, distance to barrier, latitude index, shield effect plus the second power of all these parameters. Only four of the parameters were retained as being significant in the regression equation. In the cour se of preliminary investigation it was found that the land slope parameter, when retained by the regression equation as an independent variable, had a coefficient with the sign consistently opposite to its expected influence on the precipitation. This parameter was therefore discarded in subsequent regression analyses of precipitation at meteorological stations.

The resulting regression equation was:

$$P = 11.698 - 0.0948428\,L + 0.0000509443\,E^2 + 0.000446745\,D^2 - 0.000256\,S_e^2$$

where, P is mean annual precipitation in inches, D is distance to barrier in kilometers, and S_e is shield effect in hundreds of feet.

The coefficient of correlation is 0.96 which, for the number of data and variables is significant at the one percent level. The standard error of estimate of the dependent variable is 3.65 inches. The coefficients of the variables retained in the equation have the signs corresponding to their possible physical influence on the mean annual precipitation.

The above regression equation was used with the grid physiographic data to make preliminary estimates of the mean annual precipitation in each grid square.

6.10 ESTIMATION OF EVAPORATION

The mean annual evaporation was calculated by Turc's evaporation formula. This widely used empirical formula was examined for its applicability to the study area. Moisture surplus was estimated utilizing Turc's formula for four of the gauged sub-basins in South Thompson River Basin, based on published isotherms and isohyets, and the results are compared with the long term average annual runoff of these basins in the table below:

	Station	Drainage Area (sq.mi.)	Estimated Annual Runoff (in.)	Actual Annual Runoff (in.)	Percentage Difference
8 LD-1	Adams River near Squilax	1,156	26.3	27.8	5
8 LE-69	South Thompson at Monte Creek	6,350	21.7	22.7	4
8 LC-19	Shuswap at Mable Lake	1,560	24.3	24.4	0
8 LC-3	Shuswap River near Lumby	776	30.0	30.1	0

The drainage areas were obtained by planimeter measurement of the 1:250,000 scale maps. The discrepancy between the estimated and observed values was found tobe less than 5 percent, but due to lack of precipitation and temperature data, at higher elevations, it was not possible to make an accurate estimate of average annual water loss. Turc's formula was considered to be acceptable for the present purpose of making approximate estimates of actual evaporation, leading to a reasonable estimate of the mean annual runoff.

6.11 ESTIMATION OF RUNOFF DISTRIBUTION

The preliminary estimate of mean annual precipitation at each grid square was used in conjunction with the estimated mean annual temperature distribution to calculate the approximate mean annual evaporation from each square. The evaporation was calculated by

Turc's formula. An initial estimate of runoff, from each square of the watershed, was obtained by subtracting the evaporation from the precipitation. Subsequently, a more refined estimate of runoff from the watershed was obtained by the iterative process. The initial value of K in the first trial was 1.1648 and the final value of K was 0.9636.

In this first attempt to find a meaningful regression equation for the overall basin, one value of K was obtained for the overall basin by comparing the estimated runoff with the actual flow at the gauge 8LE-69 on the South Thompson River at Monte Creek. Subsequently, as discussed later herein, separate K values were found for each of the four sub-basins at each step of the iterative procedure.

The physiographic parameters included in the precipitation correlation were the same as those for the preliminary analysis including land slope parameter estimated by both methods. In the course of the iterative computations it became apparent that the land slope parameter estimated by Horton's method did not have significant influence on the dependent variable and as a result it was discarded.

On completion of the iterative computation, the values of the runoff in each of the squares in the basin, having been adjusted by the final value of K, were then correlated with the corresponding physiographic characteristics. In addition to the parameters used in correlations of precipitation, a new parameter, namely, the area of lake in a square was introduced. The equation of final runoff-physiographic characteristics correlation is:

$$
\begin{aligned}
R = \; & 12.7505 + 0.0129242\, E\,(1 + 0.00186093\, E) \\
& + 2.69807\, S\,(1 - 0.067099\, S) + 0.000910818\, D\,(D - 222) \\
& - 0.114057\, L\,(1 - 0.00052393\, L) - 0.000634788\, A_L^{2} \\
& - 0.000255255\, S_e^{2}
\end{aligned}
$$

where R is mean annual runoff in inches, S is average land slope estimated by the plane-fit method in hundreds of feet per mile, and A_L is area of lake in a square in square kilometers.

The coefficient of correlation is .999 and the standard error of estimate is 0.8 inch. The coefficient of correlation does not have the usual statistical significance since the dependent variable itself has been derived partially by using a correlation with most of the independent variables. However, the significance of the equation so developed is demonstrated by the results of the checks done by applying this equation to four gauged sub-basins, including intermediate drainage areas located within the main basin. The boundaries of these sub-basins are shown on Plate 21. The resulting estimated flows and their corresponding observed values are tabulated below for comparison:

River	Stream Gauge Station	Sub-basin Drainage Area (sq. mi.)	Recorded Flow (cfs)	Estimated Flow (cfs)	Percentage Difference
Shuswap	8LC-3	776	1,800	1,521	15.5
Shuswap	8LC-19	784	1,090	1,151	5.6
Adams	8LD-1	1,156	2,560	2,677	4.6
South Thompson	8LE-69	3,634	5,250	5,385	2.6
TOTAL		6,350	10,700	10,734	0.3

The runoff equation derived by using an overall K-value in the iteration procedure has been used with the grid physiographic data to produce the mean annual runoff distribution for the study area as shown on Plate 28A.

6.12 FINAL PRECIPITATION DISTRIBUTION

The correlation of adjusted precipitation of the squares obtained after the last runoff iteration, plus precipitation at meteorological stations, with the corresponding physiographic factors was considered as the final correlation for precipitation. The precipitation regression equation is:

$$P = 24.6831 + 0.00000898423E^2 + 3.45975S(1-0.0708947S) + 0.000870661D(D-160) - 0.157188L(1-0.00078759L) - 0.000261813\, S_e^2$$

The coefficient of correlation is very high. However, it is not helpful in establishing the reliability of the correlation because of the method used in deriving the correlation. The precipitation equation has been used to compute mean annual precipitation for each square and the resulting distribution of precipitation over the study area is indicated by the isohyetal lines shown on Plate 26A.

The observed mean annual precipitation values for the meteorological stations located within the pilot basin are also plotted on Plate 26A for comparison. These values are consistently lower than those computed for the grid squares within which these stations lie. This result is interpreted as being due to the fact the meteorological stations are mostly situated in the valley bottoms while the grid squares cover fairly large areas which generally include parts of the higher elevation mountain slopes. Since average elevation is one of the regression equation parameters, the resulting computed precipitation value would tend to be high in comparison with valley floor observations. This result indicates that perhaps a smaller size grid is needed to obtain a more detailed pattern of precipitation distribution. However, the ten kilometer grid interval appears to be reasonably adequate for the purpose of estimating average runoff distribution.

6.13 REFINEMENT OF PRECIPITATION AND RUNOFF DISTRIBUTION

Since adequate flow data are available for four stream gauging stations in the selected basin, an attempt was made to obtain a more realistic distribution of precipitation and runoff by checking the estimated runoff from each sub-basin against the corresponding recorded data during the iterative computations.

The preliminary precipitation equation derived from meteorological station data was applied to each sub-basin separately to obtain the runoff correction factors "K". The mean runoff in each square of each sub-basin was adjusted by the corresponding value of K for such sub-basin. Where a particular square was shared by two or more sub-basins the runoff values for that square were averaged by weighing according to the respective areas in the sub-basins. A new distribution of mean precipitation was computed from these adjusted runoff values in conjunction with the estimated evaporation.

A new regression equation was then established between the new precipitation value for each square plus precipitation at meteorological stations and the corresponding physiographic parameters.

In the course of applying the iterative technique it was found that the convergence of K values were slow. An examination of the successive K values after six iterations showed a clear trend, and indicated that the K values could be improved by performing more iterations. Since the exercise had served its purpose any further computation was considered unwarranted in view of the limited time and funds available for the present study.

The regression equation established after six iterations is:

$$P = 12.6209 + 0.0000132462\, E^2 + 3.67368\, S\,(1-0.0660673\, S) + 0.000585627\, D^2 - 0.207157\, L\,(1-0.00112514\, L) - 0.000327341\, S_e^2$$

And the corresponding runoff equation is:

$$R = 0.940194 + 0.0000463718\, E^2 + 3.42803\, S\,(1-0.0627941\, S) + 0.000524631\, D^2 - 0.219441\, L\,(1-0.00122805\, L) - 0.0593442\, S_e$$

The standard errors of estimates are 2.9 inches and 1.5 inches respectively. These equations and their standard errors could be further improved by continuing the iterative procedure. The initial value of K for each sub-basin and its corresponding value after six iterations are listed as follows:

River	Stream Gauge Station	Sub-basin Drainage Area (sq. mi.)	Recorded Flow (cfs)	Value of K	
				Initial	After Six Iterations
Shuswap	8 LC-3	776	1,800	1.2590	1.0968
Shuswap	8 LC-19	784	1,090	1.0298	0.8994
Adams	8 LD-1	1,156	2,560	1.1907	0.9442
South Thompson	8 LE-69	3,634	5,250	1.1508	0.9419

The above precipitation and runoff equations have been used with the grid physiographic data to modify the initial estimates for the mean annual precipitation and runoff distribution as shown on Plates 26B and 28B.

6.14 SNOW COURSES

The British Columbia Water Resources Service conducts a comprehensive snow survey program for the basic purpose of forecasting the volume of the seasonal runoff which originates mainly from snowmelt.

There were about 200 snow courses in operation in the Province as of January, 1969 (see Plate 29), of which a large number are located at elevations above 4,000 feet. Since most of the meteorological (precipitation) stations are situated in valleys at elevations lower than 4,000 feet, snow survey data provide practically the only observed information on precipitation at the higher levels and thus are of great potential value for use in developing hydrologic models to estimate runoff.

An attempt was made to use the data collected at snow courses in the general area of the South Thompson River basin, in the development of the regression equation for mean annual precipitation. It was recognized that the snowpack water equivalent has been used as an index to provide estimates for the volume of seasonal runoff. An examination of temperature data indicated that the mean temperature at elevations greater than 4,000 feet normally remains below $32^{o}F$ from about mid-October to at least the end of March. Consequently, the precipitation which falls during this period would be expected to be mostly in the form of snow and the water equivalent of the snowpack as measured on April 1st should approximate the winter accumulation of snowfall. The general approach then, has been to attempt to evaluate the percentage of the total annual precipitation at snow course locations that is represented by the April 1st snowpack water equivalent.

A few snow courses are situated adjacent to meteorological stations. Snowpack data for these courses were compared with observed winter (October-March) precipitation at the meteorological stations. It would appear that at least up to 4,000 feet in the South Thompson River area, a great deal of melt takes place before the end of March since the water equivalent of the snowpack in all cases was considerably lower than the accumulated winter precipitation. As a result of these comparisons, several snow courses located near the 6,000 foot level were selected for further study. The locations of these snow courses are indicated on Plate 22. The physiographic data and mean April 1st snowpack water equivalent for the 1956-66 period are presented in Appendix II (Table II-5).

Several approaches were then made as follows:

(a) Mean annual precipitation at snow course locations was computed from the regression equation developed from precipitation observed at meteorological stations only (see Sub-section 6.09), and the percentage of these values represented by the April 1st snowpack water equivalent determined. The resulting percentages varied considerably and no consistent pattern was evident. Therefore, it was not possible in the study to refine the regression equations using annual precipitation values derived from the snow course data.

(b) An attempt was made to develop correlation equations relating, firstly October to March precipitation at meteorological stations, and, secondly, the percentage of October to March to annual precipitation at these stations, to physiographic parameters. The attempt was unsuccessful as elevation was not retained as a significant parameter in either of the regression equations, thus corresponding relationships could not be realistically evaluated for snow courses.

(c) Finally, snow course data were compared with annual precipitation computed from the equation developed by the regression analysis. The results indicated apparent wide variations in the proportion of water equivalent of snowpack to annual precipitation, and, since time was limited, no further attempts were made to incorporate snow survey data in the study.

However, the importance of snow course data for developing hydrologic models, in addition to use as a significant index for forecasting the volume of seasonal runoff, has been stressed in Sub-section 4.10, and it is recommended that further studies be conducted to determine the relationship between snow survey data and annual precipitation.

6.15 CONCLUSION

The above pilot study has demonstrated that the computerized grid square system is applicable to the South Thompson River basin area. It has shown that mean annual runoff from ungauged sub-basins can be estimated with reasonable accuracy using a relationship developed from flow data for the overall basin only, combined with meteorological data. It has further indicated that a more realistic areal distribution could be achieved by incorporating flow data of sub-basins wherever available. In addition, a successful regression equation or model has been developed for a region which covers parts of at least two different physiographic division. This result has important implications for hydrologic zone delineation as outlined in Sub-section 5.09.

It is believed that this approach would apply equally well to other areas in British Columbia; however, similar studies on larger basins in other physiographically different regions are needed to substantiate this belief.

SECTION 7

SECTION 7

PILOT REGRESSION STUDY - EAST KOOTENAY AREA

7.01 INTRODUCTION

The pilot regression study described herein was carried out to test one of the more promising techniques which have been developed for regionalization of streamflow data in order to estimate flow frequency characteristics of ungauged streams.

The technique used in the study has been outlined in Sub-section 4.07.03 and involves relating frequency characteristics of the various streamflow categories such as annual, seasonal, monthly and flood flows, to physiographic features of the related drainage basins. The frequency characteristics used as the dependent variable in the relationships are the mean, the coefficient of variation and the coefficient of skew, while the physiographic features such as drainage area and mean basin slope, are used as independent variables. The relationships have been developed using a stepwise multiple regression analysis.

