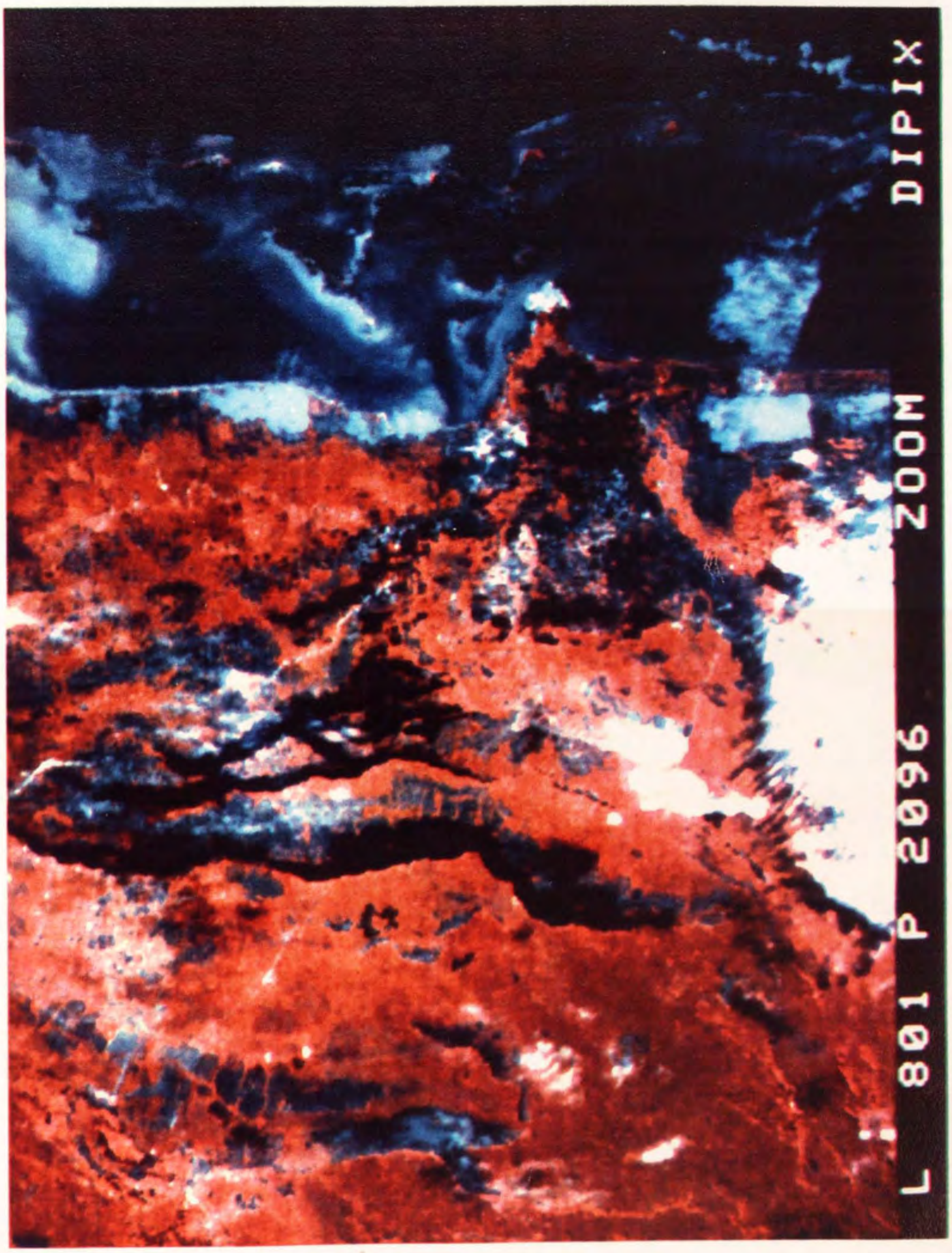
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ACKNOWLEDGEMENTS

I would like to thank the following people who have supported this research and helped in its completion :

Dr T. R. E. Chidley, supervisor, Aston University, Birmingham.

Dr W. G. Collins, assistant supervisor, Aston University, Birmingham.

Dr D. Rothery, Open University Earth Resources Department.

Dr S. Drury, Open University Earth Resources Department.

Mr E. Wickens, University College, London, Photogrammetric Department.

Dr I. Dowman, University College, London, Photogrammetric Department.

The Director of the National Aeronautic and Space Administration, U.S.A.

Mrs S. Pearce, typist at Cornwall College, Redruth.

Especial thanks to my wife Ali who gave most support of all.

Stephen Miller

REMOTE SENSING APPLICATIONS TO FLOOD HYDROLOGY IN BELIZE

A thesis presented by Stephen Thomas Miller in accordance with the regulations governing the award of the degree of Doctor of Philosophy of the University of Aston in Birmingham

June 1986

SUMMARY

The research compares the usefullness of four remote sensing information sources, these being LANDSAT photographic prints, LANDSAT computer compatible tapes, Metric Camera and SIR-A photographic prints. These sources provide evaluations of the catchment characteristics of the Belize and Sibun river basins in Central America. Map evaluations at 1:250,000 scale are compared to the results of the same scale, remotely sensed information sources. The values of catchment characteristics for both maps and LANDSAT prints are used in multiple regression analysis, providing flood flow formulae, after investigations to provide a suitable dependent variable discharge series are made for short term records. The use of all remotely sensed information sources in providing evaluations of catchment characteristics is discussed.

LANDSAT prints and computer compatible tapes of a post flood scene are used to estimate flood distributions and volumes. These are compared to values obtained from unit hydrograph analysis, using the dependent discharge series and evaluate the probable losses from the Belize river to the floodplain, thereby assessing the accuracy of LANDSAT estimates. Information relating to flood behaviour is discussed in terms of basic image presentation as well as image processing. A cost analysis of the purchase and use of all materials is provided. Conclusions of the research indicate that LANDSAT print material may provide information suitable for regression analysis at levels of accuracy as great as those of topographic maps, that the differing information sources are uniquely applicable and that accurate estimates of flood volumes may be determined even by post flood imagery.

KEY WORDS : Belize, Flooding, Remote Sensing, Hydrology

Stephen Thomas Miller
Ph.D. Thesis 1986

CONTENTS

		Page No.
Frontispiece	LANDSAT false colour composite (bands 4, 5 and 7) of scene 020/48, 26 December 1979	
Acknowledgements		i
Title page		ii
Summary		iii
Contents		iv
Contents of main text		v
List of Tables		xi
List of Figures		xvi
Main text		1-259
Appendices		260
References		275
Abbreviations		287

CONTENTS OF MAIN TEXT

		Page No.
Chapter 1	Introduction	1
1.1	The Study Region, its location and background details	1
1.2	Regional Division and the use of topographic maps	3
	1.2.i Region 1	4
	1.2.ii Region 2	5
	1.2.iii Region 3	5
	1.2.iv Floodplain	6
1.3	Use of Subcatchments	7
1.4	This Research and the place of Remote Sensing	9
	1.4.i Introduction	9
	1.4.ii The definition of river flow formulae	9
	1.4.iii The observation of flood events	12
1.5	The aims of this research	13
1.6	The Flood Studies Report	14
Chapter 2	Catchment Characteristics Selected as Independent Variables for Multiple Regression Analysis, 1:250,000 Scale Topographic Maps	18
2.1	Introduction	18
2.2	The quantification of independent variables, 1:250,000 scale maps	19
	2.2.i Area of catchments	19
	2.2.ii Mainstream slopes	19
	2.2.iii Stream frequency	20
	2.2.iv Soil/Slope index	30
	2.2.v Floodplain Area	44
	2.2.vi Mainstream length	44
	2.2.vii Form indices	45

		Page No.
Chapter 3	Catchment Characteristics Selected as Independent Variables for Multiple Regression Analysis, LANDSAT Band 7 Photographic Prints (nominally 1:250,000 scale)	46
3.1	Introduction	46
3.2	Image distortions	51
3.3	Catchment characteristics as independent variables for multiple regression analysis	54
	3.3.i Catchment and subcatchment areas	55
	3.3.ii Stream frequency	58
	3.3.iii Floodplain area	61
	3.3.iv Mainstream length	62
	3.3.v Form indices	62
Chapter 4	Evaluation of Catchment Characteristics, LANDSAT Computer Compatible Tapes	64
4.1	Introduction	64
4.2	Distortions of slide images	67
4.3	Evaluation of characteristics, LANDSAT 1:250,000 scale slides	68
	4,3,i Subcatchment areas	72
	4.3.ii Stream frequency	72
	4.3.iii Mainstream length	73
	4.3.iv Form indices	74
Chapter 5	Evaluation of Catchment Characteristics, Metric Camera Photography	76
5.1	Introduction	76
	5.1.i Image distortions of photographic prints	79
5.2	Evaluation of catchment characteristics	80
	5.2.i Area	80
	5.2.ii Stream frequency	80
	5.2.iii Mainstream slope	81
	5.2.iv Soil/slope index	84

Page No.

Chapter 5 (continued)

5.2.v Floodplain areas 84

5.2.vi Mainstream length 87

5.2.vii Form indices 87

5.3 Stereoscopic investigations to obtain planimetric accuracies and altitude information, 1:820,000 scale diapositives plotted to 1:250,000 scale. 88

5.3.i Introduction 88

5.3.ii Assessments of altitude and topographic information 90

Chapter 6 Evaluation of Catchment Characteristics from SIR-A Radar Imagery 92

6.1 Introduction 92

6.2 Large scale features observable from SIR-A imagery 95

6.2.i Distortions 95

6.2.ii Regional identification 98

6.2.iii Drainage networks 100

6.3 Evaluation of catchment characteristics 100

6.3.i Areas of subcatchments 102

6.3.ii Stream frequency 102

6.3.iv Form indices 102

Chapter 7 Comparisons of Catchment Information from Different Remote Sensing Sources and Topographic Maps 104

7.1 Introduction 104

7.1.i Distortions of remotely sensed imagery 105

7.2 Comparisons of catchment characteristic evaluation 106

7.2.i Area 106

7.2.ii Mainstream slope 112

7.2.iii Stream frequency 113

		Page No.
Chapter 7	(continued)	
	7.2.iv Soil/slope index	116
	7,2,v Floodplain areas	116
	7,2,vi Mainstream lengths	116
	7.2.vii Form indices	119
Chapter 8	The Derivation of an Independent Variable for Climate	120
8.1	Introduction	120
8.2	The climate independent variable	122
8.3	Calculation of the climate variable A.A.R.	124
	8.3.i Background	124
	8.3.ii Calculation of A.A.R.	126
8.4	Calculation of climate variable R.S.M.D.	129
	8.4.i Background	129
	8.4.ii The calculation of 1 day and 2 day, 5 year return rainfall events	130
	8.4.iii The calculation of the Areal Reduction Factor (A.R.F.)	132
	8.4.iv Calculation of the Soil Moisture Deficit (S.M.D.)	135
Chapter 9	Hydrological Studies to Derive a Dependent Variable for Multiple Regression Analysis	144
9.1	Intoduction	144
	9.1.i Hydrological background	145
	9.1.ii Flow duration	146
9.2	Flood discharge as the dependent variable for multiple regression - Peaks Over Threshold (P.O.T.) method	149
	9.2.i The theory of the P.O.T. method and calculating the dependent variable	150
	9.2.ii Checking the exponential assumption and the selection of the most suitable exceedence for the T. year flood	152
	9.2.iii Using the P.O.T. distribution for Mean Annual Flood (M.A.F.)	155
9.3	The selection of P.O.T. distributions and parameters for regression analysis	156