The object of the study was to investigate the feasibility of establishing relationships from which frequency curves of the various categories of streamflow could be constructed for gauged and ungauged streams (within the region) using the Log Pearson Type III distribution recommended in Section 4.

A regional approach of this type presupposes the existence of a large number of relatively long-term records of natural streamflow so located that a broad sampling of basin sizes and conditions is made. Many of the long-term stations in the existing stream gauging network are located on the large rivers which derive flow from several hydrologic zones. Records for such inter-regional streams cannot be used in regional analysis because of problems in assigning numerical values to the various influences which affect streamflow in these complex basins. A limited number only of longer-term records suitable for a regional analysis of the type envisaged is available within the boundaries of the selected pilot area. The size of this study region was restricted because of the time limitations.

7.02 PILOT AREA

The East Kootenay area was selected for study mainly because it was one of the more intensively gauged areas in British Columbia. It has short-term streamflow records on the smaller streams and also a station (Bull River near Wardner, Station 8NG-2) with essentially unregulated flow data which can be used to extend and adjust the records of the short-term seasonal stations to a common base period. Furthermore, the Water Survey of Canada have examined the history of water rights in the area and have made tentative estimates of required adjustments to reconstruct natural flows for those stations used in the present analysis. Streamflow records for the area were available on magnetic tape for processing by computers.

The East Kootenay area is located in the southeastern corner of British Columbia and extends from Canal Flats south to Newgate on the British Columbia - Montana border. The area straddles the Rocky Mountain Trench. It has a glaciated valley some 3 to 17 miles wide and is flanked on the west by the Purcell Mountains and on the east by the Rocky Mountains. Elevation in the area ranges from water level of 2,310 feet on the Kootenay River near the International Boundary to over 10,000 feet on many of the mountain peaks. Mean annual precipitation varies from 15 inches at Newgate, elevation 2,800 feet, to over 41 inches at Fernie, elevation 3,305 feet. The mean annual temperature varies from a low of 40°F at Fernie to 43°F at Newgate. The average annual runoff from the area is about 19 inches.

The drainage basin, shown on Plate 31, has a catchment area of 5,580 square miles.

7.03 STREAMFLOW RECORDS

Most of the long-term stations in the existing hydrometric network are located on the larger streams. In the East Kootenay area there are six stations that fall in this category. Large rivers such as the Kootenay may include several hydrologic regimes in their catchment basins and, therefore, stations on such rivers are not generally useful for regional analysis. Some stations were excluded from the study because of the inter-regional effect and others were eliminated because of fragmentary records or unaccountable amounts of streamflow diversion,

A large number of gauging stations have been installed on small streams for irrigation projects. Most of these irrigation stations have been operated seasonally from May to September; a few have records of over 10 years; others have records as short as one or two seasons; and still others have miscellaneous measurements which have been made at times of low flows.

In the study, 48 stations covering 2 or more years of record were analyzed, and of these, 18 were affected by diversions or upstream storage to an extent where adjustments were deemed necessary for summer low flow evaluations. The effects of diversions and upstream storage on other categories of streamflow were believed to be not as great, particularly when considering flood flows.

The gauging stations used in the studies are listed in Table III-1 and their locations shown on Plate 32. Bar charts showing the period and type of records for all existing and discontinued stations in the area are given on Plate 10. On this chart, a solid bar indicates continuous all-year records while an asterisk indicates that records are available for less than the full year. These bar charts clearly demonstrate the fragmentary nature of the records, despite the apparent density of the network.

7.03.01 Categories of Streamflow Analyzed

The following categories of streamflow were examined in the regional studies:

(a) Annual flow.

(b) Seasonal flow for the May to September irrigation period.

(c) Monthly flows for May, June, July, August and September.

(d) Annual flood defined as the maximum mean daily flow each year.

(e) Minimum flow defined as the mean of the 5-day summer low flow for each year.

7.03.02 Processing of Streamflow Data

The frequency characteristics required to define statistically the various categories of streamflow include: the mean ($\bar{Q}$), the standard deviation (S) or the coefficient of variation ($C_v = S/\bar{Q}$) and the coefficient of skew (C_s). Standard methods were used for computing these terms. In the study, flow data were transformed to their logarithms before computation of the parameters.

The mean values of the various categories of streamflow were computed for all stations with two or more years of records. The coefficients of variation were computed for those stations with five or more years of records. The coefficients of skew of the various categories of streamflow were computed for the long-term station on the Bull River near Wardner (8NG-2).

The computed values were then adjusted to a common base period extending from 1927 to 1966 which encompasses most of the usable recorded data. Where there are five or more years of data, adjustments were made to the means and coefficients of variation by a relationship with the long-term station through a set of statistical equations as proposed by Beard (1962) and outlined in a report by Cruff and Rantz (1965). For stations with less than five years of records, the adjustment of the mean values were made by direct correlation with longer records from a neighbouring stream. Mean annual runoff for the seasonal stations has been estimated as 133% of the May to September runoff volume. This percentage is an average value obtained from an analysis of data from stations with continuous, all year records, and is considered to be representative of the region.

The flow characteristics of stations in the East Kootenay area are summarized in Appendix III. It should be noted that the number of years of record indicated on the tables in the Appendix refers only to records available within the base period 1927 to 1966 Records prior to 1927 are available for periods as indicated by the bar charts on Plate 10 but such records are not included in the tables nor in the analysis.

7.04 BASIN PARAMETERS

It is recognized that streamflow characteristics of a river system are influenced by many complex climatic, geologic and physiographic factors. Considerable hydrologic and geologic investigations are needed before the more complex factors can be adequately evaluated and expressed numerically for use in regression analysis.

For the purposes of the present study the basin characteristics considered as independent variables in the regression studies are: drainage area, percent of total area in lakes and swamps, main channel length, main channel slope, mean basin elevation, stream density, average land slope and basin shape. Summaries of the characteristics for each of the gauged basins in the East Kootenay area are given in Table III-1. In addition to those listed in the table, a latitude index and a distance index from basin barrier were included in the regression analysis. A runoff index was used as an independent variable in the study of the coefficient of variation. Other parameters such as precipitation, geology, vegetative cover and soil types were not included in the analysis because the data were either not available or could not be evaluated quantitatively in the time available for this study.

7.05 REGIONALIZATION OF DATA

Stepwise multiple regression analysis was used to develop relationships between the frequency characteristics of the various categories of streamflow as the dependent variable and the physiographic characteristics of the drainage basins as independent variables. The regression analysis was performed on the University of British Columbia IBM 7040/44 computer using the TRIP program developed by the University of British Columbia Computing Centre. An F-test at the 5% level was used to indicate the significance of an independent variable being considered for inclusion in the regression model. The standard error of estimate was used as the unit to measure the accuracy with which the model fits the data. Natural values and logarithmic transformations of both the dependent and independent variables were examined in the regression analysis.

Two series of computations were conducted. The technique was first tested using only the data from those stations with fairly long periods of record (Case 1). Data from stations with short term records were then included to make use of all available information (Case 2). This step was taken in an attempt to improve the computed regression equations since the short-term stations provide a greater areal sampling, especially of the smaller streams.

7.05.01 Case 1

Regression analyses were made with data from stations with 10 years or more of record; namely Stations 8NG-2, 8NG-12, 8NG-40, 8NG-46, 8NG-48, 8NK-12 and 8NK-16.

Mean Flow. The regression equations developed for estimating the mean values of the nine categories of streamflow as listed in Subsection 7.03.01, are given in Table III-21. The standard errors of the estimate range from 6% for mean July flow to 39% for the mean May flow. Data from stations with less than 10 years of record were used to test the equations for general application throughout the region. The results are shown on Plates 33 to 35. Substantial differences between the values synthesized from the equations and the values from the short-term data are evident. The largest differences are found in the smaller basins. In view of the smallness of the sample size and the absence of long-term data on the smaller basins, such large variations are to be expected.

Coefficient of Variation. The regression equations developed for estimating the coefficients of variation of the various categories of streamflow are given on Table III-22 and the results presented graphically on Plates 33 to 35. Standard errors of the estimates are also indicated on the plates.

With the exception of annual flows, the relationships developed for the other eight categories of streamflow are encouraging. For annual flows, the range of the coefficients of variation in the sample is very small. It would appear then that an average of all the values of the coefficients of variation for annual flows obtained from the sample may be satisfactory for application in the region.

Coefficient of Skew. The coefficient of skew was computed for all nine categories of streamflow from records of the s tation on the Bull River near Wardner (Station 8NG-2). The results are summarized on Table III-23.

Since the value of the coefficient of skew cannot be determined with any degree of reliability from a short series of hydrologic observations, the regional coefficient of skew should be obtained from a study of as many long-term station records as are available for the area. In one approach (Cruff and Rantz, 1965), the average value of the computed skew coefficients from all the long-term records in each region was assumed to be the regional value of that statistical parameter. The Bull River gauging station is the only long-term station used in this study, and therefore the values of the coefficients of skew for the various categories of streamflow were assumed to be the regional value for use in computing the cumulative frequency curves.

Cumulative Frequency Curves. The Log Pearson Type III distribution was used in the construction of the cumulative frequency curves. From the regional relationships established for the mean, coefficient of variation and coefficient of skew for the various categories of streamflow, cumulative frequency curves were constructed for two stations; Bull River near Wardner (8NG-2) and St. Mary River near Wycliffe (8NG-12). Comparisons were made with the recorded data and the results are shown on Plates 36 to 38. A subjective adjustment to the skew coefficient for the mean September flow was necessary to obtain a reasonable fit with the observed data.

7.05.02 Case 2

Regression analyses were made assuming the adjusted records of all 48 stations are of sufficient quality and reliability for use in the study. Also a subsidiary study was made using only those stations with more than 20 square miles of drainage area to eliminate those stations with small flows in which the adjusted-to-long-term data could be of questionable value.

An attempt was made to utilize data from the short-term stations to supplement the available long-term data in defining relationships between the mean flow frequency characteristics and various physiographic parameters. The adjusted data for all 48 stations were assumed to be of sufficient quality for this purpose. An analysis was made assuming all stations belong to a homogeneous group. Attempts to define meaningful relationships using the existing information were unsuccessful .

In the subsidiary study, an analysis of the residuals between the observed and calculated values was made from a relationship based on drainage area only in an attempt to subdivide the region into smaller, more nearly homogeneous zones where such factors as precipitation, geology and other features probably have the same overall effect. The analysis served to divide the stations into two groups and new regression models were developed for each group. The first group is composed of stations gauging the larger streams which drain the higher elevation mountain slopes on both sides of the Kootenay River. The second group includes the smaller, low elevation basins along the Kootenay valley . Improvements in the standard error of most categories of streamflow were evident but no significant improvements were found in the equations for flood and summer low flow characteristics. The results from the first group are given on Table III-24.

7.06 SUMMARY AND CONCLUSIONS

Stepwise multiple regression studies were carried out in the East Kootenay area in an attempt to relate the frequency characteristics for annual, seasonal, monthly, maximum and summer low flows as the dependent variable, to a set of physiographic parameters of the basin as independent variables.

The results of the study were inconclusive as far as the accurate estimation of streamflow from the developed regression equations is concerened. The fact that the derived equations do not adequately regionalize the observed streamflow data is partly due to the shortage of data which could be used in the analysis and perhaps also to the fact that insufficient time was available to incorporate such parameters as geology, forest cover and precipitation. In general, however, the study has demonstrated the feasibility of establishing such relationships.

The study has also been valuable in pointing out a need for increased sampling of smaller basins at higher elevations and for a greater number of continuous records. The East Kootenay area is one of the more densely gauged in British Columbia. However, only seven stations were considered to have records of sufficient length for significant statistical analyses. Five of these stations are located on the larger streams In addition, the fairly extensive network of irrigation stations which are operated seasonally on the smaller streams provide mostly short-term records and are generally located at lower elevations. For accurate regionalization of streamflow data over the entire East Kootenay area, particularly for smaller streams at middle and high elevations, the available data would appear to be of limited use. It is recognized that the existing hydrometric network has not been designed nor operated to collect data for the purpose of carrying out regional analyses. However, the results of the pilot study do indicate the possibility that gauging stations in such a network could provide useful support to a regional network if additional expenditures were made to ensure firstly, continuity of records and secondly, a detailed accounting of upstream diversions and storage modifications of natural flow.

It is recommended that regression studies of this type be continued on a research basis, but the practical application of the method may depend on the collection of more long term data than is presently available in British Columbia.

SECTION 8

SECTION 8

CORRELATION OF STREAMFLOW RECORDS KOOTENAY AREA

8.01 INTRODUCTION

The study described herein was carried out to test a technique for correlation of concurrent records of two stations, as a means of transferring information from one stream to a neighbouring stream and for delineating basins of similar hydrologic characteristics.

The technique used in the study has been outlined in Sub-section 4.07.02 and involves correlating base stations having long term continuous records, with stations having relatively short periods of records as a means of transferring some of the reliability of the long term station to the short term record. The method devised by W. B. Langbein has been used extensively in hydrologic analyses over the past decade and there has been considerable interest in this technique as a potential tool in network evaluation and planning. The possible usefulness of the method in network planning is based on the concept of a system of long-term base stations supplemented by an auxiliary system of short-term stations to provide areal sampling. It follows that the short-term stations would be discontinued when a satisfactory correlation with a nearby long-term base station was established. It is essential, if useful results are to be obtained, that the streams being compared should drain areas which have similar climatic and physiographic characteristics as indicated by a high coefficient of correlation.