		Page No.
Chapter 10	Multiple Regression Analysis	172
10.1	Introduction	172
10.2	Correlation and multiple regression	173
	10.2.i Correlation	173
	10.2.ii Regression analysis	176
10.3	Worked examples of the regression equations	183
Chapter 11	Remote Sensing Investigations of the 1979 Belize River Flood	186
11.1	Introduction	186
	11.1.i General description of the floodplain area from topographic maps	187
11.2	Investigations using 1:250,000 scale LANDSAT imagery	188
	11.2.i Introduction	188
	11.2.ii 1:250,000 scale band 7 photographic prints	189
	11.2.iii 1:250,000 scale c.c.t. false colour composite slides	192
Chapter 12	The Hydrology of the 1979 Flood	195
12.1	Introduction	195
12.2	Construction of unit hydrographs for the 1969 and 1971 flood	196
	12.2.i Background	196
	12.2.ii Alternative methods of hydrograph separation	198
	12.2.iii Construction of 4-day unit hydrographs and conversion to 1-day	206
	12.2.iv Application of 1 day 10 m.m. unit hydrographs for the 1979 flood	215
12.3	Return period comparisons for the 1979 flood	218
	12.3.i 7 day rainfall events	218

Page No.

Chapter 13 Investigations into the 1979 flood, 1:50,000 scale LANDSAT c.c.t. Slides 223

13.1 Introduction 223

13.2 General features of the 1:50,000 scale LANDSAT c.c.t. slides 224

13.3 Specific features of the 1:50,000 scale LANDSAT c.c.t. slides 226

13.3.i Estimates of flood extent at the time of scene acquisition 226

13.3.ii The maximum flood event 229

13.4 Relations between Belize river and local catchment contributions and LANDSAT observed flood volumes 229

13.4.i Floodplain catchment contribution 230

13.4.ii Correlations between hydrograph and LANDSAT flood estimates 231

Chapter 14 Image Processing Techniques Used To Investigate The 1979 Flood 233

14.1 Introduction 233

14.2 Piece-wise stretching 233

14.2.i Method of piece-wise stretching 234

14.3 Supervised classification 240

14.3.i Supervised classification of the lower floodplain area 241

14.4 Conclusions regarding image processing techniques 247

Chapter 15 Conclusions 248

15.1 Introduction 248

15.2 The use of remotely sensed data in quantifying catchment characteristics 249

15.2.i Background 249

15.2.ii Conclusions regarding catchment characteristic evaluation 250

15.3 The use of LANDSAT imagery in the evaluation of flooding 255

15.4 Costs of purchase and use of remote sensing materials 256

LIST OF TABLES

Table No.		Page No.
1.1	Map series used	4
1.2	Gauging stations within the Belize and Sibun catchments	8
1.3	Belize River Catchment, Regional divisions, areas from 1:250,000 scale maps	10
1.4	Aims relating to remotely sensed information	13
1.5	Aims relating to hydrological investigations and floods	14
1.6	Outline of F.S.R. investigations used in this thesis	15
2.1	Selected catchment characteristics for use with Belize data	18
2.2	Regional and subcatchment areas, 1:250,000 and 1:50,000 scale maps	20
2.3	Areas above gauging stations, 1:250,000 scale maps	21
2.4	1085% Mainstream slopes	26
2.5	Stream frequencies of subcatchments, 1:250,000 and 1:50,000 scale maps	29
2.6	Stream frequencies for catchment areas above gauging stations	29
2.7	Results of basin slope values, box, control and intersection methods	31
2.8	Comparisons of 1:50,000 and 1:250,000 scale map average basin slopes	32
2.9	Comparisons of overall slopes within subcatchments, 1:250,000 scale	33
2.10	Combination of basin slopes and soil types to give soil/slope classes	34
2.11	Occurrence of soil/slope classes within subcatchments (1:250,000 scale)	35
2.12	Soil indices for the Belize river catchment regions	36
2.13	Soil indices for catchment areas above gauging stations	37
2.14	Floodplain areas above gauging stations	44
2.15	Mainstream lengths above gauging stations	45
2.16	Values of circularity index and length:width ratio	45
3.1	LANDSAT scene details	46
3.2	Distortions of LANDSAT photographic enlargements at 1:250,000 scale	52

Table No.		Page No.
3.3	Photographic distortions of LANDSAT photographic enlargements at 1:250,000 scale	53
3.4	Catchment characteristics measured from LANDSAT 1:250,000 scale prints	54
3.5	Regional and subcatchment areas obtained from LANDSAT prints	57
3.6	Areas above gauging stations by regions, LANDSAT prints	58
3.7	Stream frequency of regional subcatchments, LANDSAT prints	61
3.8	Stream frequencies above gauging stations, LANDSAT prints	61
3.9	Floodplain areas above gauging stations, LANDSAT prints	61
3.10	Mainstream lengths, LANDSAT prints	62
3.11	Form indices from 1:250,000 scale LANDSAT prints	63
4.1	Projected image distortions (LANDSAT slides), slide B3R, f.c.c., 25.3.75	68
4.2	Selected characteristics for investigation	69
4.3	Brightness values for f.c.c. images, Tape 020/48, 25.3.75	72
4.4	Subcatchment areas, LANDSAT slides	72
4.5	Stream frequencies, LANDSAT slides	73
4.6	Mainstream lengths within subcatchments, LANDSAT slides	74
4.7	Form indices derived from LANDSAT slides	74
5.1	Metric Camera Belize diapositive details	76
5.2	Distortions of Metric Camera 1:250,000 scale prints	79
5.3	Areas of catchments, Metric Camera prints	80
5.4	Stream frequency values, Metric Camera prints	81
5.5	1085% Mainstream slope values, Metric Camera	81
5.6	Overall basin slopes, Metric Camera	84
5.7	Mainstream length, Metric Camera prints	87
5.8	Form indices, Metric Camera prints	87
6.1	Scale size of (nominal) 1:250,000 scale SIR-A prints	97
6.2	Area of subcatchments, SIR-A prints	102
6.3	Stream frequencies, SIR -A prints	102

Table No.		Page No.
6.4	Subcatchment mainstream lengths, SIR-A prints	102
6.5	Form indices of subcatchments, SIR-A prints	102
7.1	Regression formulae linking remotely sensed images to maps	105
7.2	Regional areal measurement	106
7.3	Areas above gauging stations by region, map and LANDSAT print comparisons	108
7.4	Total areas above gauging stations, map and LANDSAT comparisons	109
7.5	Standard errors of LANDSAT region measurement	110
7.6	Areas of subcatchments, comparison of all sources	111
7.7	Standard errors of subcatchment measurement	110
7.8	Mainstream slope, 1085% method	112
7.9	Mainstream slope, Tayslo method	112
7.10	Stream frequency values	113
7.11	Stream frequency relationships	114
7.12	Regression formulae linking 1:250,000 maps to remote sensing sources, stream frequency	114
7.13	Comparisons of basin slopes, Metric Camera and 1:250,000 scale maps	116
7.14	Comparison of floodplain areas, maps and LANDSAT prints	116
7.15	Mainstream lengths above gauging stations, maps and LANDSAT prints	118
7.16	River lengths within subcatchments	117
7.17	Form indices comparisons, maps and LANDSAT prints	119
7.18	For indices comparisons (subcatchments)	119
8.1	Examples of percentage errors for selected stations	125
8.2	Inter-isohyetal areas for the Belize and Sibun river catchments	127
8.3	A.A.R. values for catchment areas above gauging stations	129
8.4	Rainfall records used in analysis	130
8.5	Calculated 1-day 5 year rainfall returns	132

Table No.		Page No.
8.6	1:2 day ratios (U.K. and Belize by A.A.R. bands)	132
8.7	1 day R1:R2 A.R.F. ratios (averaged)	133
8.8	Final 1 day 5 year rainfall values by catchment areas above gauging stations	134
8.9	Range of evapotranspiration parameters used in the calculation of soil moisture deficits	136
8.10	Maximum soil moisture deficits	137
8.11	Minimum soil moisture deficits	138
8.12	Belize International Airport 1:2 day event ratios and return periods	139
8.13	San Ignacio 1:2 day event ratios and return periods	140
8.14	Norland Farm and Cooma Cairn 1:2 day event ratios and return periods	141
8.15	Data for the calculation of Areal Reduction factors	142
9.1	River gauging stations	144
9.2	Data for use in P.O.T. model	155
9.3	Plotting positions of reduced variate y and discharge Q	159
9.4	P.O.T. parameters for all gauging stations (Abstraction method 2)	162
9.5	P.O.T. parameters for all gauging stations (Abstraction method 1)	153
9.6	Variance and standard errors of P.O.T. distributions (method 2)	164
9.7	Probability check for suitable value of λ for large return periods	166
9.8	Dependent variables used in regression analysis	157
10.1	Primary set of catchment characteristics as independent variables	173
10.2	Correlation matrix of map independent variables	174
10.3	Correlation matrix of LANDSAT print independent variables	174
10.4	Correlation matrix if LANDSAT versus map variable values	175
10.5	Dependent variables for use in multiple regression analysis	177
10.6	Parameters of regression equations using R.S.M.D.	176
10.7	Parameters of regression equations using A.A.R.	178

Table No.		Page No
10.8	Regression parameters for dependent variable Qo (map)	179
10.9	Regression parameters for dependent variable β (map)	180
10.10	Regression parameters for dependent variable Qo (LANDSAT)	181
10.11	Regression parameters for dependent variable β	182
10.12	Worked examples of the regression equations for Qo and β, 25 year flood	183
10.13	Details of Kendal and Big Falls (South) gauging stations	184
10.14	Worked examples for Kendal and Big Falls (South)	185
11.1	Aims of the 1979 flood study	187
11.2	Inventory of water bodies	189
11.3	Operator specified contrast stretch values	192
12.1	Percentage weighting for rainfall stations	197
12.2	Weighted rainfall values for gauging stations	197
12.3	Flow volumes for gauging stations, 1969 and 1971	214
12.4	Method 2 response runoff as m.m. rainfall over catchments	214
12.5	Values of Tp, Qp and w for all stations	215
12.6	Daily rainfall amounts, 1979 flood	215
12.7	Weighting percentages of rainfall stations, 1979	216
12.8	Weighted rainfall for gauging stations, 1979	216
12.9	Flow component volumes, 1979 flood	217
12.10	Listing of 7 day rainfalls (Belize International Airport)	218
12.11	Return periods of 1979 rainfall for gauging stations	218
12.12	P.O.T. estimated return periods of 1979 discharge peaks	219
12.13	Estimated losses to the floodplain	220
13.1	Slide projection distortions, 1:50,000 scale (LANDSAT slides)	224
14.1	Parameters of piece-wise stretches	234
14.2	Confusion matrix of training areas - classification accuracy	242
14.3	Classification Summary 1	242
15.1	Comparisons of regression formulae predictions	254
15.2	Cost of material purchase and use	257

LIST OF FIGURES

Figure No.		Page No.
1.1	Regional division of the Belize and Sibun catchments	2
1.2	Flow diagram of the thesis structure	17
2.1(a)	1:250,000 Map 1085% Mainstream Slope (Mopan branch, Belize river)	23
2.1(b)	1:250,000 Map 1085% Mainstream Slope (Macal branch, Belize river)	24
2.2	1:250,000 Map 1085% Mainstream Slope (Sibun river)	25
2.3	Drainage network subcatchment 3a (1:250,000 scale) topographic maps	27
2.4	Drainage network subcatchment 6b (1:250,000 scale) topographic maps	27
2.5	Drainage network subcatchment 28 (1:250,000 scale) topographic maps	28
2.6	Drainage network subcatchment 4 (1:250,000 scale) topographic maps	28
2.7	Basin Slope classes subcatchment 3a (1:250,000 scale) topographic maps	38
2.8	Soil/Slope classes subcatchment 3a (1:250,000 scale) topographic maps	38
2.9	Basin Slope classes subcatchment 28 (1:250,000 scale) topographic maps	39
2.10	Soil/Slope classes subcatchment 28 (1:250,000 scale) topographic maps	39
2.11	Basin Slope classes subcatchment 6b (1:250,000 scale) topographic maps (10 m.m. grid)	40
2.12	Basin Slope classes subcatchment 6b (1:250,000 scale) topographic maps (5 m.m. grid)	40
2.13	Basin Slope classes subcatchment 4 (1:250,000 scale) topographic maps (10 m.m. grid)	41
2.14	Basin Slope classes subcatchment 4 (1:250,000 scale) topographic maps (5 m.m. grid)	41
2.15	Basin Slope classes subcatchment 6b (1:250,000 scale) topographic maps (10 m.m. grid)	42

Figure No.		Page No.
2.16	Basin Slope classes subcatchment 6b (1:250,000 scale) topographic maps (5 m.m. grid)	42
2.17	Basin Slope classes subcatchment 4 (1:250,000 scale) topographic maps (10 m.m. grid)	43
2.18	Basin Slope classes subcatchment 4 (1:250,000 scale) topographic maps (5 m.m. grid)	43
3.1	LANDSAT scene coverage of Belize	47
3.2	LANDSAT image 020/48, 25 March 1975, band 7 contact print	48
3.3	LANDSAT image 020/49, 25 March 1975, band 7 contact print	49
3.4	LANDSAT image 020/48, 26 Dec 1979, band 7 contact print	50
3.5	Drainage network subcatchment 28 (1:250,000 scale) LANDSAT prints	59
3.6	Drainage network subcatchment 4 (1:250,000 scale) LANDSAT prints	59
3.7	Drainage network subcatchment 3a (1:250,000 scale) LANDSAT prints	60
3.8	Drainage network subcatchment 6b (1:250,000 scale) LANDSAT prints	60
4.1	Configuration of slide projection	67
4.2	Drainage network subcatchment 6b, c.c.tapes, false colour composites (1:250,000 scale)	70
4.3	Drainage network subcatchment 3a, c.c.tapes, false colour composites (1:250,000 scale)	70
4.4	Drainage network subcatchment 4, c.c.tapes, false colour composites (1:250,000 scale)	71
4.5	Drainage network subcatchment 28, c.c.tapes, false colour composites (1:250,000 scale)	71
5.1	Metric Camera scene coverage	77
5.2	Drainage networks, Metric Camera subcatchments (1:250,000 scale) topographic maps	82
5.3	Drainage networks, Metric Camera subcatchments (1:250,000 scale) Metric Camera prints	82
5.4	1085% Mainstream Slope, Metric Camera subcatchments (1:250,000 scale) topographic maps	83
5.5	1085% Mainstream Slope, Metric Camera subcatchments (1:250,000 scale) Metric Camera diapositives.	83

Figure No. Page No.

Figure No.		Page No.
5.6	Altitude contours, Metric Camera subcatchments (1:250,000 scale) topographic maps	85
5.7	Altitude contours, Metric Camera subcatchments (1:250,000 scale) Metric Camera diapositives	85
5.8	Basin Slope classes, Metric Camera subcatchments (1:250,000 scale) topographic maps	86
5.9	Basin Slope classes, Metric Camera subcatchments (1:250,000 scale) Metric Camera diapositives	86
5.10	Parallax relationships, Metric Camera	88
6.1	SIR-A radar, scene coverage of Belize	93
6.2	SIR-A contact print of scene coverage	94
6.3	Dependence of range resolution of pulse length	96
6.4	Dependence of azimuth resolution on antenna beamwidth and ground range	96
6.5	Topographical features from SIR-A photographic prints	101
7.1	Stream orders of Landsat prints and 1:250,000 scale maps	115
8.1	Mean annual isohyets, Belize	121
8.2	Longterm variation of rainfall, Belize City	122
8.3	Rain gauge network density percentage error relationships	125
8.4	Location of rainfall stations	128
8.5	Theissen polygon distribution for the calculation of 1 day/ 5 year rainfall	131
9.1	Flow duration curves for the Belize river	147
9.2	Relationship between P.O.T. and Maximum Series flow	150
9.3	P.O.T. check graph, Benque Viejo	167
9.4	P.O.T. check graph, Cristo Rey	167
9.5	P.O.T. check graph, Iguana Creek	168
9.6	P.O.T. check graph, Banana Bank	168
9.7	P.O.T. check graph, Big Falls Ranch	169
9.8	P.O.T. check graph, Bermudan Landing	169
9.9	P.O.T. CHECK GRAPH, Davis Bank	170
9.10	P.O.T. check graph, Gracie Rock	170
9.11	Mean Annual flood (series) versus P.O.T. Mean Annual Flood	171
11.1	Flood water overspill points and flood routes	193

Figure No. Page No.

12.1 Unit hydrograph separation and lagtime evaluation 198

12.2 Runoff hydrograph used for the synthesis of unit hydrographs, Iguana Creek 1969 200

12.3 Runoff hydrograph used for the synthesis of unit hydrographs, Iguana Creek 1971 201

12.4 Runoff hydrograph used for the synthesis of unit hydrographs, Banana Bank 1969 202

12.5 Runoff hydrograph used for the synthesis of unit hydrographs, Banana Bank 1971 202

12.6 Runoff hydrograph used for the synthesis of unit hydrographs, Big Falls Ranch 1969 203

12.7 Runoff hydrograph used for the synthesis of unit hydrographs, Big Falls Ranch 1971 203

12.8 Runoff hydrograph used for the synthesis of unit hydrographs, Bermudan Landing 1969 204

12.9 Runoff hydrograph used for the synthesis of unit hydrographs, Bermudan Landing 1971 204

12.10 Runoff hydrograph used for the synthesis of unit hydrographs, Davis Bank 1971 205

12.11 Conversion of unit hydrographs from 4 days to 1 day 206

12.12 Obtaining conversion parameters of 4 day to 1 day hydrograhs, Iguana Creek 207

12.13 Obtaining conversion parameters of 4 day to 1 day hydrograhs, Banana Bank 208

12.14 Obtaining conversion parameters of 4 day to 1 day hydrograhs, Big Falls Ranch 209

12.15 Obtaining conversion parameters of 4 day to 1 day hydrograhs, Bermudan Landing 210

12.16 Obtaining conversion parameters of 4 day to 1 day hydrograhs, Davis Bank 211

12.17 Reconstructed 1-day surface flow unit by hydrographs 212

12.18 Reconstructed 1-day surface flow unit by hydrographs 213

12.19 Flood hydrograph of the 1979 event, Iguana Creek 221

12.20 Flood hydrograph of the 1979 event, Banana Bank 221

12.21 Flood hydrograph of the 1979 event, Big Falls Ranch 221

Figure No. Page No.

12.22 Flood hydrograph of the 1979 event, Bermudan Landing 222

12.23 Flood hydrograph of the 1979 event, Davis Bank 222

13.1 Cross-sectional depths through the N.W. lagoonal area 228

14.1 Histogram (band 7) of Lower floodplain area 235

14.2 Operation of piece-wise stretches 236

14.3 Piece-wise stretch (band 7) of Lower floodplain, No.1 237

14.4 Piece-wise stretch (band 7) of Lower floodplain, No.2 239

14.5 Piece-wise stretch (band 7) of Lower floodplain, No.3 239

14.6 Clustering of Land Cover types 240

14.7 (a), (b) (c) Progressive presentation of land cover themes, unfiltered 244

14.8 (a), (b), (c) Progressive presentation of land cover themes after Bayesian filter 245

14.9 False colour composite of the Lower floodplain 246

14.10 Final land cover classification of the Lower floodplain 246

Unbound Material

Map A Major catchments, regions, subcatchments and drainage networks, 1:250,000 scale topographic maps

Map B Major catchments, regions, subcatchments, drainage networks and cloud cover, 1:250,000 scale LANDSAT band 7 prints

Map C Metric Camera contour and altitude information

Map D LANDSAT band 7 prints, floodplain areas

Map E LANDSAT f.c.c. slides, Upper and Middle floodplain areas

CHAPTER I : INTRODUCTION

1.1. THE STUDY REGION, ITS LOCATION AND BACKGROUND DETAILS

The country of Belize is situated on the Caribbean coast of Central America, to the north lies Mexico, to the south and west, Guatamala. Its location covers an area from approximately longitude 88° 15' to 89° 15' W. and latitude 15° 50' N. to 18° 00' N. This area is about 22,500 square kilometres. The general physical nature of the country is of a central mountainous upland, the Maya Mountains, surrounded by rolling limestone plains that descend to the coastal floodplain areas of the north and east. The limestone plateau of the western border of the Maya Mountains extends well into Guatamala. The climate is subtropical, humid and rainfall is generally heavy, concentrated into the last six months of each year. Although the length and severity of the dry season is variable, the months from February to May provide little rainfall.

The Study Region within Belize is the combined area of the Belize and Sibun river catchments. They are of contrasting size. The Belize river catchment, its western tip extending into Guatamala, covers an area in excess of 8,000 square kilometres. The adjacent Sibun catchment is, by comparison, some 1,200 square kilometres in extent. Both rivers originate from headwaters in the Maya Mountains and while the Belize turns west for some distance before entering the Caribbean sea and has two large tributary rivers, the Sibun takes a straightforward course to its mouth, only 15 kilometres to the south of its larger neighbour.

The Belize river catchment, covering a third of the country, dominates the pattern of hydrology in the region. It is the only river for which hydrological records of any extent are available. The Sibun river is important for the reasons that it shares its floodplain with the Belize and supplements the hydrological records by the provision of data from one further gauging station. The locations of these river catchment areas and their topographic regions are shown in text map figure 1.1.