8.02 PILOT AREAS

The East Kootenay area and vicinity was selected for the main study for the same reasons as those outlined in Sub-section 7.02. Supplementary studies were also attempted for stations in the Similkameen River basin, which was selected for similar reasons. The pilot study areas are shown on Plates 31 and 51.

8.03 METHOD OF CORRELATION

All correlations were computed using an IBM 360 computer following the technique described by Langbein (1960) in which correlations are made in terms of the deviations in logarithmic units from the geometric mean of the discharge for each calendar month. The computer programs used in this study are listed in Appendix V.

A regression equation was developed for each month using concurrent monthly discharges at two stream gauging stations. The equation so established was subsequently used for estimating flows at the dependent station from records at the independent station. The coefficient of correlation of the regression equation was adjusted for sample size.

8.04 DATA AND ASSUMPTIONS

The correlation studies were carried out using published stream flow data. In the main study in the Kootenay area selected stations in southeastern British Columbia were used in addition to those within the East Kootenay River Basin. In the subsidiary study in the Similkameen River basin, only selected stations within the basin were used.

The stations used in the study are listed on Tables IV-1, IV-2, and IV-3. In the analyses, the assumption was made that upstream diversion and artifical storage were small enough not to affect monthly mean discharges at most of the stations. Correlation coefficients were computed for all possible pairs of stations with concurrent records.

In the study it was assumed that a high coefficient of correlation identifies basins of similar hydrologic characteristics while a low coefficient of correlation indicates basins of dissimilar hydrologic regime. It is recognized that chance correlations can often occur between basins of different hydrologic zones, particularly when relations are established from relatively short-term records and therefore the results should be viewed in the light of climatic and physiographic factors.

8.05 CORRELATION RESULTS

Typical results of the coefficient of correlation studies are shown on Plates 71, 72 and 75. Basins with similar flow characteristics can be identified by patterns of high correlation coefficients. For example, the station on the Bull River near Wardner (8NG-2) has records which correlate well with streamflow at most of the stations draining 40 square miles or larger in the East Kootenay area (see Plate 71).

The relationship between distance and the value of the coefficient of correlation is illustrated on Plate 75 which shows the results of correlations between Station 8NP-1 and the other stations considered. High correlation coefficients exist between the base station (8NP-1) and streams to the west of the base station. An analysis of these results and the results of other similar correlations using different base stations (not shown in the report) indicate the possibility of a single hydrologic zone extending in a belt about 50 miles wide along the International Boundary from the Alberta-British Columbia border to as far west as the Granby River. This zone would be classed as a "physically" homogeneous zone as outlined in Section 5. However, this possibility would have to be confirmed by more detailed study including the use of data from neighbouring streams in the U. S. A. In contrast, the trend in a northward direction deteriorates fairly rapidly with distance. Generally, for base stations located near the Canada - U. S. A. border, the values of the correlation coefficients drop significantly north of about latitude 50° north. This deterioration can possibly be explained by the rapid topographic and climatic changes which occur in moving northward into more rugged mountainous terrain. The implications for zone definition are discussed further in Sub-section 5.09.

8.06 EXTENDING MONTHLY STREAMFLOW DATA

8.06.01 Accuracy of Correlations

In order to assess the accuracy that can be expected from the Langbein method of extending streamflow records, the following test was devised. The long-term records for the Bull River near Wardner (Station 8NG-2) was sectioned into as many 2 year, 4 year, 8 year, 12 year and 16 year records as possible. Each section of the data was correlated with concurrent monthly flow records for each of the following stations: St. Mary River near Wycliffe (Station

8NG-12) and Elk River at Phillips Bridge near Elko (Station 8NK-5). The resulting regression equations were used to synthesize monthly mean flows for Station 8NG-2 from records of Station 8NG-12 and Station 8NK-5.

Differences between the synthesized data and the actual records were computed. The cumulative frequency distributions of the differences expressed as percent error are plotted on Plates 73 and 74.

An indication of the relatively good accuracy of the synthesized data can be obtained from a study of the graphs. At the 68% cumulative frequency level, the estimated standard deviation of the errors range from $\pm$ 18% using a relation based on 2 years of concurrent records to about $\pm$ 12% using the relation based on the long term concurrent data. The accuracy of the synthesized data shows little improvement with relations developed from overlapping records beyond eight years. It must be noted, however, that the stations used in the analyses are highly correlated (R=about 0.9). Further studies are required to test results for stations that are not so highly correlated.

8.06.02 Variation of Correlation with Length of Record

Plots of the correlation coefficients against the length of overlapping records are also shown on Plates 73 and 74. Enveloping curves are drawn to indicate the range of correlation coefficients as a function of the number of years of concurrent record used to establish the relationship. For periods of overlapping records of less than about 8 years, the correlation coefficient is seen to vary greatly from sample to sample. Hence, the correlation coefficients developed from short overlapping records may not be a good indicator of the possible accuracy with which the records may be extended. The United States Geological Survey have used a rigorous statistical approach to develop a technique for direct determination of how much longer a gauging station must be operated to obtain an estimate of the mean flow that is bounded within specified limits of statistical error. The findings of the study have not yet been published.

8.07 CONCLUSIONS

The above pilot study has demonstrated the potential usefulness of the correlation technique in relation to problems associated with hydrometric network design. In the light of the results discussed above, further investigation of the implications of this technique is recommended. In particular, additional correlation studies should be carried out wherever possible in the rest of the Province, using available data, as an aid to possible further refinement of the hydrometric network requirements.

SECTION 9

SECTION 9

REGIONAL NETWORK DESIGN

9.01 GENERAL

An important objective of the present study has been the design of a first stage regional hydrometric network, which will adequately sample stream runoff patterns to provide data for an inventory of the water resources of British Columbia.

The existing network has developed in response to specific project demands, and it is only in recent years, with the advent of the computer and the development of the relatively new science of hydrometric planning and design, that it has been possible to formulate a plan of stream gauging stations, the implementation of which would satisfy at least the basic needs for regionalizing streamflow data, throughout British Columbia.

The existing hydrometric network in the Province reflects the progress of economic development When the existing network is considered in terms of a regional hydrometric network, there is an imbalance in the the distribution of stream gauging stations. The coverage in the southern part of the Province is much greater than in the northern part where it is sparse and generally limited to large basins.

The importance and value of water as related to the development of British Columbia are such that systematic planning is considered mandatory if the hydrometric network is to provide the data necessary for a proper inventory of the water resources of the Province.

In planning a hydrometric network, it is essential to distinguish between two different categories; namely, a regional network and what can be called a project network.

(a) The objective of the regional network is to provide the information needed for estimating to an acceptable degree of accuracy, through various techniques of statistical and regional analysis, the flow characteristics at any point along any stream in the area covered by the network, for water resources planning. The regional network will have a density of station coverage which depends mainly on the hydrologic diversity of an area. A minimum level of data collection is therefore required in a regional network regardless of the state of present or prospective economic development.

(b) A network of project stations develops in response to particular water management needs. The station density of such a network is thus dictated by the specific point requirements of the user for project design and operation.

In the present assignment, the study has been directed primarily towards the design of a first stage regional network for British Columbia. It is recognized that the regional network should be developed in co-ordination with the existing project network. As of December 1968, there were about 500 discharge and water level stations in continuous operation. The results of the pilot regression study of the East Kootenay area (see Section 7) have indicated that data collected by the present network in that area, mainly for project or water management requirements, does not provide sufficient information for general water resources planning purposes. Since the East Kootenay region is one of the more intensively gauged in the Province, the general basic need for more hydrometric stations is evident. Consequently, emphasis in the design of the network has been placed on the requirements for additional stations needed to back up the present network.

Although the present network is predominantly project oriented, many of the existing stations should be incorporated into the design of the proposed network. No attempt has been made to distinguish all of the existing stations which should be included in the regional network. If a given station is presently located in what appears to be a suitable or desirable location, it was simply assumed to be acceptable as there was insufficient time to analyze the records for each station. It is recommended, however, that a thorough appraisal of the existing stations in relation to the designed network be carried out to assess which ones are needed to fulfill the requirements of the regional network and which ones might be considered redundant, in terms of the regional network.

The proposed additional stations have been selected after a study of 4 mile and 16 mile to the inch maps and a detailed investigation of individual sites was not possible. A more thorough study of both representative basin and individual station location including on-site examination, will possibly reveal particular locations or basins to be unsuitable for gauging or perhaps not representative of the region. In this case, selection of alternative locations would be recommended, keeping in mind that, wherever possible, sites should be selected where the regimen of natural flow will be less likely to be disturbed by man.

Before proceeding to an outline of the planning concepts considered to be suitable for British Columbia, some of the more general concepts will be reviewed in the following sub-sections.

9.02 GENERAL CONCEPTS OF NETWORK DESIGN

A comprehensive review of current thinking on hydrometric network planning is contained in the Proceedings of the Symposium on the Design of Hydrological Networks held in Quebec City in 1965. Many of the concepts presented at this Symposium are also summarized in the World Meteorological Organization publication "Guide to Hydro-meteorological practices," published in 1965. The main inspiration for principles outlined in this section has been drawn from these two important volumes. However, the design of the proposed network has been based to a considerable extent on the experience of the study team, with British Columbia conditions.

9.02.01 Network Density

The impracticability of gauging every stream in the Province dictates the need to develop a rational approach to the selection of those streams which should be sampled to provide the maximum amount of information possible with the minimum expenditure of time and money. The concept of estimating streamflow characteristics on ungauged streams from data observed on other streams using various analytic techniques has been stressed in Section 4. Network design thus seeks a proper balance between point measurement and areal analysis.

The next problem to be considered is the determination of the optimum number of point measurements required. This number will depend to a large extent on the particular technique being used to regionalize the collected data. Ideally, the optimum network density for a given technique could be determined by statistical methods. This approach requires that, in a particular hydrologic zone, a sufficient amount of data be collected from a fairly dense network of hydrologic stations, where such stations provide an adequate sampling of the range of all the important variables. The records so obtained would then be analyzed to selectively reduce the number of stream gauges in the network to the minimum necessary to provide regional estimates of streamflow data consistent with the desired degree of accuracy. This information, if determined for a selected pilot area, would be a valuable guide for the design of the network in other regions with similar climatic and physiographic characteristics. It is considered that in British Columbia, at the present time, more data would be required before this approach could be applied.

In a general fashion, it is still possible to make some assumptions concerning required densities of hydrometric stations. One of the most important aspects of statistical analysis is the significance of the results. For example, in order for a regression equation to be meaningful, it is essential to be able to form sound estimates of the reliability of the coefficients of the equation. To ensure an acceptable reliability for a given region, a certain minimum number of samples of the independent variables is required, as discussed in Section 4. It is a general statistical principle that there should be a minimum of about five sample measurements for each independent variable in the equation. As an illustration, if the regression model requires six independent variables to produce estimates of the dependent variable for a specified geographical area to a desired degree of accuracy, then at least 30 samples are needed. This specified geographical area corresponds to the statistically homogeneous hydrologic zone described in Section 5. In effect, this more general approach to evaluating network density requirements presupposes knowledge of the boundaries of limits of the zones within which a given regression model will be valid. As described in Sections 4 and 5, it has not been possible in the short time available to define the boundaries for statistically homogeneous zones in British Columbia.

The statistical approaches to determining minimum or optimum hydrometric network densities in British Columbia are presently limited by the lack of suitable data. Therefore, the design of the network must be based on a more qualitative assessment of network requirements, keeping in mind the need for data which will ultimately permit application of a more quantitative approach.

Ideally, the design of the network should be based on comprehensive economic studies which would evaluate desirable accuracy levels for the data collection program. Regional differences in these accuracy levels may be expected because of the variation in hydrologic regimes and the need for information. Specific or acceptable standards have not yet been established for British Columbia. It will therefore be necessary for additional studies to be carried out to establish desirable accuracy goals for the different types of streamflow, for the different regions of the Province, and for the various needs for hydrometric data. The U. S. Geological Survey has established a set of accuracy goals for the planning of streamflow data programs in the U. S. A., which could serve as a useful guide in selecting accuracy standards for Canadian conditions.

9.02.02 Network Planning

It is considered that the basic aim of the regional hydrometric network is to provide the information needed to estimate or synthesize the streamflow characteristics of any area in the Province with a minimum number of stations. As discussed by Langbein in a paper presented at the Symposium on the Design of Hydrological Networks, there seems to be general agreement that efficiency can be gained if the network is composed of long term base stations supplemented by short-term secondary stations.

Under this concept, a base network of long-term stations would be established and operated continuously over a long period of time, but not necessarily indefinitely. A period of about 50 years has been suggested as a possible duration. A few of the base network stations should be designated as bench-mark stations to be operated for an indefinite time period to document natural hydrologic changes with time. These stations should be located on small basins which are likely to remain essentially unchanged in future years. Both bench-mark and long-term stations are first order stations which use the best available techniques for accurately gauging streamflow.

An auxiliary network of short-term stations may be used to sample areal variations on smaller basins to provide additional information required for the application or development of regionalizing techniques. They would function just long enough to establish good correlation between them and nearby base network long-term stations. However, opinions are divided on the length of time for which short-term stations should operate and the duration may depend on the computational model being used to generalize observed data. The East Kootenay pilot correlation study discussed in Section 8, was conducted to assess the results of correlations between monthly streamflow records for a short-term station and those for a long-term station.

This study has produced some interesting preliminary information on the accuracy of the correlations and the variations of the correlations with the length of record at the short-term station. In addition, it is understood that the U. S. Geological Survey has developed criteria for estimating the length of time for which short-term stations need be operated for different conditions and purposes. More study of this problem will be required however before definitive conclusions can be reached. Short-term stations would normally be second-order stations which use simpler, perhaps portable, measuring techniques. Since such stations are less expensive, they could be operated in greater numbers.