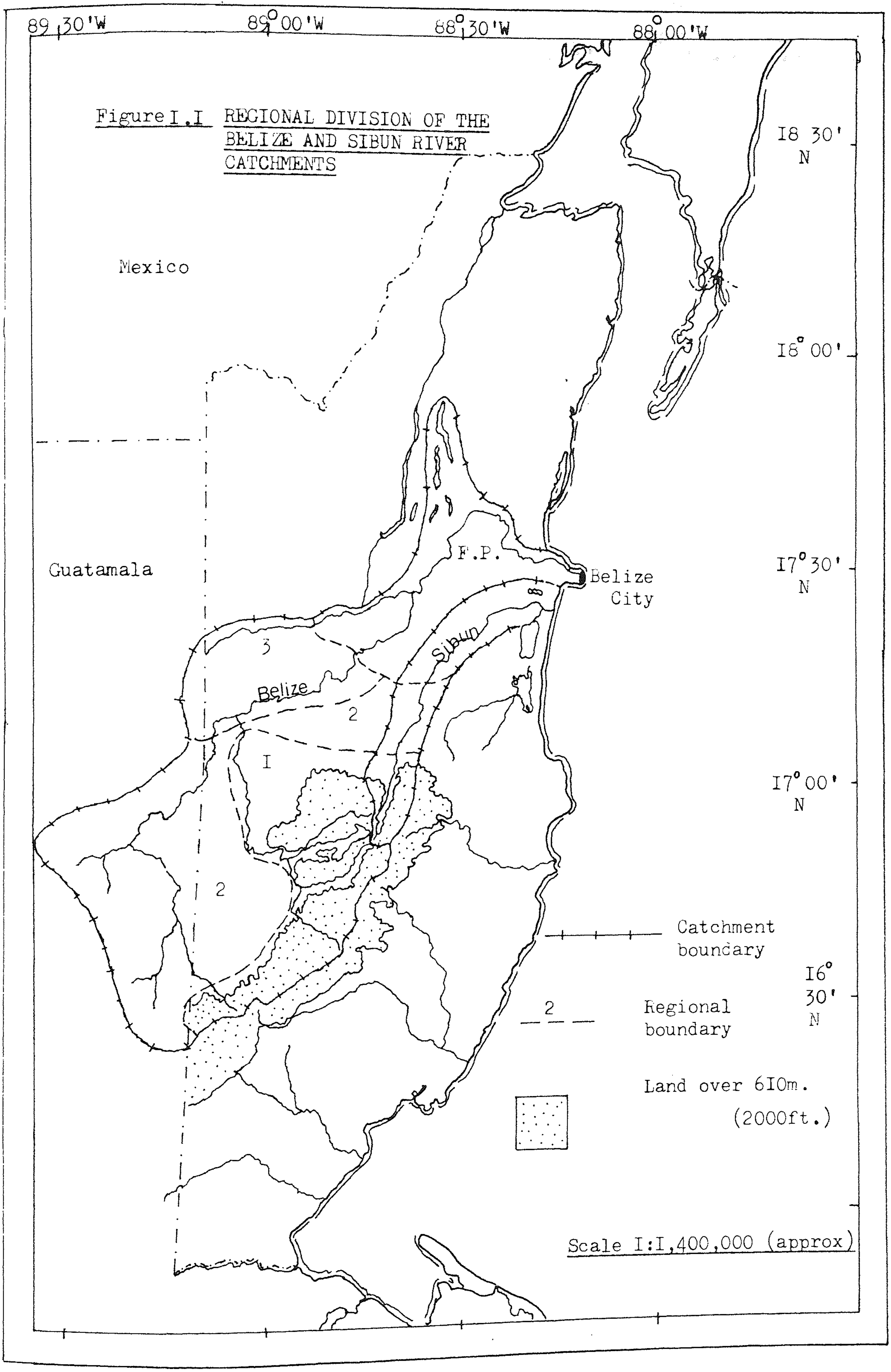


Figure I.I REGIONAL DIVISION OF THE BELIZE AND SIBUN RIVER CATCHMENTS

Vegetationally, both catchments are varied (1). Upland areas are dominated by two main vegetation types: dense broadleaved evergreen and semi evergreen forest confined to the peripheral areas of the central upland mass and transitional broadleaved forest with pine forest - orchard savannah covering the central upland. The limestone hill region to the north of this upland is covered by deciduous and semi evergreen vegetation, extending in a dense arc from the south western borders of Belize to the coastal floodplains in the north east. The floodplains are more diverse vegetationally, reflecting not only the localisation of soil development but also the importance of permanent standing water, determined by low ridge features, the topographical expression of Pleistocene alluvial and coastal deposits. In these areas cohune palm forest, pine forest and orchard savannah, marsh forest and riparian broadleaved types are present without particular predominance. While climate (with rainfall totals increasing southwards over the upland) can be seen to exert some influence upon vegetation, the primary arbiter is soil type.

Below are given more detailed descriptions of the physical geography of Belize which places the broad regional subdivisions in the context of the research method of this thesis. It also outlines the availability of topographic map information and the manner in which it is used.

1.2 REGIONAL DIVISION AND THE USE OF TOPOGRAPHIC MAPS

This research is based on the relative effectiveness of study methods applied to large regional areas. For the rapid assessment of catchment characteristics it is therefore essential to subdivide the large homogeneous regional areas identified and described beow into smaller, sub-catchment areas for which hydrological evaluation can be made. These evaluations may then be applied to the regions that these subcatchments represent and these combined into values for the catchment whole.

Two scales of maps, both topographic and those obtained from remotely sensed information are used in this research. These scales are 1:250,000 and 1:50,000. The use of two scales illustrates a dilemma within hydrological work that covers large areas, yet seeks to achieve the greatest possible definition and identification of physiographic features. In this research, 1:250,000 scale maps are used as basic reference since they present the most practical form of coverage and provide vegetation as well as topographic information. Where possible, direct comparisons of results are given with those from 1:50,000 scale maps, to establish the relationships between the scales.

Remotely sensed data (especially LANDSAT imagery) is also most conveniently presented at 1:250,000 scale, though this research investigates the possibility of its use at 1:50,000 scale, in the study of flood events.

TABLE 1.1 MAP SERIES USED

Map Scale		Series Information
1:250,000	:	DOS 649/1 edition - DOS 1980 (2 sheets, N/S)
1:250,000	:	1501 Air edition 2 - GSGS (2 sheets N.E. 16-13 and N.E.16-9)
1:50,000	:	ET55 edition DOS - 4499 3 DOS 1979
	:	ET55 edition DOS - 4499 2 DOS 1976

Four distinct regional divisions can readily be identified. They are described below. Typical subcatchments within each region were selected by the visual inspection of terrain features and drainage networks, which relate closely to their geological natures. Details of regional and subcatchment subdivision are given on 1:250,000 scale map A.

1.2.i Region I

This region consists of the upland areas of the Mountain Pine Ridge and the Maya Mountains. Altitudes range from about 400 to 1000 metres. The topography is hilly or mountainous and the region is almost totally uninhabited, the largest population being approximately 200 at Augustine Forestry Station.

The area is unaffected by agriculture, logging camps in the area are mostly disused though testify to a small scale timber industry, the area's only economic activity.

The area is predominantly impermeable in nature with igneous (granitic) and metamorphosed (slates and shales) lithologies predominating. River drainage densities are high with a predominance of first order streams. Rainfall is often in excess of 2,500 m.m. per annum and the vegetation type is mostly mixed pine forest - orchard savannah. The area of the region as defined by 1:250,000 topographic maps is 1923 km^2 or 23% of the Belize river catchment.

1.2.ii Region 2

Region 2 represents middle altitude areas from about 200 to 500 metres and is sparsely populated. The area is hilly rather than mountainous, the western portion being the relatively flat Vacca plateau. The area is one of hard Cretaceous limestone and as a consequence, drainage densities are low. Valley slopes are low to moderate and karst features and underground drainage is typical. Shifting 'milpa' agriculture is associated with widely scattered, small village settlements. The logging of the deciduous, semi evergreen and seasonal forests takes place peripheral to the central upland area. The total regional area is 3428 km^2 or 42% of the Belize river catchment.

1.2.iii Region 3

This region lies mostly to the north and west of the Belize river and is of low altitude, between 20 and 200 metres above sea level. It has an undulating, sub-horizontal topographic form, the most distinctive features being hill ridges trending S.W. - N.E., approximately parallel to the main drainage of the Belize river. While it is more densely populated than regions 1 and 2, the population is small, the largest towns being of approximately 2,000 inhabitants. Some agricultural activity exists and cattle grazing is practiced to a small extent, though the influences on the natural land cover of palm forest, deciduous forest and high marsh forest, are negligible.

The predominant geological lithology is soft Eocene limestone(2). Valley slopes are low, as are drainage densities. Ephemeral drainage patterns are indicated on 1:50,000 scale maps but karst features are not evident. The total area of the region is 1363 km^2 or 16% of the Belize catchment.

1.2.iv Floodplain

The description and definition of floodplains generally and that of the Belize river are not straightforward. They may be defined by a specific return period flood(3) and thus be variable in area, or as areas likely to be flooded by a hypothetical maximum flood. They may or may not be typically flat plains displaying river - marginal levees, backswamps and ox-bow lakes. Their rivers may extend to complex distributary systems or even connect to other rivers from which they are hydrologically separate at times of low flow.

In the light of these difficulties of definition and for the purpose of multiple regression analysis, the floodplains of the Belize and Sibun rivers were defined in two ways, so that alternative descriptive values could be obtained and tested in regression. Definitions of both types are given below.

1. Gross Floodplain

This definition is determined by the estimated maximum possible inundation of the downstream reach of both rivers. Its boundaries cannot be expressed by contour levels, the 20 and 40 metre levels on 1:50,000 scale maps and the 100 metre levels on the 1:250,000 scale maps being clearly inadequate. The defined floodplain includes all the land indicated as low-lying, swampy or lagoon covered. This floodplain is separated from the New river in the N.W. as no connection is evident on 1:50,000 scale maps. The S.E. boundary is drawn by bisecting the floodplain shared with the Sibun river(4).

2. Specific Floodplain

This area is the land marginal to the river that appears on all maps, likely to flood and includes areas of ponds, swamps and lagoons adjacent to the river. It does not extend to the catchment boundaries except where extensive swamps and lagoons indicate hydrological connections with the river.

It was thought important to test both these definitions in regression analysis since the peak flow of both rivers were expected to be closely determined by overspill to the floodplain and either definition might lend itself to measurement from remotely sensed information. Floodplain characteristics are closely related by geology, slopes and soil types to Region 3, and any evaluations of these characteristics within the floodplain are closely linked to investigations in this region. Table 1.2 below gives details of the hydrological gauging stations within the Belize and Sibun catchments.

1.3 USE OF SUBCATCHMENTS

Each region, excluding the floodplain, was sub-divided into a series of subcatchments, defined by drainage patterns and contour lines on 1:250,000 scale maps. A total of 44 subcatchments were so defined each having its most downstream junction with the Belize river or one of its two main tributaries, the Macal and the Mopan branches. Thus each subcatchment was a drainage basin in its own right.