Linsley and Crawford, in a paper also presented at the Quebec City Symposium on the Design of Hydrological Networks, have suggested that the use of short-term stations could be effective if rainfall and evaporation data are used as the basis for correlation. If this concept were adopted, it would be necessary to develop a well integrated total network of meteorologic and hydrometric stations. The acquired meteorologic data would also be used in conjunction with the regionalization of hydrologic data to provide estimates of streamflow characteristics for ungauged streams. Linsley and Crawford conclude that with data from both base long-term and short-term streamgauge networks and an expanding network of rainfall and evaporation stations, reasonable progress should be made toward the ultimate goal of wholly adequate flow estimates for any small stream.

In order to be able to regionalize streamflow information, it is essential to have natural flow regime data. Ideally then, regional network stations should be placed on streams where flows could be measured under natural conditions. In some parts of British Columbia, it may not be possible to realize this ideal situation, in which case stations may be located on modified regime streams where the flows are affected by man's activities. Some investigation will thus be required to assess the nature and extent of man made changes on streamflow. As an illustration, knowledge of the influence of lakes and reservoirs on natural flow regimes may be important to an understanding of regional hydrology in some areas, but because of their unique characteristics, it is not possible to regionalize information collected on them. In general, stations monitoring modified regime streams would be considered part of a secondary or perhaps project network rather than part of the regional base network.

9.03 PHILOSOPHY OF NETWORK DESIGN FOR BRITISH COLUMBIA

9.03.01 General

The principal purpose of a regional hydrometric network for British Columbia is to describe or explain the regional hydrologic regimes of the Province. The network should be designed so as to provide the information necessary to estimate or synthesize with a sufficient degree of accuracy the basic hydrologic characteristics of any area.

As it is not feasible to gauge every stream, gauging must be done on a sampling basis. This means that the network should include the capability to interpolate or regionalize the data collected, in order to be able to estimate information for the ungauged areas. This combination of sample gauging and regionalization of data by analytical techniques should provide sufficient information for most planning and design purposes. As discussed in Section 4 the network design is closely related to and must be compatible with the computational methods being used. One of the major objectives of the study was the assessment and testing of available techniques for regionalizing hydrologic data. It was considered initially that the network could then be designed to provide the information required for successful application of the more promising techniques. However, as indicated in Sections 6, 7 and 8, it was not possible in the time available to carry the testing of the techniques selected for evaluation beyond the point of assessing them as either promising or inconclusive. The lack of suitable data for regionalizing the various streamflow characteristics, as indicated by the East Kootenay pilot study, points up the need for additional data. This data will be required both to test promising regionalizing techniques and to provide the necessary basic information to be regionalized. As explained in Section 4, computational methods are in a stage of rapid development and hence the main aim of network planning at this stage must be to "keep all the options" open for the future and to feed back data to assist in the rapid development of computational techniques appropriate to British Columbia.

There seems to be general agreement that an ultimate stream gauging network should comprise several categories of stations which, in effect, form a series of complementary or intermeshing sub-networks. Typical of these categories are those proposed by the U. S. Geological Survey, for example, "current purpose data," and "data to document natural changes with time." The general validity of these categories is recognized, but at the same time it is considered that for the next few years, the data needs of British Columbia would be best served by a set of stations which can be classed as general purpose until further study permits a more specialized classification. In addition, there is a need at this stage to avoid a rigid classification of stream gauging stations which might result in obscuring or confusing the basic problem which is the urgent need for additional data in British Columbia.

The concepts which have been used as the basis for design of the regional network for British Columbia are outlined in the following sub-sections.

9.03.02 Proposed Regional Network

As discussed above, there is an immediate need for additional hydrometric stations in the Province which will provide basic data suitable for the application and development of promising regionalizing techniques. In particular, there is a pressing requirement for additional information on small streams with the emphasis placed both on areal and elevation stratification sampling. To meet these needs a first stage base network of hydrometric stations is proposed. In the design of the base network, specific recommendations are made for additional long-term stations only, and there has been no attempt to propose specific locations for other types of stations such as bench-mark, short-term, or peak flow stations. It is considered that specific proposals for secondary networks can be more usefully made at a later date following more detailed study. Some general suggestions are made however concerning secondary and research basin networks needed to provide important supplementary information.

(a) Base Network

In order to provide a suitable framework for the development of the regional network, a base network composed of long-term first order stations is proposed. This base network consists of two categories of stations: namely, representative basin stations and main stream stations. A representative basin is one which has been selected for systematic sampling of small streams within an established hydrologic zone and which, as far as possible, is typical of the basins in the zone. Following World Meteorological Organization terminology for temperate regions, a main stream is one which drains a catchment area of greater than about 400 square miles in mountainous regions and greater than about 1000 square miles in flat regiona. In this report a small stream is considered to be one which drains an area of less than 400 square miles, and a minimum drainage area of about 10 square miles is proposed for small basins which are included in the regional network. A major stream has been defined as one which has one or more main streams as tributaries. The roles of the representative basin and main stream stations are described in the following paragraphs.

(1) Representative Basin Stations

The main feature of the proposed base network is the representative basin concept which has been developed to permit a rational, detailed sampling of smaller streams to provide information representative of each hydrologic zone. The value of the hydrologic zones as an integral part of the network design now becomes evident. Since these zones have been selected to delineate areas of physiographic and hydrologic similarity, strategically placed representative basins in each zone can provide an adequate sampling of all physiographic variations in the Province with a minimum number of stations. The data collected should reflect the characteristic runoff behaviour within the given zone. As a general rule, an attempt is made to locate small stream stations within selected main stream basins. Where this procedure is not possible or desirable, a series of representative basin stations are placed on neighbouring small streams which may not necessarily belong to a single main stream basin but which are nonetheless representative of the area.

Several important considerations govern the decision to recommend a network of representative basins to sample smaller streams rather than a system of randomly scattered stations. By concentrating the smaller basins within one or more of the main stream basins, a much more detailed and comprehensive understanding can be gained of the hydrology of the area. The representative basins will thus function to some extent as research basins and as such will provide data for developing and testing the analytical techniques as well as the basic input for regionalizing the data. Secondly, the problem of access to the stations for servicing the gauges is simplified and the overall operating costs can be kept to a minimum if several stations are located reasonably close together. This very practical consideration is extremely important in a rugged and undeveloped area such as British Columbia.

A detailed description of the criteria for gauging representative basins is given in Sub-section 9.04.02.

As a general rule, representative stations should be placed in basins which have a natural flow regime which has not been modified by water management schemes such as storage or diversions. Ideally, these basins should then be preserved in their natural state and kept free from man-made interference of the natural flow. However, in many cases this may not be possible, in which event it will be necessary to carry out a detailed accounting of diversions and other modifications in order to be able to reconstitute the natural flow. Otherwise, the data cannot be used for estimating the flow on other rivers, an integral function of the regional network program.

The problems of assessing the effect of man's activities on hydrologic regimes have not been included in the scope of this report. Nonetheless, the need for a detailed investigation of modified regime streams is recognized. As one example, this problem is particularly acute in the southern interior of British Columbia where water is in limited supply and the demands for its use are correspondingly great. For this particular area, it has been recommended that priority be given to an appraisal of streamflow modifications as discussed in the description of Zone 6 in Sub-section 9.04. However, it is considered in general that the immediate effort would best be deployed in extending the natural regime network and avoiding the need for regional network stations on modified regime streams unless suitable natural flow streams cannot be found in any particular zone.

(2) Main Stream Stations

To supplement the representative basin network, it is proposed that gauges be installed on main streams. The major streams should be adequately sampled and probably most of the main streams should be gauged. Since streamflow integrates hydrologic variations for entire drainage basins, this additional system of major and main stream stations should provide a good overall inventory of water for the entire Province and a good understanding of its streamflow regimes. The main stream stations will also provide the necessary key to the extension across the hydrologic zones of information gathered on small streams in the representative basins. Most major streams are already adequately gauged but many additional main stream gauges will be required.

When priorities are established for installation of stations, it is recommended that at least one representative basin or series of representative basins be instrumented in each of the hydrologic zones as a first step since these stations are considered to be the main feature of the proposed base network. Second priority could be given to establishing the network of additional main stream stations with the remaining representative basin stations having third order priority.

As mentioned in Sub-section 9.02, it is desirable to have a few bench-mark stations to document long-term trends. However, it is understood that the Water Survey of Canada is participating in a program to establish bench-mark basins in the Province, so no further recommendations are made in this report.

(b) Secondary Network

The proposed base network outlined above is composed of a minimum number of long-term stream gauging stations. A secondary network of hydrometric stations or measurements is required to supplement the base network. As outlined below, the particular functions of this network are to provide immediate additional coverage of peak and low flows and eventually to increase the areal sampling of small streams as required for data regionalization purposes. Specific station locations have not been proposed, since more time would be required to design these supplementary networks than was available. A few general suggestions are presented to indicate the need for a secondary network, which are described in more detail in Section 4.

(1) Peak Flow Measurement

Flood or peak flows are periodic events, and do not need to be monitoried on a continuous basis. A secondary network of crest-stage gauges, which may be operated on a long-term basis is sufficient to monitor peak-flows. It is considered that considerable effort should be devoted to the development of simple techniques for measuring peak flows, and establishing a plan for the location of measurement points.

(2) Low Flow Measurement

Low or base flows cannot generally be regionalized by regression on basin parameters since they are dependent upon the ground water and geological regimes. Hence, some flow data is required at individual sites. Information on base flows can best be obtained by periodic spot measurements. This data can then be related to simultaneous flow at suitable long-term base stations. If sufficient information is available, correlations can be attempted between low flow and geology.

(3) Short-term Stations

As indicated in Sub-section 9.02, an auxiliary network of short-term stations may be the most economic method of sampling areal variations on smaller basins. No short-term stations are proposed at this time as it is considered that efforts should first be concentrated on developing the base network. It is recommended, however, that more attention be given to research and development of more portable stream gauging stations.

(c) Research Basin Network

In order to support the development needs of the regional hydrometric network, it may be desirable to form a small network of research basins as suggested in the following paragraphs:

(1) A research basin which is set up on small water sheds to investigate important components of the hydrologic cycle as dictated by the requirements for development of computational models to estimate runoff. Evaporation and snow melt are examples of two important problems which need attention in British Columbia. Many of the existing International Hydrology Decade research projects fall within this category.

(2) As mentioned earlier, the representative basins propos ed for the base network function as reasearch basins to some extent. If future studies indicate the need, some of these representative basins could be more intensively instrumented for network design purposes such as for development of modelling techniques to regionalize observed data. In addition to possible increased hydrometric coverage, additional information will be required on meteorological elements such as precipitation, temperature and snowpack water equivalent in selected representative basins. It is recommended that the planning of such research basins be closely coordinated with the planning of meteorological and snow course networks.

(3) In many areas it may not be possible to establish representative basins on streams where the natural flow regime has remained undisturbed. If detailed accounting of diversions, storage, land management or other man-made changes becomes necessary, it may be desirable to set up a type of research basin program in a few selected areas where the emphasis would be on the determination of the magnitude and nature of the modifications to natural flow.

9.04 ACTUAL NETWORK DESIGN

9.04.01 General

As outlined in Sub-section 9.02, the regional hydrometric network can be sub-divided into two main categories; namely, a base network and a secondary network. The actual design of the base network of continuous long-term stations is discussed in the following paragraphs.

As of December, 1969, there were over 500 discharge and water level stations in continuous operation in British Columbia. These existing stations have been included on the maps showing the proposed network (Plates 81 to 116). As mentioned previously, it was not deemed desirable at this time to distinguish all of these stations which could usefully be incorporated in the regional network without a thorough assessment of their records. Some existing stations are suggested for inclusion as part of the representative basin network but it should be emphasized that an appraisal of these stations has not been carried out. No seasonal or miscellaneous record stations have been considered in this report, as they would not be included in the base network.

The proposed base hydrometric network thus consists of a combination of existing continuous recording discharge and water level stations and the proposed additional discharge stations.

The nature of the terrain in British Columbia is such that large areas of the Province are practically inaccessible with most of the population residing in the richer valley floors. In many regions, particularly in the North, the existing network of roads is consequently very limited. Accessibility is thus one of the chief problems to be overcome in the development of the hydrometric network. This factor must be taken into account in the design and planning of the network and some attention has been given to locating representative basin stations in areas which appear from available maps to be reasonably accessible, that is, close to existing roads or to lakes.

9.04.02 Criteria Adopted

(a) Main Streams

As a general rule, most main and major streams are gauged to provide the necessary areal coverage of the entire Province. Where existing stations are suitably located on main streams, they have been accepted as part of the base network. As a result of adhering to this concept, some stations have been located in fairly remote areas. In a few cases, where two main stream basins are close together and more or less identical in size and shape, only one of the basins has been gauged. A suggested list of the major and main streams in British Columbia as determined from the 16 mile to the inch maps is presented in Appendix VI.

(b) Representative Basins

The concept of representative basins has been used to sample the smaller size catchment areas. As mentioned previously, the minimum basin area which should be gauged for regional network purposes is about 10 square miles while the upper limit is approximately 400 square miles. Beyond these two figures, no other restrictions have been placed on small basin size since there is a general need for data on basins of all sizes. These basins are generally selected within the zones so as to provide adequate coverage in both an east-west and north-south direction. That is, so as to permit interpolation between basins. Where the zone is relatively small and compact, only one representative large basin or series of small basins may be required (see Plate 94). If the zone is elongated (see Plates 104 and 105), as many as three main representative basins or series of basins have been recommended.

In many areas, it is possible to obtain a representative sampling of smaller basins within one larger main stream basin. In several zones, however, it has been necessary to sample a series of small basins which do not lie within a single main stream watershed in order to obtain adequate coverage. As a general rule, the principle of placing gauges in an east-west line across several zones has been followed. This procedure is used to sample variations across major physiographic regions such as the Columbia Mountains, the Coast Mountains and the North Interior.

The following general procedure has been used for placing stations in representative basins:

For a single main stream basin:

(1) A station is placed at the upper reach of the main stream to gauge a small drainage area of between 10 and 100 square miles depending upon the particular basin and area.

(2) A station is located at the mouth of the main stream. (This station could also be classified as a main stream station but has been considered in this report as belonging to the representative basin network shown in Plates 80 to 116.

(3) A third gauge is located on the main stream at a point where the flow between it and the upstream gauge is approximately double (or greater) or where there is a significant inflow between this station and both the upstream and downstream stations. If the main stream is relatively short in length, this third gauge may not be necessary.

(4) A gauge is placed on a small tributary which flows into the main stream at about the mid-point to obtain a sample of the centre portion of the main stream basin.

(5) Another small tributary at the lower reaches of the main stream is gauged to complete the sampling of areal or vertical stratification.

The side of the main stream on which the small tributaries are gauged will depend upon the drainage pattern of any given stream basin. In mountainous areas where even very small streams drain valleys with steep sides there are good arguments for gauging small tributaries on both sides of the main valley at both low and middle elevations, particularly where the valley is oriented in a direction perpendicular to the prevailing winds (i.e., westerly).

In mountainous areas, where main stream basins drain steep slopes such as in the Coast and Rocky Mountains, the gauging of small side tributaries provides a stratified sampling of low, middle and high elevation bands.

In other regions of more uniform relief, such as the flat Interior Plateau or even the Northern Interior uplands, the gauging of the lower, middle and higher reaches of the main stream provides an areal sampling which is required to pick up hydrologic variations created by climatic changes which can occur over regions of relative topographic uniformity.

In some areas, there are no single main stream basins which are appropriately situated so as to permit an adequate areal sampling. In this case, small basins, usually located in a west-east line in two or more main stream or larger basins are sampled. (See Plate 94).

The following paragraphs outline the reasons for the selection of proposed base network stations in each of the 29 Hydrologic Zones.

9.04.03 Hydrologic Zone Network

Zone 1: Vancouver Island

(See Plate 81.)

Vancouver Island, oriented in a northwest-southeast direction, is characterized physically by a ridge of mountains along its axis and hydrologically by very high runoff yields. There are several important lakes on the Island but few large rivers.

Most of the streamflow regimes in the western and southern parts of Vancouver Island are modified to some extent by storage, hydro-power diversions or the effect of extensive logging operations. Hence, it is unlikely that many of the existing stream gauging stations, most of which are concentrated along the eastern side of the Island, are monitoring natural flow regimes. One of the important objectives of the proposed base network must thus be the establishment of stations on streams which, as far as possible, have not yet been affected by man-made changes.

Three principal series of representative basin stations are proposed to sample variations from West to East across the mountains and also in the north-south direction.

The southernmost series comprises seven stations, two in the San Juan River basin, two to sample tributaries on both sides of Lake Cowichan, and three in the Nanaimo River basin. Three existing stations (8 HA-1, 8 HB-33 and 8 HB-34) are included in this series.

The second series of representative basin stations samples the middle of the Island. Three additional stations are proposed for the west side and two for the east side. It is recommended that special efforts be made to locate the two eastern stations on streams which will likely remain essentially unmodified by man's activities.

The northern series is composed of seven stations, one on a small stream flowing into Muchatat Inlet, four in the Gold River basin and two on the White River. Two existing stations are included in this series; namely, 8 HC-1 and 8 HC-2.

Two additional stations are proposed for the northern end of the Island, one main stream station on the Nimpkish River and one small stream station at the head of Alice Lake.

Zone 2: The Lower Fraser Valley

(See Plate 82.)

This zone comprises the flat alluvial plain of the Fraser River with its system of small, meandering streams. In this heavily populated area, the flow regimes of most if not all of even the smallest streams are certain to be modified. In view of the importance of the Lower Fraser Valley, in terms both of agricultural and urbanization, it is recommended that at least one small basin be preserved in its natural state as a representative basin to document and study the hydrology of this area. The selection of such a basin will require detailed study and no recommendations can be made at this time.

Zone 3: Coastal Mountains

(See Plates 83, 84 and 85.)

This zone lies along the rugged western slopes of the Coast Mountains and is characterized hydrologically by streams which drain high elevations, are fed by permanent glaciers and have a very high runoff yield.

Accessibility is one of the chief factors to be overcome in establishing stream gauging stations in this extensive zone. It is not surprising therefore that the present network is relatively sparse.

In adhering to the concepts of network planning outlined in this report, seven additional stations are proposed for the following rivers to complete the gauging of the main streams in the zone: Kitlope, Kimsquit, Kingcome, Dean, Southgate, Klinaklini and Toba.

The recommendations for additional representative basin stations have been strongly influenced by considerations of access to the suggested sites. Because of this factor, the proposed network is possibly only a skeleton of what may eventually be required to adequately define the regional hydrology of the coastal area. However, more study and indeed more data will be required before the need for a greater number of stations can be properly assessed. The proposed network should provide a practical beginning from which such an appraisal can evolve.

In the north, the highway between Prince Rupert and Terrace provides easy access to small tributaries of the Skeena River for sampling of variations from West to East. A series of three representative basin stations is proposed including the two existing stations 8 EC-11 and 8 EC-12. Two additional small stream stations near existing settlements are proposed for the northern area, one above Kincolith (Portland Inlet) and one near Kemano (Gardner Canal).

In the center portion of the zone, a series of four stations is proposed for the Wannock River basin, including one existing station (8 FA-2) situated above Rivers Inlet. Two existing small stream stations near Bella Coola (8 FB-4 and 8 FB-5) are also recommended for inclusion in the representative basin network.

In the south, the highway between Squamish and Lillooet provides ready access for west-east sampling of tributaries of the Chekamus and Green Rivers. A total of seven stations comprises this series of representative basin stations, including three existing stations (8 GA-54, 8 GA-56 and 8 GA-57). One main stream and one small stream station are proposed for streams flowing into the head of Toba Inlet.

A separate problem is posed by the rivers flowing into the Fraser River and Burrard Inlet at the extreme southern end of the zone. These rivers supply water for the heavily populated Lower Mainland (domestic use, hydro-electric power, etc.) and thus are already subject to much use. It is recommended that at least three representative basin stations be located on small streams which are or can be preserved in their natural state and which are spaced so as to sample variations from West to East. An existing station (8 GA-10) in the Capilano River basin (Greater Vancouver Watershed) is suggested as one such station, and it is proposed that the two additional stations could be located on tributaries flowing into Stave Lake and Harrison Lake respectively.

Finally, the Chilliwack River basin, situated along the Canada-U. S. A. border, is proposed as part of the representative basin network. The four existing stations (8 MH-1, 8 MH-56, 8 MH-103 and 8 MH-16) are sufficient and no additional stations are proposed for this basin.

Zone 4: Fraser Canyon

(See Plate 86.)

This zone is characterized by the narrow Fraser Canyon bounded on the east and west by steep sided mountains. Drainage areas are small and runoff relatively high.

The existing network appears to adequately sample the smaller streams at the southern end of the zone. Hence, only one series of representative basin stations is proposed to sample west-east variations across the center of the zone. On the west bank of the Fraser, four additional stations are proposed for the Nahatlatch River where there is relatively good access. On the narrow east bank, one new small stream station is proposed for a location opposite the mouth of the Nahatlatch River to continue the west-east series.

Zone 5: Cascade Mountains

(See Plate 86.)

This small zone comprises the northern extension of the relatively low Cascade Mountains into Canada. The main streams are gauged by existing stations. Two tributaries of the upper Similkameen River basin are proposed as representative basins to sample the variations from high to low elevation. One of these basins is already gauged by station 8 NL-36 and one additional station is proposed.

Zone 6: Southwest Interior

(See Plate 87.)

This zone covers the southern portion of the interior plateau and includes the highly developed Okanagan and central Thompson

River valleys. It is characterized by very low runoff yields due to low annual precipitation and high summer evaporation.

Because of its limited supply and fairly intensive use, water in this zone is a vital commodity and the existing hydrometric network has perhaps the highest density of stations of any region in the Province. As a result of this extensive development, most of the streams are already affected by diversions or storage for irrigation, municipal and other uses. In consideration of the above factors, few new stations are being proposed for this zone at this time. Instead, it is strongly recommended that priority be given to an appraisal of water management and other modifications to streamflow in this area. Such an appraisal is mandatory to judge the suitability of existing stations for inclusion in the base network and to assess the usefulness of existing streamflow records for planning purposes.

For the plateau area west of the Okanagan Valley, the Nicola River basin above Nicola Lake and the Meadow Creek basin in the Lac le Jeune area are suggested as possible representative basins for the base network. There are six existing stations in these basins. It is possible that the locations of most of these stations are unsuitable due to the problems of accounting for diversions and storage. In this case, additional small basins where natural flow regimes can be measured should be selected. These small basins should be located both in the mountains to the west of Lake Okanagan and north of Merritt, important source areas, and if possible, in the flat plateau area where the problems of irrigation and evaporation are most critical.

One additional main stream station is proposed for Spius Creek near Merritt.

In the Okanagan Valley, most of the streams appear to be subject to water management schemes. However, for base network purposes, it is recommended that a series of representative basin stations be selected or located near the mid-point of Lake Okanagan to sample variations from West to East across the valley. To illustrate this concept, Lambly Creek basin on the west side of the Valley and Mission Creek basin on the east side are suggested as representative basins. For the Lambly Creek basin, two additional stations are proposed to complement the two existing stations (8 NM-138 and 8 NM-139), one at the mouth of Lambly Creek and the other on a small tributary at a medium elevation. In the Wilson Creek Basin, one additional station at the headwaters is proposed to complement the three existing stations (8 NM-116, 8 NM-129 and 8 NM-137).

Where small lakes at the headwaters of these and other streams are dammed to form reservoirs, it is recommended that the flow from these reservoirs be monitored so that natural flows downstream can be reconstituted.

Zone 7: Southern Monashee Mountains

(See Plate 88.)

This zone covers the southern end of the general west-facing slopes of the Columbia Mountain area. It is characterized by broad river valleys, a north-south drainage pattern and runoff yields which increase from west to east.

The existing hydrometric network in this zone is relatively sparse with several stations concentrated on the major rivers. However, because of the nature of the drainage pattern, a minimum number of base network stations should provide fairly good coverage.

The West Kettle River basin is proposed as the representative basin to take advantage of two existing stations (8 NN-15 and 8 NN-19). Two additional stations are proposed, one on the main stem of the West Kettle (a main stream station) and one on a small tributary.

A main stream station is proposed for the Kettle River above the junction with the West Kettle, and a small stream station is proposed for the Granby River to augment the sampling of west-east variations.

Zone 8: Kootenay Highlands

(See Plate 88.)

This small zone covers a region of uniform rugged highlands with a relatively non-uniform drainage pattern. Runoff yields are moderate.

The base network should provide a sampling of small basins across the zone in both the north-south and east-west directions. The existing road system provides fairly good access to most streams. The Salmo River basin above existing station 8 NE-74 is proposed as a representative basin and three additional stations are recommended for this basin. Two other new stations are proposed to sample small streams flowing into Kootenay Lake. It is suggested that existing stations (8 NH-84 and 8 NJ-61) could be incorporated into the base network if they are gauging natural flow regimes.

No additional main stream stations are required in this zone.

Zone 9: East Kootenay Area

(See Plate 89.)

This zone straddles the southern portion of the Rocky Mountain Trench and takes in the steep eastern slopes of the Purcell Mountains and the equally rugged western slopes of the Rocky Mountains. Near the Canada-U. S. A. border, the mountains of both ranges are lower and the relief more uniform. Small glaciers cap the higher peaks on both sides of the Trench in the northern half of the zone.

The existing network at the southern end of the zone appears to be relatively dense but some of these stations are situated on streams affected by diversions or storage. Further north, except for a few stations gauging small streams in the Trench area near Windemere Lake, most of the stations are located on the main stem of the Columbia or Kootenay Rivers. Consequently, although the existing network provides adequate coverage of the main streams, there is almost no sampling of small basins, especially at higher elevations.

To sample the variations from West to East across the zone, a series of three lines of representative basin stations is proposed. These lines of stations are situated about 50 to 60 miles apart so as to permit interpolation of data in the north-south direction.

The northernmost series of additional representative basin stations is located along the Trans-Canada Highway between Rogers Pass and Kicking Horse Pass. Three stations are located on the eastern slope of the Purcell Mountains, two in the Beaver River basin and one on a small tributary of the Columbia River. Five stations are situated in the Kicking Horse River basin on the western slope of the Rocky Mountains. These stations have been placed as outlined above in Sub-section 9.03.02 with three stations on the main stem of the river and two on side tributaries so as to provide a good sampling of different elevation bands.

The central series of representative basin stations is located along latitude 50.5° north. Toby Creek which drains into the Columbia River from the west contains three additional stations while two more are proposed for the Palliser River basin which flows into the Kootenay River from the east. It is recommended that the existing gauge on the Windemere Creek (8 NA-24), which drains into Windemere Lake from the Stanford Range adjacent to the Rocky Mountain Trench, be included in this representative station network to complete the series.