The selection of subcatchments 'typical' of each region was made by visual inspection of a traced copy of the 1:250,000 scale maps, on the basis of the following criteria:

1. That the drainage pattern was similar to other subcatchments of the region in form and density.
2. That the subcatchment would be contained wholly within the region boundaries. An exception was made in the case of one subcatchment, to observe the results of analysis of a subcatchment with the combined characteristics of two regional types (in this case Regions 1 and 2).
3. That the subcatchment should be small enough for the rapid evaluation of catchment characteristics.

The selection of suitable subcatchments was easily made due to the homogeneous nature of the regions. Expected time savings by the use of this

TABLE 1.2 GAUGING STATIONS WITHIN THE BELIZE AND SIBUN RIVER CATCHMENTS

	GAUGING STATIONS	ABBREVIATION	LOCATED WITHIN REGION	GRID REFERENCE	SHEET NO.	1:50,000 SHEET D.O.S.SERIES
1.	BENQUE VIEJO	B.V.	2	719:890	23	E755 (DOS 44 99) ED. 4 1973
2.	CRISTO REY	C.R.	1	815:953	23	" "
3.	IQUANA CREEK	I.C.	2	953:058	23	" "
4.	BANANA BANK	B.BK.	2	112:121	24	" "
5.	BIG FALLS RANCH	B.F.R.	FLOOD PLAIN	319:351	19	" "
6.	BERMUDAN LANDING	B.L.	FLOOD PLAIN	376:416	20	E755 (D.O.S. 44 99) ED. 3.1973
7.	DAVIS BANK	D.B.	FLOOD PLAIN	518:509	16	E755 (D.O.S. 44 99 ED. 5.1975
8.	GRACIE ROCK	G.R.	FLOOD PLAIN	467:222	21	E755 (D.O.S. 44 99 ED. 4.1973

method of restricted areal coverage was as high as 86%, particularly important in the evaluation of some regression independent variables.

The subdivision of the Sibun catchment was achieved by similar techniques. The Sibun catchment may be divided into exactly similar regional types with the exception of Region 3, which is not present. The subcatchment notation as shown in table 1.3 below was adopted from the overall subdivision of the catchment.

1.4 THIS RESEARCH AND THE PLACE OF REMOTE SENSING

1.4.i Introduction

It is not the aim of this research to review the broad spectrum of remote sensing, its methods of use and applications in any other way than to define the course through which the research passes and to identify areas of previous work that provide useful information for its procedure, without needless duplication. Excellent synopses of remote sensing in its manifold forms may be obtained from publications, journals and newsletters of institutions involved in its use. Such details as are presented relate closely to this thesis and are made by references to the subject under investigation. Below are given the main subtopics of the thesis concerning the role that remote sensing plays(5).

1.4.ii The definition of river flow formulae

The derivation of flow or flood formulae by the study of catchment characteristics has been developed by hydrologists for many years. They are based on the observable fact that areas of differing climate, topography, geology, soils and vegetation have different flow characteristics. Areas of similar physical natures have similar flow characteristics(6). That river flow is related to such factors is indisputable but the complexity of the inter relationships has caused many difficulties. So much so, that while these influencing conditions may be used to define flow formulae, their basis is statistical and a direct cause and effect relationship may not be assumed(7). The quantification

TABLE 1.3 BELIZE RIVER CATCHMENT, REGIONAL DIVISIONS - AREAS DERIVED FROM 1:250,000 SCALE MAPS

REGIONS	TYPE	AREA (km^2)	% TOTAL CATCHMENT	SELECTED SUBCATCHMENT
1	IMPERMEABLE UPLAND	1923	22.3%	6b
2	PERMEABLE MIDDLE LAND AND PLATEAU	3428	41.6%	3a
3	PERMEABLE LOW LAND	1363	16.5%	28
FLOOD PLAIN		1528*	18.5%	

* GROSS FLOOD PLAIN AREA

of these influencing factors may be obtained from maps(8) but the scale and detail of map information varies, indeed may vary from area to area with the same scale(9). While this is a problem, the localisation of such flow formulae and their general inability of inter-regional transference prevents serious misuse where due considerations are made. Remote sensing information may be used in the primary evaluation of catchment characteristics(10) where other sources of information are lacking, or to identify subtle changes in seasonal characteristics(11). Such seasonal variation in information is not available from topographic maps.

In the past the identification of river channel size, highly correlated to flow has not been possible by satellite, however with ground resolution sizes of 25, 15 or 10 metres available(12), (13), such characteristics will undoubtedly become significant in the quantification of river flow and flooding(14). This research concentrates largely on the use of LANDSAT multispectral scanner (m.m.s.) data, alternative source coverage being limited. Although various workers have attempted to refine flow formulae either by the observation of multi temporal changes in catchment characteristics, or by the integration of remotely sensed data with that of topographical and land use maps(15). This research extends the field of such work in two ways: first it assesses the suitability of direct substitution of topographic map information by that obtained from satellite and details the likely accuracies of this information. These values are then used directly in multiple regression analysis to determine the usefulness of such satellite values. Second, it attempts this in the context of the use of only two catchments with restricted hydrological and meteorological data and with no possibility of ground survey. Previous research has provided itself with the maximum number of small catchments, easily equipped with dense hydrological and meteorological networks(16) to provide an extensive coverage of ground data. This does not reflect the true working conditions outside Europe and the U.S.A. and while it may represent the potential value of remotely sensed information in favourable circumstances, it cannot present the limitations of this information in terms of the developing world. In addition the accessibility to image processing equipment is extremely difficult for hydrologists working in the very areas that could benefit most from the use of remotely sensed information. Consequently an important aspect of this research is its evaluation of photographic materials that are easily and cheaply produced and which can be used in the field(17).

1.4.iii The observation of flood events

One of the most frequent applications of remotely sensed imagery, particularly LANDSAT m.s.s. imagery, has been the observation of flood events (18), (19). This imagery is normally used in two ways: by the synchronous over flight of imaging satellites at the time of predicted flood, or by coincidental over flight. The former is difficult to contrive but has been used in the past with some success and where circumstances permit, may be coordinated with ground surveys(20). The latter is obviously more frequently used and may still provide significant information despite its coincidental nature(21).

This research uses a single scene of post flood imagery. Past research has largely been directed at flood mapping, the location and extent of flooding(22). Some workers have extended this to include the progressive development of flood events(23), but multitemporal imagery is necessary in this case as is a flood period long enough to allow the use of specially ordered aquisitions.

It also aims, not only to describe simple methods of flood extent measurement but also to define flood volumes by the use of elevation data from topographic maps. It defines the relative merits of both photographic print material and image processed computer compatible tapes (c.c.ts) and their respective costs. The scale of flood inundation is linked directly to a flood flow hydrological series by the use of return period estimation. The hydrological data base generates both a flood magnitude distribution and synthesised hydrographs of the flood event. The return period of the flood event is found by comparison with rainfall return periods. The limit of channel flow determined by the flood magnitude distribution provides an estimate of the river contribution to the flood.

Estimates of the observed flood volume obtained from LANDSAT imagery are compared to that of the river contribution, taking into account the contribution from the local catchment. Thus, not only can the identification of the flood period and the extent of the flood be estimated, but also a correlation between the observed volume and the synthesised volume can be made using the same hydrological data base as used in multiple regression analysis.

1.5 AIMS OF THE RESEARCH

The general outlines of the aims of this research have been discussed in the previous section. When considered in detail, they are many and fall into two distinct groups. These aims are considered in the light of circumstances that operate in developing countries - typically the lack of detailed hydrological, meteorological and ground truth data, a shortage of facilities and severe financial restrictions. These aims are grouped below in tables 1.4 and 1.5.

TABLE 1.4 AIMS RELATING TO REMOTELY SENSED INFORMATION

1. To assess the most appropriate sources for the coverage of large regional areas.
2. To determine which source provides the most accurate quantifications of catchment characteristics.
3. Which methods of map production and types of information format are most appropriate when costs and reproduction accuracies are considered.
4. To identify the variety and useful ness of the catchment characteristics that may be obtained from remote sensing sources.

5. To determine whether LANDSAT m.s.s. information can be used to provide regression analysis flood formulae and test their statistical accuracies when compared to similar formulae obtained from topographic maps.

TABLE 1.5 AIMS RELATING TO HYDROLOGICAL INVESTIGATIONS AND FLOODS

1. To select and develop the most useful hydrological base for the provision of flood flows (or parameters describing these flows), to be used in regression analysis as dependent variables.
2. To develop regression flood formulae suitable for the identification of flood flows of various return periods, throughout the region.
3. To synthesise by the use of unit hydrographs, the river flows directly related to the flood event presented by the LANDSAT image.
4. To link LANDSAT flood scene information of flood volume to a particular return period.
5. To identify any correlation between the predicted flood of the flow hydrographs and the flood volume estimated from the LANDSAT image.
6. To identify the behaviour of the flooding and investigate the methods by which it may be accurately defined.

Figure 1.2 presents a flow diagram showing the interrelation of these aims and the structure of the thesis. These aims represent the middle scale investigations of this thesis and within each chapter, conclusions will be drawn concerning the details of method, procedure and materials. Chapter 15 provides a discussion of the overall conclusions of the research and will, in particular, draw upon items listed in the tables above.

1.6 THE FLOOD STUDIES REPORT

Continual reference is made throughout this thesis to the National Environment Research Council Flood Studies Report, referred to hereafter as the F.S.R. It is an enormously comprehensive hydrological document. Its coverage includes many items irrelevant or peripheral to this work but contains a wide range and great depth of investigation into hydrological methods, their suitable applications and details of qualifying conditions. Its usefulness as the basis of hydrological investigations in the related chapters of this thesis cannot be overestimated. While many of its results are restricted to the United Kingdom by virtue of its supportive data, its exploration of method is universally applicable.