The southernmost series of representative basin stations is situated just north of latitude 49.5^{o} north and samples the lower mountains found at this end of the zone. The St. Mary River which flows into the Kootenay River near Cranbrook has been selected as the representative basin on the eastern slopes of the Purcell Mountains. The two existing stations located on the main stem of the St. Mary (8 NG-12 and 8 NG-46) are reasonably well placed and are included in the representative basin network. Three additional stations are proposed to sample small drainage basins at low, middle and high elevations.

To the east, the normal upslope or east-west drainage pattern in the Rockies is disrupted by the north-south orientation of the Bull and Elk Rivers, both of which are classed as main streams. The existing stations on the Bull (8 NG-2) and the Elk (8 NK-16) Rivers are included in the representative basin network. Four additional stations, two each on the Bull and Elk Rivers, are proposed to sample small tributaries draining the east- and west-facing slopes of these two rivers.

Only one additional main stream station is proposed for this zone and it is located on the White River.

Zone 10: Selkirk Mountains

(See Plate 90.)

This elongated zone is characterized by steep rugged mountains which are dissected in the south by several ribbon like lakes. Most of the streams have very high yields and in the north are fed by permanent glaciers. Accessibility is one of the main problems to be faced in gauging this mountainous area.

Three series of representative basin stations are proposed to sample variations from West to East across the zone. The two southernmost series are linked with series of stations in adjacent Zones 9 and 11 to complete the sampling of small basins from West to East across the entire Columbia Mountain range.

In the South, a series of five stations is proposed which comprises two existing stations (8 NE-6 and 8 NH-7) and three additional stations.

The middle series of representative basin stations is located along the Trans-Canada Highway between Revelstoke and Rogers Pass.

Two existing stations (9 ND-13 and 8 ND-14) and four additional stations are proposed for this series.

At the northern end of the zone, two additional stations are located near the Yellowhead Highway to sample streams lying in the lee of the Cariboo Mountains.

The base network proposed for this zone is composed of a bare minimum number of stations. It is considered that this network should provide the information upon which the design of a more complete network for this difficult and remote area can be based.

Zone 11: South Thompson Area

(See Plate 91.)

This zone covers the upper bowl-shaped drainage area of the South Thompson River, and is characterized by several important lakes. Annual runoff varies from very low near the Interior Plateau to relatively high at the Monashee Mountains divide.

The base network should provide greater sampling of smaller basins in the higher yield eastern portion of the zone. A minimum six additional representative basin stations are proposed to meet these requirements. Three are located in the upper Shuswap River basin above Sugar Lake, one on the Shuswap itself and two on small tributaries draining the eastern and western slopes of the valley. Two additional stations are located on small streams along the Trans-Canada Highway between Salmon Arm and Revelstoke and the sixth station is situated on the Seymour River. Existing stations 8 LC-34 and 8 LE-77 are recommended for inclusion in the representative basin network.

The proposed stations have been selected so as to continue or complete the west-east sampling of small streams across the Columbia Mountains (refer to Zones 10 and 9). Since the Shuswap River is presently under study for possible diversion to the Okanagan Valley, it has not been considered appropriate to recommend a greater number of stations in this area at this time.

No additional main stream stations are required in this zone.

Zone 12: Central Rocky Mountains

(See Plates 92 and 93.)

This zone covers the central portion of the Rocky Mountain Trench with its steep, rugged eastern and western facing valley slopes. The small streams in this zone are characterized by a general east-west drainage pattern and high runoff yields augmented by melt from the many permanent glaciers.

As with many of the mountainous areas of the Province, the remote location of much of this zone poses certain problems as far as stream gauging is concerned. The placement of representative basin stations follows the principle of continuing the series of stations sampling west-east variations from one zone to the next.

Since the southern boundary between Zones 12 and 9 is somewhat arbitrary, the series of stations located along the Trans-Canada Highway at the northern end of Zone 9 can be considered as applicable to the southern portion of Zone 12.

A second series of representative basin stations is proposed for streams along the Yellowhead Highway and includes three existing stations (8 NC-3, 8 KA-7 and 8 KA-8) plus two additional stations.

Three additional representative basin stations are proposed for streams draining the higher elevations of the McGregor River basin.

An additional three main streams stations are also proposed for this zone to gauge the Morkill, Holmes and Raush Rivers.

Zone 13: Cariboo Mountains

(See Plate 94.)

This zone covers the western slopes of the Cariboo Mountains where the foothills rise gradually from the interior plateau to encounter the steep high elevation slopes that descend abruptly from the snow covered topographical divide to the east. The hydrology of the zone is dominated by high yields from streams draining the higher elevations which feed principally the Quesnel and Clearwater River systems. There are also a number of important lakes in this area.

The existing hydrometric network provides reasonably good coverage of both the lakes and the important streams draining high and lower elevations.

As topographic variation within Zone 13 is relatively uniform, four additional stations only are recommended, in order to augment the sampling of smaller streams. The first proposed station is located at the upper reaches of the Horsefly River while the other three gauge small tributaries in the high yield area of the upper Clearwater River. In addition to these four new stations, three of the existing stations are to be included in this series of representative basin stations to complete the sampling of streamflow variations in the west-east line from dry plateau to wet mountain tops; namely, stations 8 KH-40 and 8 KH-20 on the Horsefly River near Horsefly and station 8 LA-13 at the outlet of Hobson Lake.

No additional main stream stations are required in this zone.

Zone 14: Upper Fraser River

(See Plate 95.)

This zone covers the area at the great bend of the Fraser River and is characterized by northward flowing streams with moderately high runoff yields.

Two complementary series of representative basin stations are proposed to sample north-south and east-west variations. The Bowron River basin is proposed as the principal representative basin. In addition to the existing main stream station on this river, 8 KD-4, four new stations are proposed, one on the Bowron itself and three on tributaries. To complete the east-west pattern from the Bowron River to the Rocky Mountain Divide (Zone 12), three additional representative basin stations are proposed for the southeast corner of the zone.

One additional main stream and one new small stream station are proposed for the Herrick Creek basin in the northeast part of the zone.

Zone 15: Central Interior

(See Plates 96 and 97.)

This zone comprises the dry central interior plateau. The major streams in the area drain eastward into the Fraser River which flows southward along the eastern border of the zone.

In the north, the Nechako River system is dominated by a series of large lakes which are not typical of the plateau area in general. In addition, part of the Nechako River is regulated for the purposes of diverting water westward to Kemano. For these reasons, no representative basin stations are being recommended for this river basin.

Most of the existing stations are concentrated along or adjacent to the main stems of the Fraser and Nechako Rivers. The base network should thus be designed to sample smaller basins in the vast ungauged area in the center of the plateau.

Two series of representative basin stations are proposed to achieve this goal. To sample variations from north to south, the Nazko River basin has been selected. In addition to the existing main stream station 8 KF-1, five new stations are proposed. To sample east-west variations, five additional stations are proposed for the West Road River basin.

Six additional stations are recommended for the following rivers to complete the areal coverage of this zone: Dean, Euchiniko, Chilcotin (2), Endako and Beaver.

The proposed number of representative basin stations appears small in comparison to the size of the zone. However, it is deemed advisable at this time to collect at least some information on the hydrologic variations across the zone before proceeding to a more ambitious expansion of the base network. One particular problem which needs investigating, for example, is the minimum size of basin which should or need be gauged by base network stations in this large, relatively uniform area of very low runoff yields.

Zone 16: Eastern Slopes - Coast Mountains

(See Plates 98 and 99.)

This zone lies along the eastern slopes of the rugged Coast Mountains between latitudes 50.5^{o} and 54.5^{o} north and is bounded on the west by the topographical divide and the east by the interior plateau. It has been sub-divided into three sections on the basis of drainage pattern and directions of flow. In general, runoff yields vary from moderate to high near the divide to very low near the plateau.

The existing hydrometric network in this zone is very sparse despite the importance of the eastern slopes as a source area for the dry plateau country to the east. Once again, accessibility must play an important role. The establishment of additional snow courses in this region is recommended as a relatively inexpensive method of sampling the more inaccessible areas.

Sub-Zone 16A

Rivers in this zone flow eastward into the Fraser River system. Most of the existing stations are concentrated in the Bridge and Seton River hydro-electric development complex at the southern end of the zone and are gauging flows affected by storage or diversion.

The Taseko River basin is proposed as the main representative basin for the zone. The establishment of five additional stations is recommended, four of which are located on small tributaries to sample the possible variations from high to low elevation including at least one glacier-fed stream.

One additional station is proposed for the Hurley River.

Sub-Zone 16B

Rivers in this zone originate near the edge of the interior plateau and flow westward through deep valleys into the Pacific Ocean. The existing network consists of four stations only.

A series of representative basin stations is proposed for the Bella Coola River basin in order to incorporate existing stations, to take advantage of the proximity of settlements and roads, and to complement the proposed system of representative basin stations in the Bella Coola and Wannock River basins on the coastal side of the mountains (Zone 3). In addition to existing stations (8 FB-6 and 8 FB-7), four new stations are proposed.

One additional main stream station is proposed for the Iltasyuko River.

Sub-Zone 16C

Water in this zone again flows towards the east. This area is dominated by large lakes, particularly those which form the headwaters of the Nechako River system which is regulated for diversion to the west. For this reason and since lakes have unique characteristics which makes regionalization of lake flow data questionable, no new stations are recommended for this zone at this time.

Zone 17: Nass-Skeena River Basins

(See Plate 100.)

This zone encompasses a rather complex area. It contains the major valleys of the Nass and Skeena Rivers flanked on the west by the glacier dominated lee slopes of the Coast Mountains and on the east by the western slopes of the Skeena Mountains. Runoff yields are moderate to high over the entire zone due to the funnelling of moist Pacific air into the heart of the zone via the gorges of these two major rivers.

Two series of representative basin stations are proposed, one to sample the lee side of the Coast Mountains at the southern end of the zone and the second to sample west-east variations further north.

The southern series comprises three additional stations located in the Kitsumkalum River basin near Terrace. There is good access to this basin via existing roads.

The northern series of representative basin stations consists of five additional stations located in the Upper Nass River basin, two on the Nass itself and three on smaller tributaries. It is also recommended that consideration be given to including the existing station 8 DA-5 in this series to complete the west-east sampling of small basins.

A total of eleven additional main and major stream stations are proposed for this zone for the following rivers: Kitwanga, Telkwa, Skeena, Babine, Sicintine, Bulkley, Kiteen, Cranberry, White, Bowser and Bell-Irving.

Zone 18: North Central Plateau

(See Plate 101.)

This zone covers the northern end of the Interior Plateau and is characterized by the large, important lakes of the Stuart and Babine River systems. Runoff yields, although still relatively low, are higher than in the main plateau area to the south.

Two series of representative basin stations are proposed for this zone. The choice of basins for this purpose is limited and essentially dictated by the dominance of the lakes system. It is considered, however, that the minimum number of stations recommended will provide a basic insight into variations both from south to north and from east to west.

One series of three additional stations is proposed for the Nilkitkwa River basin located in the northwestern part of the zone.

A second series of representative basin stations is proposed for the Salmon River basin in the eastern end of the zone and comprises two existing stations (8 KC-1 and 8 KC-2) plus four additional stations.

Three additional main stream stations are proposed for the Crooked, Fulton and Bulkley Rivers.

Zone 19: Albertan Plateau

(See Plate 102.)

This zone comprises the southern portion of the interior plains area, most of which is drained by streams flowing into the Peace River which passes through its center. Runoff yields in the zone are generally low.

The existing network consists of nine stations, five of which are located on major rivers. There is thus a need for increased sampling of smaller basins.

Two series of representative basin stations are proposed. One series of stations is located in the southern half of the zone and comprises one existing station (7 FD-1) and two new stations in the Kiskatinaw River basin plus one additional station on the upper Red Willow River. This latter station has been placed in this basin rather than in the Kiskatinaw basin because of easier access via an existing road.

The second series is located in the northern half of the zone in the Beatton River basin and is composed of four additional stations.

Three additional mainstream stations are proposed for the Doing, Bucking Horse and Cameron Rivers.

Zone 20: Fort Nelson Lowlands

(See Plate 103.)

This zone covers the northern portion of the interior plains area and is characterized by relatively uniform low relief and a rather marshy terrain. This region is drained by several moderately large river systems but runoff yields are low.

The sparseness of the existing network which consists of only three stations, all located on major rivers, points out the problems of accessibility and the remoteness of this zone. These two factors have been taken into account in considering the recommendations for representative aasin network and the number of new stations proposed has been kept to a minimum.

One series of three additional stations is proposed to sample the potential higher yield area along the ridge at the southern end of the zone. One of these stations is located on the Kahntah River, a main stream while the other two are located in the Gutah Creek basin adjacent to the headwaters of the Kahntah River Basin. The positions of these latter two stations have been selected so as to take advantage of existing roads.

A second series of five additional representative basin stations is proposed for the Snake River basin to sample smaller streams in the central portion of the zone.

One additional small stream station is proposed for the foothills area of the Rocky Mountains (Tanaka Creek) to complete the west-east series of stations located in Zones 21, 22 and 23 to the west and in the Snake River basin to the east.

A total of eight additional main stream stations are also proposed for the following rivers:

Kotcho, Hay, Fontas, Sikanni Chief, Prophet, Kiwigana, Petitot and Beaver.

Zone 21: Eastern Slopes - Rocky Mountains

(See Plates 104 and 105.)

This zone lies along the British Columbia portion of the eastern slopes of the northern Rocky Mountains. Most of the streams drain eastward into the interior plains region. Runoff yields, although higher than in the area to the east, are still relatively low in comparison with the mountain zones to the west.

Only one existing station lies within the boundaries of the zone although there are a few major river stations in Zones 19 and 20 to the east which gauge flow arising in Zone 21.

In order to sample variations from north to south, three main representative basins are proposed. Within these basins, the stations are placed so as to adequately sample smaller basins from high to low elevations in the east-west direction. It should also be pointed out that these three basins form one link in the series of basins selected to provide a more or less continuous east-west sampling across the mountainous areas of the interior of the Province.

In the north, a series of five additional representative basin stations are proposed for the Tuchodi River basin. These stations are placed in the typical manner prescribed in Sub-section 9.03.02 for single main stream basins. It should be noted that streams in the northern third of the zone are fed by permanent glaciers.

Near the center of the zone, another "typical" series of five additional stations is proposed for the Graham River basin.

In the south, a third series of six additional stations is proposed for the Murray River basin.

An additional seven main stream stations are also proposed for the following rivers: Racing, Dunedin, Prophet, Halfway, Moberly, Sukunka, and Wapiti.

Zone 22: Northern Rocky Mountains

(See Plates 106 and 107.)

This narrow, elongated zone lies along the western slopes of the northern Rocky Mountains. Most of the streams drain into the Rocky Mountain Trench and have moderate runoff yields.

Three series of representative basin stations are proposed for this zone following the same reasoning outlined for Zone 21.

Five stations are proposed for the northernmost series. Four of these are located in the Kwadacha River basin, including one existing (7 EA-2) and three new stations. One additional station is located on an adjacent low elevation small stream.

Near the center of the zone, three additional stations are proposed for the Ospika River basin.

In the south, a series of four additional stations is proposed, three in the Misinehinko River basin and one on an adjacent low elevation small stream.

Two additional main stream stations are proposed for the Gatoga and Akie Rivers.

Zone 23: Omineca Mountains

(See Plates 108 and 109.)

This zone covers the eastern portion of the north interior mountains or rugged uplands while Zone 24 covers the western portion. All streams in Zone 23 drain eastward into the Rocky Mountain Trench and have moderate runoff yields.

The existing network covering streams within the zone consists of two stations only located at the southern end of the zone.

The nature of the topography is such that the base network should provide an areal rather than an elevation sampling of medium to smaller basins. Two series of representative basin stations are thus proposed, both of which link up with the general west-east series of stations in adjacent zones.

The northernmost series consists of two additional stations located in the Bower Creek basin, near Ware.

Further south, a second series of six representative basin stations is proposed for the Omineca River basin. Two of these stations are located on the main stem of the Omineca, one existing (7 EC-1) and one new, and four additional stations are situated on smaller tributaries to provide an adequate west-east sampling.

The proposed number of representative basin stations is minimal as it is considered that further study is required before a greater number of small stream stations should be recommended.

A total of six additional main stream stations are proposed for the following rivers: Ingenika, Pelly, Mesilinka, Osilinka, Manson, and Frog.

Zone 24: North Central Uplands

(See Plate 110.)

This zone is centered over the north interior mountains and is composed mostly of rough, irregular uplands which are carved into blocks by the headwaters of several important streams.

The existing network covering streams within the zone consists of only three stations, one of which lies outside the zone. All are located on main rivers in the western corner of the zone which lies near the Coast Mountains and receives a proportionately higher precipitation than does the rest of the region.

The topography of this zone is such that the base network should provide an areal sampling of smaller drainage basins rather than an elevation sampling. Two series of representative basin stations have thus been selected to give adequate east-west coverage in both the northern and southern parts of the zone. These two lines of stations are situated approximately 90 miles apart.

The northern series of representative basin stations straddle the parallel of latitude 57.5° north. Four stations are located on the Spatszizi River, a tributary of the Stikine River, and another further upstream on the Chukachida River. The sixth station, which normally would have been placed so as to gauge a relatively small drainage area at the headwaters of the Chukachida River, has been displaced to the south to cover a small basin of equal size and similar topography which drains into a tributary of the Finlay River. This basin was selected because of its proximity to an existing road for ease of access.

The southern series of representative basin stations are all located in the Sustut River basin which drains into the Skeena River. Six stations are proposed, three on the main stem of the Sustut and three on small tributaries, including one at the outlet of Bear Lake. This latter station is included as there are several lakes of similar size in the zone and because of its convenient location. Both the Spatszizi and Sustut Rivers are classed as main streams.

No additional stations are proposed for streams located in the north-west corner of the zone since the characteristics of this particular area are not representative of the rest of the zone and the existing stations should provide adequate coverage. One proposed main stream station is shown on Mess Creek but most of the runoff at this station originates in Zone 25.

Five additional main stream stations are proposed for the following rivers: Pitman, Stikine, Finlay, Firesteel and Skeena. These stations are well distributed and complement the smaller stream stations to give good overall areal sampling.

Zone 25: Lee Slopes - Northern Boundary Ranges

(See Plates 111 and 112.)

This zone covers the lee slopes of the Northern Boundary or Coastal Mountain ranges, an extremely rugged area characterized by extensive permanent snowfields and glaciers. Most of the zone is drained by small high elevation, high yield streams.

The existing network, covering streams within the zone, consists of seven stations, one of which lies outside the zone boundary.

A total of seven additional main stream stations are proposed for the following rivers: Sloko, Sutlahine, Chutine, Scud, More, Jekill and Samotua. One additional main stream station is located in Zone 24 but most of the runoff originates in Zone 25.

It is considered that the combination of existing stations and proposed main stream stations is sufficient to adequately sample the zone and no additional small stream stations are recommended.

Zone 26: Yukon Plateau

(See Plate 113.)

This zone is centered over the southern portion of the Yukon Plateau which lies in the rain shadow of the Coast Mountains, and includes the major Teslin and Atlin Lake systems. Runoff yields in this zone vary from low in the central valley bottom to moderate along the eastern and western boundaries.

The existing network consists of a number of stations in both the northwestern and southeastern corners of the zone while the central portion is essentially ungauged.

The nature of the drainage pattern makes this zone a difficult one to gauge in terms of a representative basin network. However, there is a need to sample variations from west to east across the plateau. To provide this sampling, a series of eight additional representative basin stations are proposed, three in the Nakina River basin to the west of the Teslin River, and five in the Jennings River basin on the east side of the Teslin.

Four additional main stream stations are proposed for the following rivers: Sheslay, Inklin, Tahltan and Klastline.

Zone 27: Liard Plain

(See Plate 114.)

This zone encompasses a semi bowl-shaped area with the Liard Plain at its centre and the Cassiar and Rocky Mountains and Liard Plateau around its southern perimeter. All the streams in this zone flow eventually into the Liard River which passes through the northeastern sector of the zone. Runoff yields within the zone are relatively low.

The existing network consists of ten stations, six of which are located on major rivers. Hence, as in most of northern British Columbia, there is a requirement for increased sampling of smaller streams.

Three series of representative basin stations are proposed to sample the western, southern and eastern parts of this semi-circular zone.

On the eastern slopes of the Cassiar Mountains, one new and two existing stations (10 AC-4 and 10 AC-5) comprise the proposed western series.

Along the southern perimeter, a series of four additional stations is proposed, three in the Dall River basin and one on the Major Hart River.

To the east, a series of five additional representative basin stations is proposed, three in the Trout River basin at the northern extension of the Rocky Mountains, and two in the Smith River basin which flows into the Liard River from the north.

A total of ten additional main stream stations are proposed for rivers in this zone. Stations on the following eight rivers are located within the zone boundaries: Eagle, Turnagain, Rapid, Red, Rabbitt (2), Fishing Creek, Grayling and Crow. The tenth station is located on the Little Rancheria River near the Alaska Highway in the Yukon Territory.

Zone 28: Northern Coast

(See Plate 115.)

This small zone covers an area of high glacier covered mountains where the streams are assumed to have a high yield. There are no existing stations within the zone and only one additional small stream station is proposed for the Haines River for inventory purposes.

Zone 29: Queen Charlotte Islands

(See Plate 116.)

This zone comprises the off-shore Queen Charlotte Islands. The relatively few streams have a high runoff yield.

The existing network consists of only two stations (8 OA-2 and 8 OB-2). Two additional stations are proposed to increase the areal sampling of small streams. All of these stations could be considered as representative basin stations.

9.05 CONCLUSION

A plan for a first stage regional hydrometric network of long-term base stations has been formulated, and the addition of approximately 300 new stations is recommended. The proposed locations for these stations are shown on Plates 80 to 116 to illustrate the areal distribution of the recommended network. The existing network of stations in continuous operation, numbering approximately 500, has also been shown on these Plates. The design of the proposed network has been based not only on the concepts which have been developed herein for the initial planning of a regional network in British Columbia, but has also been influenced by the experience and judgement of the study team. The network has been outlined in detail firstly to illustrate the design concepts in concrete terms, and secondly with the purpose of providing a practical basis for the early implementation of the network.

At this preliminary stage of network planning, the acquisition of data and hence the implementation of an adequate network of base stations is of primary importance. Some general suggestions for secondary networks have also been presented but no specific proposals for secondary network stations have been made. Further studies will be needed to establish criteria and to design networks for additional peak and low flow measurements and eventually, if found necessary, for short-term stations.

There is an urgent requirement for an assessment of existing station records to appraise the value of these records for regionalization purposes and to indicate which existing stations could be incorporated into the regional base network. The particular need for a detailed accounting of modifications to natural streamflow in some areas of the Province has been pointed out. An appraisal of existing stations will thus reveal also the extent to which an investigation of modified regime streams is required.

Detailed planning of the regional network will ultimately depend on knowledge of the accuracy requirements for data collection and data use, and additional studies are recommended to establish accuracy goals for network design in British Columbia.

Network design is an evolutionary process and the present study represents only the first phase of this process. As it develops, the network should be responsive to improvements in instrumentation, computational techniques and the over-all methods of collection, analysis and processing of data. If an adequate program of planning and development is carried out in these three areas then the optimum network will evolve in a logical and orderly fashion.

SECTION 10

SECTION 10

REFERENCES

BOOKS AND MANUALS

Beard, L. R.	Statistical Method in Hydrology. U. S. Army District, Corps of Engineers, Sacramento, California, 1962.
Bruce, J. P. Clark, R. H.	Introduction to Hydrometeorology. The Pergamon Press Limited, Toronto, 1966.
Chapman, J. D. Turner, D. B.	British Columbia Atlas of Resources. British Columbia Natural Resources Conference, 1956.
Chow, V. T.	Handbook of Applied Hydrology. McGraw-Hill Book Company, New York, 1964.
Ford, P. M.	Multiple Correlation in Forecasting Seasonal Runoff. U. S. Bureau of Reclamation Eng. Monograph No. 2, 2nd ed., rev., June 1959.
Kendrew, W. G. Kerr, D.	The Climate of British Columbia and the Yukon Territory. Queen's Printer and Controller of Stationery, Ottawa, 1955.
Kuiper, E.	Water Resources Development. Butterworth & Company, London, 1965.
Langbein, W. B. Hoyt, W. G.	Water Facts for the Nation's Future. The Ronald Press Company, New York, 1959.
Linsley, R. K. Kohler, M. A. Paulhus, J. L. H.	Applied Hydrology. McGraw-Hill Book Company, New York, 1949.
	Guide to Hydrometeorological Practices. World Meteorol. Organization. WMO-No. 168. TP. 82, 1965.

BOOKS AND MANUALS (Cont'd)

Proceedings of Hydrology Symposium No. 4 - Research Watersheds. National Research Council of Canada, 1964.

Runoff from Snowmelt. U. S. Army Corps of Engineers, Engineering and Design Manual 1110-2-1406. January, 1960.

REPORTS

Chin, W. Q. — Formula and Tables for Computing and Plotting Drought Frequency Curves. Canada Dept. of Energy, Mines and Resources, Inland Waters Branch, Tech. Bull. No. 8, 1967.

Collier, E. P., Nix, G. A. — Flood Frequency Analysis for the New Brunswick Gaspe Region. Canada Dept. of Energy, Mines and Resources, Inland Waters Branch, Tech. Bull. No. 9, 1967.

Coulson, A. — (i) Flood Frequencies of Nova Scotia Streams. Canada Dept. of Energy, Mines and Resources, Water Resources Branch, Tech. Bull. No. 4, 1967.

(ii) Tables for Computing and Plotting Flood Frequency Curves. Canada Dept. of Energy, Mines and Resources, Water Resources Branch, Tech. Bull. No. 3, 1966.

Coulson, A., Gross, P. N. — Measurement of the Physical Characteristics of Drainage Basins. Canada Dept. of Energy, Mines and Resources, Inland Waters Branch, Tech. Bull. No. 5, 1967.

Davis, D. A., Coulson, A. — Hydrologic Zones in the Headwaters of the Saskatchewan River. Canada Dept. of Energy, Mines and Resources, Inland Waters Branch, Tech. Bull. No. 6, 1967.

Glassco, J. G., Therrien, F. E., Sellar, W. — Final Report of the Royal Commission on Government Organization. Government of Canada, February, 1963.

Glennie, J. F. — A Hydrological Study of the 1948 Flood in the Stuart River Basin, British Columbia. The University of British Columbia, April, 1963.

Lyons, R. O'N. — LACOR Program for Streamflow Correlation. Canada Dept. of Northern Affairs and National Resources, Water Resources Branch, Tech. Bull. No. 2, 1965.

REPORTS (Cont'd)

Thomas, D. M.
Benson, M. A. — Streamflow Generalization in the Potomac River Basin. U. S. Geol. Surv. Administrative Report, November, 1965.