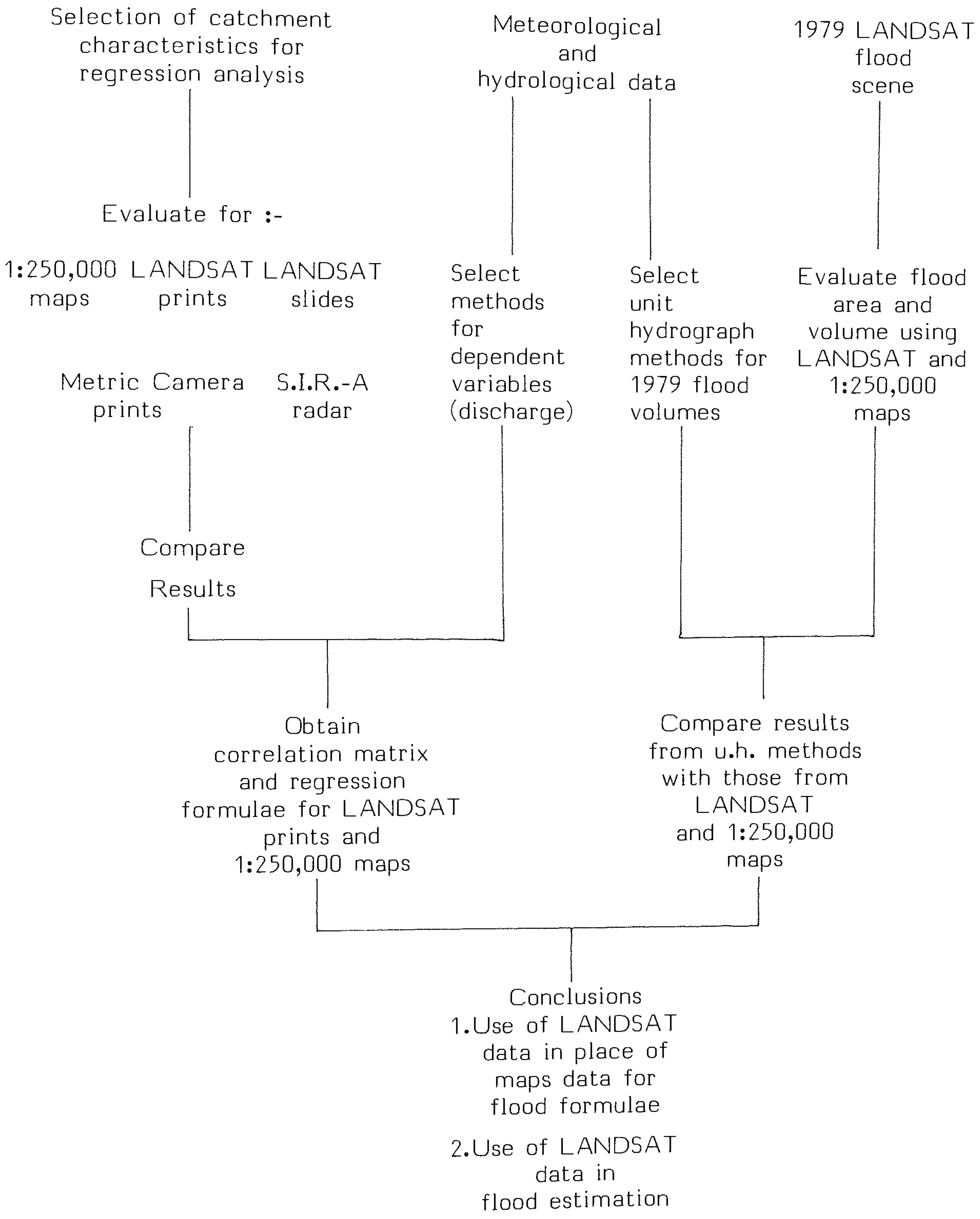
The complexity of analysis that the F.S.R. undertakes is frequently not possible using the limited information available from Belize, but alternative methods of approach are often described and the fundamental tenets of methodology are supported by a wealth of reference material. The extensive use of the F.S.R. by hydrologists, establishes its importance in works of hydrological methodology and the statistical analysis of hydrological data. Table 1.6 below details the areas of the Report most used in this thesis.

TABLE 1.6 OUTLINE OF F.S.R. INVESTIGATIONS USED IN THE THESIS

Volume	Chapter	Subject Details
2	2	Data used in statistical analysis.
2	3	Data used in hydrographic analysis : storm rainfall, hydrographs, antecedent conditions, catchment characteristics.
2	1	Statistics for flood hydrology : statistical distributions, distribution parameters.
2	2	Statistical flood frequency analysis : annual maximum series, peaks over threshold series, estimations of flood returns.
2	4	Flood peaks from catchment characteristics : selection, measurement, correlation, regression analysis, effects of errors in the data.

2	6	Unit hydrographs : limitations of theory, applications and definitions, time base conversions, rainfall profiles.
3	2	Regional analysis of point rainfall extremes : graphical analysis, annual maximum series.
3	3	Estimation and mapping of 5 year rainfall : relations of various 5 year rainfall durations.
3	5	Areal rainfall : areal reduction factor of point rainfall

FIGURE 1.2 FLOW DIAGRAM OF THE STRUCTURE OF THIS THESIS



CHAPTER 2 CATCHMENT CHARACTERISTICS SELECTED AS INDEPENDENT VARIABLES FOR MULTIPLE REGRESSION ANALYSIS, 1:250,000 SCALE TOPOGRAPHIC MAPS

2.1 INTRODUCTION

Previous workers (24) have investigated a wide range of catchment characteristics available for entry into multiple regression derived flood formulae. Their careful selection is extremely important especially when values will be regressed against a limited number of observation stations, as in the case of the Belize and Sibun rivers. The use of non-correlated independent variables is desirable but many characteristics are closely related and the determination of these relationships is a necessary step in selecting the most suitable for use(25), (26). The first stage in selection is the construction of a correlation matrix, though the usefullness of principal components analysis has been proven(27). In this research, least correlated characteristics were adopted from the F.S.R.(28), to a great extent. It was in some cases necessary to modify such characteristics or adapt them, though in all cases a correlation matrix obtained from Belize data was constructed before final selection. The final group of variables chosen for use is given below in table 2.1. A more detailed discussion is given in chapter 10, 'Multiple Regression Analysis'.

TABLE 2.1 SELECTED CATCHMENT CHARACTERISTICS FOR USE WITH BELIZE DATA

1. Area
2. Mainstream slope
3. Stream frequency
4. Soil/slope index
5. Flood plain area
6. Mainstream length
7. Circularity index
8. Length : width ratio

(9. Rainfall variable)

The selected group reflect all main physiographic features of the river catchment. The addition of a floodplain variable (no.5), important in Belize and Sibun catchments where channel flows are sometimes determined by floodplain presence, was expected to behave in a similar way to the lake variable proposed by the F.S.R.(29). The variables 6, 7 and 8 were added to provide representation of those obtainable from satellite imagery.

2.2 THE QUANTIFICATION OF INDEPENDENT VARIABLES, 1:250,000 SCALE MAPS

2.2.i Area of catchments

The total catchment area, regional and subcatchment areas were measured by digitiser linked to a microcomputer. Measurements were made from the traced outline Map A. A variable time/distance registration of boundary coordinates was used for flexible and accurate measurement. Areas greater than the digitiser tablet were subdivided and measured by sections. The accuracy of 1:250,000 map results were checked against those at 1:50,000 scale in the case of subcatchments, details are given in table 2.2. below. The most significantly different result relates to subcatchment 3a, where the lack of contour details and river drainage led to difficulties of boundary definition in the cases of both scales.

Since the accuracy of 1:250,000 scale maps was sufficient and was directly comparable to scales commonly used for LANDSAT material, this scale was used to obtain ground truth values for comparison with remotely sensed values. Table 2.3 below presents details of the areas of catchments above gauging stations, measured from 1:250,000 scale maps.

2.2.ii Mainstream Slope

This variable was measured using blue line representation on the maps. While some workers(30), (31), (32) have suggested extending this representation to the catchment divide, this was unnecessary in the case of the 1:250,000 scale maps of Belize.

TABLE 2.2 REGIONAL AND SUBCATCHMENT AREAS 1:250,000 and 1:50,000 SCALE MAPS

BELIZE RIVER

REGION	1:250,000 AREA (km^2)	SUBCATCHMENTS	AREA (km^2) 1:250,000	AREA (km^2) 1:50,000	%DIFFERENCE
1	1923	6b	432.2	434.5	- 0.5%
2	3428	3a	271.2	294.7	- 8.7%
3	1363	28	79.2	82.3	- 3.9%
GROSS FLOOD PLAIN	1528	4	161.2	166.2	- 3.1%
TOTAL CATCHMENT	8242				

SIBUN RIVER

REGION	
1	371
2	341
3	0.0
GROSS FLOOD PLAIN	511
TOTAL CATCHMENT	1223

TABLE 2.3 AREAS ABOVE GAUGING STATIONS. 1:250,000 SCALE MAPS

	GAUGING STATIONS	REGION 1 (km^2)	% OF TOTAL	REGION 2 (km^2)	% OF TOTAL	REGION 3 (km^2)	% OF TOTAL	GROSS FLOOD PLAIN (km^2)	GROSS FLOOD PLAIN % OF TOTAL	TOTAL AREA (km^2)
1.	BENQUE VIEJO (MOPAN)	378	11.3	2792	83.3	181	5.4	0	0	3351
2.	CRISTO REY (MACAL)	1366	91.6	118	7.9	81	0.5	0	0	1492
3.	IGUANA CREEK	1792	34.4	2911	55.8	510	9.8	0	0	5213
4.	BANANA BANK	1922	31.8	3258	53.9	860	14.2	0	0	6040
5.	BIG FALLS RANCH	1922	27.1	3422	48.3	1345	19.0	391	5.5	7080
6.	BERMUDAN LANDING	1922	27.0	3422	48.0	1345	18.9	434	6.1	7123
7.	DAVIS BANK	1922	24.2	3422	43.1	1345	16.9	1253	15.8	7942
8.	GRACIE ROCK	379	43.2	341	38.8	0.0	0.0	158	18.0	878

The 1085% method of slope calculation(33) was used to determine values for this variable. The Belize river has two main tributaries, the Mopan and the Macal rivers which, while having contrasting hydrological regimes, discharge approximately similar volumes at flood flow. At periods of non-flood flow, the Mopan has by far the greater discharge, from a larger catchment. Mainstream slope calculation is given below in figures 2.1 and 2.2, for the Belize and Sibun rivers. Slopes are measured for the reaches of the rivers between gauging stations and the catchment divide for all stations and averaged as proposed by previous research(34). Table 2.4 presents the respective Mopan and Macal slope values and ratio by gauging station, as well as the area-weighted average.

2.2.iii Stream frequency

Various measures of drainage density have been adopted in the past(35) (36). Stream frequency, defined as the number of stream junctions per unit area is a choice suited to rapid manual calculation and is less open to misinterpretation than alternative choices. It has been shown to work well in large number of multiple regression analyses(37).

Stream frequency is obviously regional in character, related closely to the topography and geology of each region. Stream frequency was measured for the four selected subcatchments (6b, 3a, 28 and 4) so that the results could be applied to their respective regions. Subcatchment 4 was selected to identify any problems occuring when mixed regional type information was collected and used. Values are given below in table 2.5.

Measurement for multiple regression analysis values was undertaken by the use of 1:250,000 scale maps. In addition, 1:50,000 scale map values were also obtained to provide a convenient framework in which to place those values of remotely sensed data. Values of stream frequencies above gauging stations as shown below, in table 2.6, were obtained by taking an average value of 1:250,000 scale frequencies appropriate for each region and weighting them according to the percentage area of the catchment. Figures 2.3, 2.4, 2.5 and 2.6 illustrate the drainage in the subcatchments.

Figure 2.1(a) MOPAN 1085% MAINSTREAM SLOPE

Station				Slope
BV	=	120m / 60km	=	0.0020
IC	=	20m / 12.5km	=	0.0016
BBk	=	20m / 15km		
BFR	=	20m / 18km	=	0.0011
BL	=	20m / 20km	=	0.0010
DB	=	20m / 22.5km	=	0.0009

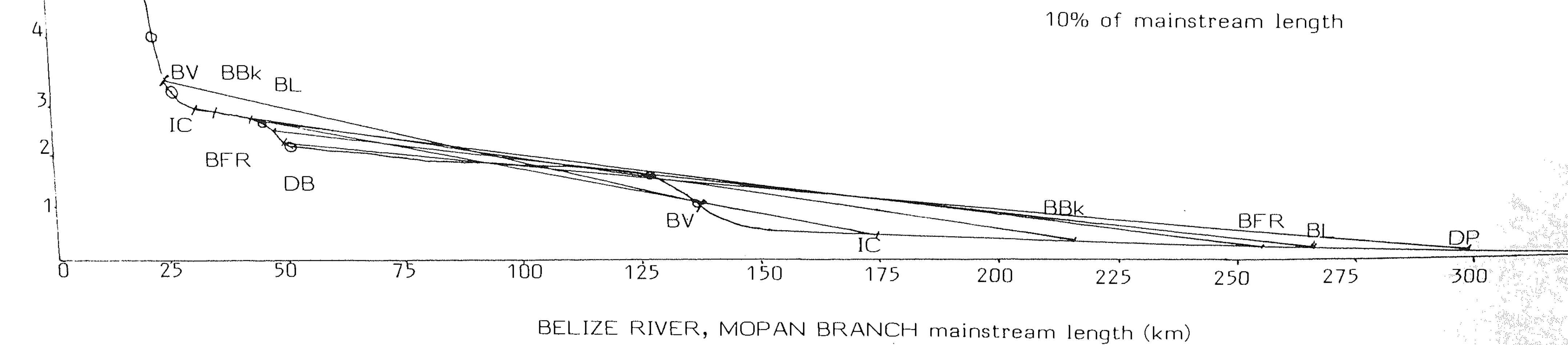
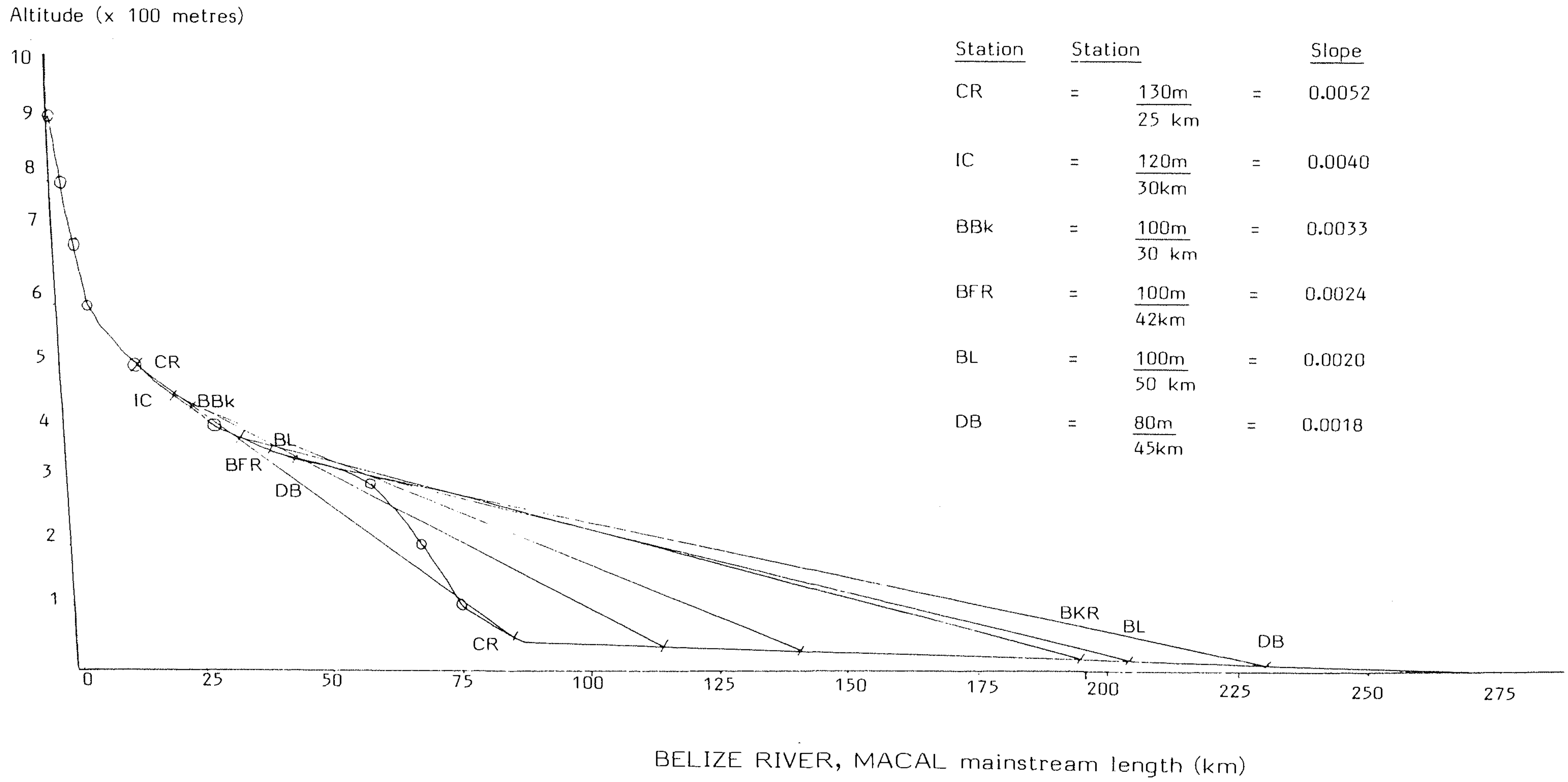


Figure 2.1(b) MACAL 1085% MAINSTREAM SLOPE



Station		Station		Slope
CR	=	$\frac{130m}{25\ km}$	=	0.0052
IC	=	$\frac{120m}{30km}$	=	0.0040
BBk	=	$\frac{100m}{30\ km}$	=	0.0033
BFR	=	$\frac{100m}{42km}$	=	0.0024
BL	=	$\frac{100m}{50\ km}$	=	0.0020
DB	=	$\frac{80m}{45km}$	=	0.0018

Figure 2.2 I:250,000 MAP I085% MAINSTREAM SLOPE (SIBUN RIVER)

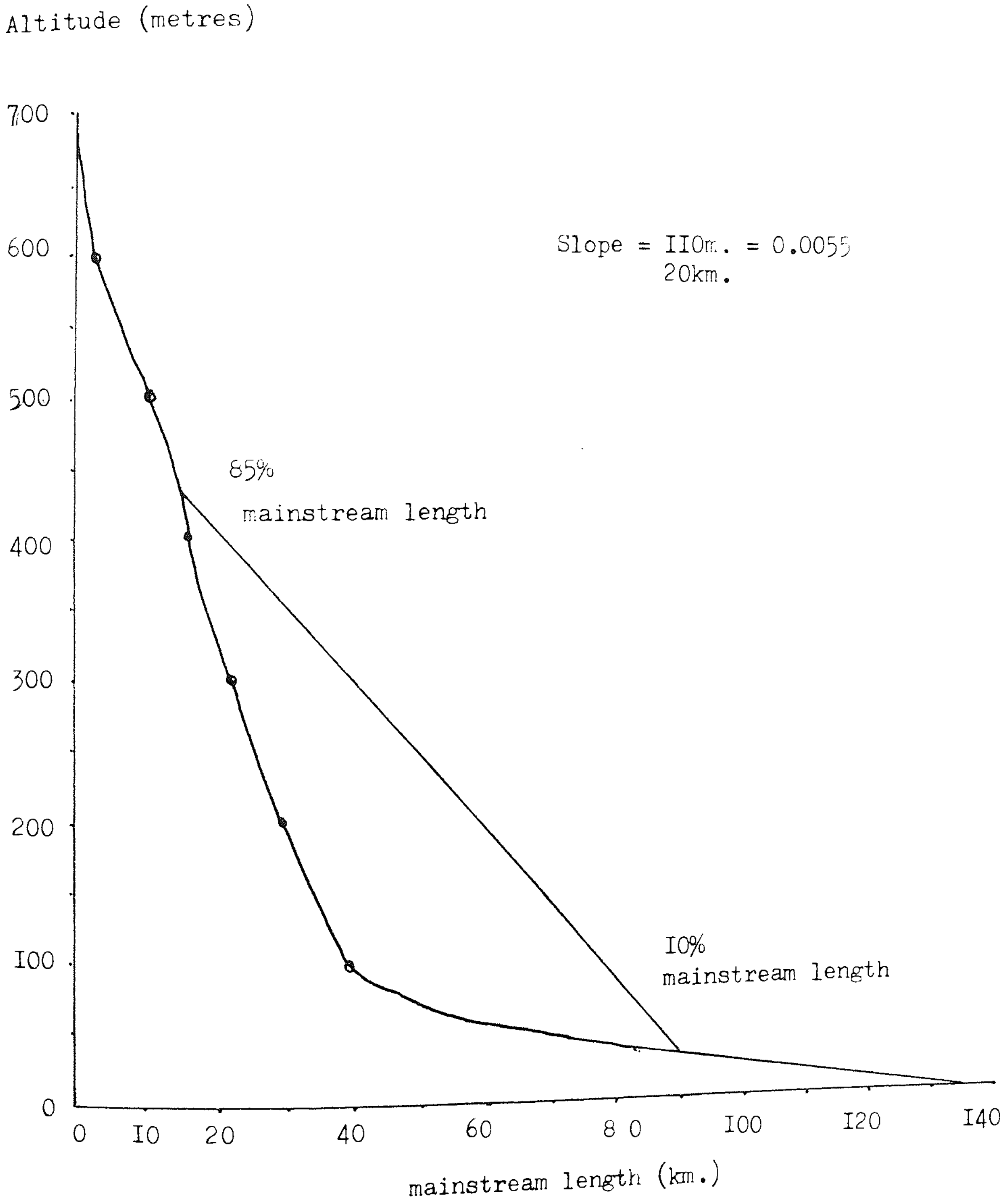


TABLE 2.4 1085% MAINSTREAM SLOPES

GAUGING STATIONS	1085% SLOPE (MACAL)	1085% SLOPE (MOPAN)	MACAL/MOPAN RATIO	AREA WEIGHTED SLO
1. B.V.	-	0.0020	-	0.0020
2. C.R.	0.0052	-	-	0.0052
3. I.C.	0.0040	0.0016	2.5	0.0025
4. B.BK	0.0033	0.0013	2.5	0.0019
5. B.F.R.	0.0024	0.0011	2.1	0.0015
6. B.L.	0.0020	0.0010	2.0	0.0013
7. D.B.	0.0018	0.0009	2.5	0.0012
8. G.R.	-	-	-	0.0055