Walker, E. R. — A Synoptic Climatology for Parts of the Western Cordillera. McGill University Arctic Meteorol. Res. Group, Sci. Report No. 8, Publication in Meteorol. No. 35, February, 1961.

A Major Program of Water Resources Research in Canada. Science Council of Canada, Report No. 3, September, 1968.

Hydrometeorological Systems - Progress Report of Task Committee on Hydrometeorological Systems. Proc. Am. Soc. Civil Eng., J. Hydraulics Div., Vol. 93, July, 1967.

Pacific Northwest Hydrologic Data Collection Program. U. S. Columbia Basin Inter-Agency Committee, Subcommittee on Hydrology, January, 1959.

Pacific Northwest Hydrologic Data Collection Program - Stream Gauging Changes from 1958 to 1965. U. S. Columbia Basin Inter-Agency Committee, Subcommittee on Hydrology, October, 1966.

Preliminary Report on Flood Control and Hydro-Electric Power in the Fraser River Basin. Fraser River Board, Victoria, British Columbia, 1958.

Final Report on Flood Control and Hydro-Electric Power in the Fraser River Basin. Fraser River Board, Victoria, British Columbia, 1963.

Ten-Year Comprehensive Plan for Collection of Basic Climatologic and Hydrologic Data in Alaska. U. S. Inter-Agency Committee on Water Resources, Subcommittee on Hydrology, March, 1965.

REPORTS (Cont'd)

Water Resources of the Nooksack River Basin and Certain Adjacent Streams. U. S. Washington State Dept. of Conservation, Water Supply Bull. No. 12, 1960.

PAPERS AND ARTICLES

Amorocho, J. — The Non Linear Prediction Problem in the Study of the Runoff Cycle. Am. Geophys. Union Water Resources Res., Volume 3, No. 3, 1967.

Ansley, R. W. — Statistical Interpretation of Canadian Hydrometric Data. M. Sc. Thesis - University of Alberta, Edmonton, 1959.

Beard, L. R.

(i) Use of Interrelated Records to Simulate Streamflow. Proc. Am. Soc. Civil Engrs., J. Hydraulics Div., Volume 91, September, 1965.

(ii) Optimization Technique for Hydrologic Engineering. Am. Geophys. Union Water Resources Res., Volume 3, No. 3, 1967.

Benson, M. A.

(i) Use of Historical Data in Flood Frequency Analysis. Trans. Am. Geophys. Union, Volume 31, 1950

(ii) Allocation of Streamflow Station Within a Country. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 67, Volume 1, 1965.

Benson, B. A.
Matalas, N. C.

(i) Synthetic Hydrology Based on Regional Statistical Parameters. Am. Geophys. Union Water Resources Res., Volume 3, No. 4, 1967

(ii) Effect of Interstation Correlation on Regression Analysis, J. Geophys. Res., Volume 66, No. 10, October, 1961.

Bisson, J. L. — Mathematical Model of Marmot Creek Watershed. M. A. Thesis - University of Toronto, 1965.

Bodhaine, G. L.

(i) Flood-Frequency Relationships in the Pacific Northwest. Proc. Am. Soc. Civil Engrs., J. of Hydraulics Div., Volume 86, November, 1960.

(ii) Water Resources of the Columbia-North Pacific Region. Paper presented at Meeting of Pacific Northwest River Basins Commission in Vancouver, Washington, December, 1968.

Bostock, H. S. — Physiography of the Canadian Cordillera - With Special Reference to the Area North of the Fifty-fifth Parallel. Canada Dept. of Mines and Resources, Geol. Surv., Memoir 247, 1948.

Bruce, J. P., Richards, T. L., Sporns, U. — Critical Meteorological Conditions for Maximum Inflow, Wind Set-up and Waves, Portage Mountain Reservoir, Peace River, British Columbia. Canada Dept. of Transport, Meteorol. Branch, Climatological Studies No. 2, 1965.

Carter, R. R. — Low Flow Investigations in the Yellow River Basin. U. S. Geol. Surv. Water Resources Bull., May, 1954.

Carter, R. W. — Streamflow and Water Levels - Effects of New Instruments and New Techniques on Network Planning. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 67, Vol. 1, 1965.

Cavadias, G. S. — Evaporation Applications in Watershed Yield Determination. Proc. Hydrology Symposium No. 2 - Evaporation, National Research Council of Canada, 1961.

Chapman, J. D. — The Climate of British Columbia. Paper presented to Fifth British Columbia Natural Resources Conf., February, 1962.

Chow, V. T. — (i) On the Determination of Frequency Factor in Log-Probability Plotting, Trans. Am. Geophys. Union, Vol. 36, 1955.

(ii) The Log-Probability Law and Its Engineering Application. Proc. Am. Soc. Civil Engrs., Vol. 80, Separate No. 536, November, 1954.

PAPERS AND ARTICLES (Cont'd)

(iii) Determination of Hydrologic Frequency Factor. Proc. Am. Soc. Civil Engrs., J. Hydraulics Div., Vol. 85, July, 1959.

Clark, R. H. — Canada's Surface Water Resources. Eng. J., Eng. Inst. of Canada, October, 1968.

Clark, R. H.
Bruce, J. P. — Extending Hydrologic Data. Proc. Hydrology Symposium No. 5 - Statistical Methods in Hydrology, National Research Council of Canada, 1966.

Cruff, R. W.
Rantz, S. E. — A Comparison of Methods Used in Flood-Frequency Studies for Coastal Basins in California. U. S. Geol. Surv. Water-Supply Paper 1580-E, 1965.

Dalrymple, T. — Flood Frequency Analysis. Manual of Hydrology, Part 3, U. S. Geol. Surv. Water-Supply Paper 1543-A, 1960.

Davies, L. B.
Rockwood, D. M. — Hydrometeorological Analysis of a Maximum Probable Flood for the Portage Mountain Project, Peace River, British Columbia, Proc. U. S. Western Snow Conf., April, 1966.

Durrant, E. F.
Blackwell, S. R. — The Magnitude and Frequency of Floods on the Canadian Prairies. Proc. Hydrology Symposium No. 1 - Spillway Design Floods, National Research Council of Canada, 1959.

Gumbel, E. J. — Statistical Theory of Droughts. Proc. Am. Soc. Civil Engrs., Vol. 80, Separate No. 439, 1954.

Harms, A. A.
Campbell, T. H. — An Extension to the Thomas-Fiering Model for the Sequential Generation of Streamflow. Am. Geophys. Union Water Resource Res., Vol. 3, No. 3, 1967.

Jacoby, S. L. S. — A Mathematical Model for Nonlinear Hydrologic Systems, J. Geophys. Res., Vol. 71, No. 20, October, 1966.

PAPERS AND ARTICLES (Cont'd)

Jeffrey, W. W. — Watershed Management Problems in British Columbia - A First Appraisal. Am. Water Resources Assoc., Water Resources Bull. Vol. 4, No. 3, September, 1968.

Kalinin, G. P. — Calculation and Forecasts of Streamflow From Scanty Hydrometric Readings. World Meteorol. Organization Flood Control Series No. 15, 1960.

Koelzer, V. A.
Ford, P. M. — Effects of Various Hydroclimatic Factors on Snowmelt Runoff. Trans. Am. Geophys. Union, Vol. 37, No. 5, October, 1956.

Kohler, M. A.

(i) Coordinated Network Planning. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology, Publication No. 68, Vol. 2, 1965.

(ii) Design of Hydrological Networks, World Meteorol. Organization, Tech. Note No. 25, 1958.

Kuiper, E.

(i) One Hundred Frequency Curves of North American Rivers. Proc. Am. Soc. Civil Engrs., J. Hydraulics Div., Vol. 83, October, 1957.

(ii) Practical Flood Frequency Analysis. Proc. Hydrology Symposium No. 1 - Spillway Design Floods, National Research Council of Canada, 1959.

Langbein, W. B.

(i) Topographic Characteristics of Drainage Basins. U. S. Geol. Surv. Water-Supply Paper 968-C, 1947.

(ii) Stream-Gauging Networks. Proc. Intern. Assoc. Sci. Hydrology, General Assembly of Rome, Publication No. 38, 1954.

(iii) Numbers of Streamgauging Stations in Various Countries with Analysis of their Distribution in the United States. Intern. Assoc. Sci. Hydrology, Bull. No. 18, December, 1957.

(iv) National Network of Hydrological Data, Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 67, Vol. 1, 1965.

(v) Hydrologic Data Networks and Methods of Extrapolating or Extending Available Hydrologic Data. World Meteorol. Organization Flood Control Series No. 15, 1960.

Langbein, W. B.
Hardison, C. H.
Extending Streamflow Data. Proc. Am. Soc. Civil Engrs., Vol. 81, Separate No. 826, 1955.

Linsley, R. K.
Techniques for Surveying Surface-Water Resources. World Meteorol. Organization Tech. Note. No. 26, 1958.

Linsley, R. K.
Crawford, N. H.
Coordination of Precipitation and Streamflow Networks. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 68, Vol. 2, 1965.

Matalas, N. C.
(i) Time Series Analysis. Am. Geophys. Union Water Resources Res., Vol. 3, No. 3, 1967.

(ii) Mathematical Assessment of Synthetic Hydrology. Am. Geophys. Union Water Resources Res., Vol. 3, No. 4, 1967.

(iii) Probability Distribution of Low Flows. U.S. Geol. Surv. Profess. Paper 434-A, 1963.

Neff. E. L.
Principles of Precipitation Network Design for Intensive Hydrologic Investigations. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 67, Vol. 1, 1965.

O'Riordan, J. — The Use of Climatic Data to Estimate Irrigation Water Requirements in the South Central Interior of British Columbia. M. A. Thesis - University of British Columbia, August, 1966.

Paulhus, J.
Erickson, C. E.
Riedel, J. T. — Estimation of Mean Annual Precipitation from Snow-Survey Data. Trans. Am. Geophys. Union, Vol. 33, 1952.

Powell, J. M. — Annual and Seasonal Temperature and Precipitation Trends in British Columbia since 1890. Canada Dept. of Transport, Meteorol. Branch, Cir. 4296, CLI-34, September, 1965.

Quick, M. C. — A Hydrometeorological Study of the Fraser River. University of British Columbia, November, 1965.

Schermerhorn, V. P. — Relations between Topography and Annual Precipitation in Western Oregon and Washington. Am. Geophys. Union Water Resources Res., Vol. 3, No. 3, 1967.

Schneider, W. J. — Areal Variability of Low Flows in a Basin of Diverse Geologic Units. Am. Geophys. Union Water Resources Res., Vol. 1, No. 4, 1965.

Searcy, J. K. —
(i) Flow-Duration Curves. U. S. Geol. Surv. Water-Supply Paper 1542-A, 1959.

(ii) Graphical Correlation of Gauging Station Records. Manual of Hydrology, Part 1, U. S. Geol. Surv. Water-Supply Paper 1541-C, 1960

Sharp, A. L.
Gibbs, A. E.
Owen, W. J.
Harris, B. — Application of the Multiple Regression Approach in Evaluating Parameters Affecting Water Yields at River Basins. J. Geophys. Res. Vol. 65, No. 4, With Discussion by H. C. Riggs in Vol. 65, No. 10, 1960.

Simons, W. D. — Effects of Temperature on Winter Runoff. Proc. U. S. Western Snow Conf., April, 1967.

PAPERS AND ARTICLES (Cont'd)

Snyder, F. F. — Large Floods From Melting Snow and Rain. Proc. Intern. Assoc. Sci. Hydrology, General Assembly of Brussels, Vol. IV, 1951.

Solomon, S. I.
Woolley, J. A.
Denouvilliez, J. P.
Cadou, C.
Chart, E. J. — The Use of a Square Grid System for Computer Estimation of Precipitation, Temperature, and Runoff in a Sparsely Gauged Area. Paper Presented at the 49th Annual Meeting of Am. Geophys. Union, April, 1968.

Spreen, W. C. — A Dtermination of the Effect of Topography on Precipitation. Trans. Am. Geophys. Union, Vol. 28, 1947.

Stichling, W.
Blackwell, S. R. — Drainage Area as a Hydrologic Factor on the Glaciated Canadian Prairies. Proc. Intern. Assoc. Sci. Hydrology, General Assembly of Toronto, Publication No. 45, 1957.

Szesztay, K. — Some Aspects of Hydrological Network Design With Special Regard to Mountainous Areas. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 68, Vol. 2, 1965.

Underhill, A. G. — The Effects of a Change in Vegetation on Runoff Characteristics of Alberta Streams. Alberta Dept. of Agriculture, Water Resources Branch, 1962.

Uryvaev, V. A. — Basic Principles Governing the Design of a Hydrological Network. Proc. Symposium on Design of Hydrological Networks, Quebec, Intern. Assoc. Sci. Hydrology Publication No. 67, Vol. 1, 1965.

Williams, P.
Peck, E. L. — Terrain Influences on Precipitation in the Intermountain West as Related to Synoptic Situations. J. Appl. Meteorol., Vol. 1, September, 1962.

Wong, S. T. — A Multivariate Statistical Model for Predicting Mean Annual Flood in New England. Ann. Assoc. Am. Geographers, Vol. 53, No. 3, 1963.

PAPERS AND ARTICLES (Cont'd)

Yevjevish, V. — Mean Range of Linearly Dependent Normal Variables with Application to Storage Problems. Am. Geophys. Union Water Resources Res., Vol. 3, No. 3, 1967.

Young, G. K.
Pisano, W. C. — Operational Hydrology Using Residuals. Proc. Am. Soc. Civil Engrs. J. Hydraulics Div., Vol. 94, July, 1968.