Figure 2.3. DRAINAGE NETWORK SUBCATCHMENT 3a (I:250,000 SCALE) TOPOGRAPHIC MAPS

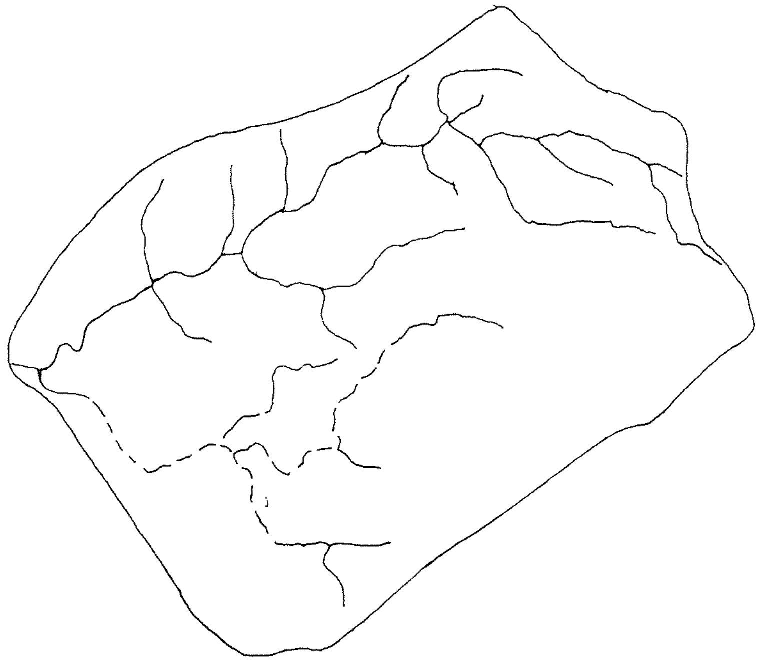


Figure 2.4 DRAINAGE NETWORK SUBCATCHMENT 6b (I:250,000 SCALE) TOPOGRAPHIC MAPS

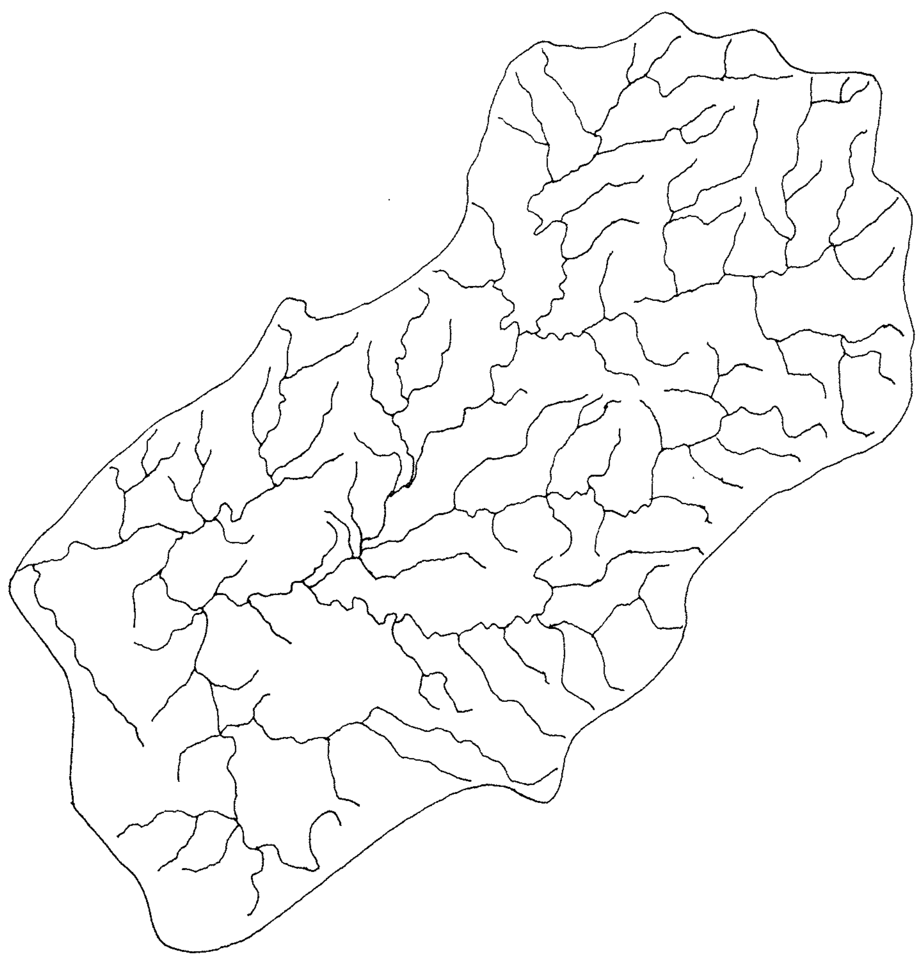


Figure 2.5. DRAINAGE NETWORK SUBCATCHMENT 28 (I:250,000 SCALE) TOPOGRAPHIC MAPS

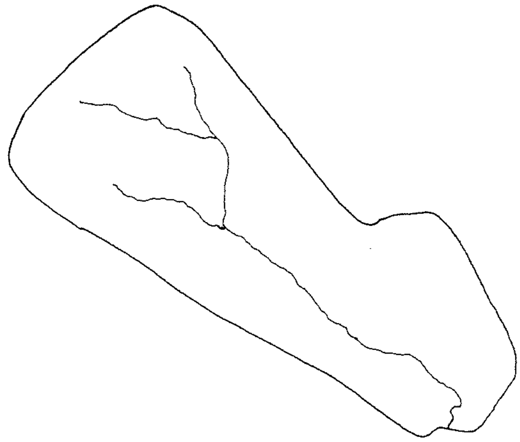


Figure 2.6. DRAINAGE NETWORK SUBCATCHMENT 4 (I:250,000 SCALE) TOPOGRAPHIC MAPS

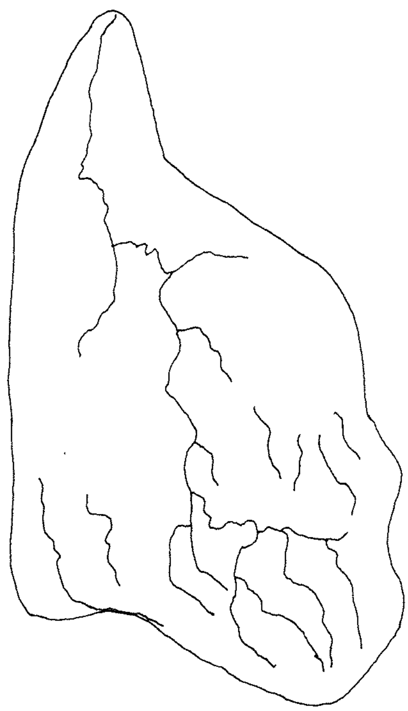


Table 2.5 STREAM FREQUENCIES* OF SUBCATCHMENTS, 1:250,000 AND 50,000 SCALE MAPS

Sub-catchment	1:250,000 scale str.frequency(a)	1:50,000 scale Str.frequency(b)	Ratio (b)(a)
6b	0.180	1.780	9.89
3a	0.066	0.380	5.76
28	0.063	0.422	6.70
4	0.056	0.530	9.46

Table 2.6 STREAM FREQUENCIES* FOR CATCHMENT AREAS ABOVE GAUGING STATIONS

Station	Str.frequency	Station	Str.frequency
Benque Viejo	0.079	Big Falls Ranch	0.096
Cristo Rey	0.170	Bermudan Landing	0.096
Iguana Creek	0.105	Davis Bank	0.093
Banana Bank	0.102	Gracie Rock	0.115

* Stream frequencies are in the form : number of stream junctions per square kilometre

The linear regression relationship between the two map scales is given by:

1:50,000 scale values = 11.127 x 250,000 scale values - 0.226

$$y = 11.127z - 0.226 \qquad (2.2.1)$$

The following comments may be made by observation of table 2.5.

1. Subcatchment 4 has a low value, indicating the significant loss underground, of many streams originating in the impermeable headwater area. These, in crossing the Region I/2 boundary are lost within the Cretaceous limestone. This results in many observable rivers which are subsequently lost, and a low stream frequency value.

2. At 1:250,000 scale, almost twice (1.78 times) as many rivers are presented on the map in permeable areas compared to impermeable areas, when differences between 1:250,000 and 50,000 values are considered. This probably relates to the difficulty in placing rivers in areas

of highly dissected, mountainous terrain and illustrates an important fact that the drawing and interpretation for topographic base maps can exercise, perhaps unexpected control upon the quantification of drainage patterns. Two different interpretations of water courses were evident, each from the two 1:50,000 series, when adjacent. Where the stipulations of which symbol constitutes a water course are rigidly set, the use of different map series may lead to different results.

2.2.iv Soil/Slope index

The soil/slope index method presented here is based on that used by the Flood Studies Report(38) and is perhaps the most time-consuming of all the physiographic variables to measure. Previous research(39) has indicated that both basin slope and soil type relate closely to the runoff from river catchments.

Basin slope values can be measured relatively easily from any scale map but the measurement of contributions from soil types usually needs details of soil distribution and structure. Infiltration/run-off characteristics are highly variable with time and place, thus the method of soil/slope index proposed by the F.S.R. is necessarily generalised and combines the two elements of basin slope and soil type.

Basin Slopes:

These were measured by the division of the subcatchments into 10 m.m. squares on both map scales, to match U.T.M. coordinates. Within each square, the maximum and minimum slopes were measured and averaged. It has been shown that the box sampling method(40) has as high an accuracy as the intersection method commonly used in such circumstances(41). The intersection method has two main disadvantages. First, the point values of the intersection method are not convenient for conversion into maps. Second, that the assumption of an average distribution of maximum values closest to the intersections, may not be correct.

TABLE 2.7 RESULTS OF BASIN SLOPE VALUES BOX CONTROL AND INTERSECTION METHODS
(SUBCATCHMENT 6b 1:50,000 SCALE)

BOX METHOD			GRID INTERSECTION METHOD	
SLOPE (°)	° DIFFERENCE FROM CONTROL	CONTROL SLOPE (°)	SLOPE (°)	° DIFFERENCE FROM CONTROL
11	- 2	13	28	+ 15
11	- 3	14	28	+ 14
8	+ 1	7	11	+ 4
13	0	13	11	- 2
8	- 4	12	24	+ 12
13	- 1	14	28	+ 14
13	+ 1	12	15	+ 3
23	- 1	24	28	+ 4
28	+ 2	26	28	+ 2
5	0	5	15	+ 10
9	- 4	13	22	+ 9
11	0	11	28	+ 17
13	- 2	15	18	+ 3
4	+ 1	3	5	+2
7	- 1	8	15	+7

Table 2.8 COMPARISONS OF 1:50,000 AND 1:250,000 scale MAP AVERAGE BASIN SLOPES

Subcatchment	1:50,000 Scale (a)	1:250,000 Scale (b)	Difference (a)-(b)
6b	14.9°	11.2°	3.7°
3a	6.4°	5.5°	0.9°
28	2.0°	2.0°	0°
4	8.8°	4.6°	4.2°

A comparative set of values was obtained from each method and set against control values. The control values were obtained by taking the average of up to 70 slope values per 10 m.m. square. Table 2.7 presents the results of this procedure for subcatchment 6b at 1:50,000 scale. Table 2.8 gives subcatchment slope values for both scales. Table 2.7 shows the intersection method to overestimate slope values and has a higher standard error of estimate. The box method was used for all subcatchments at both scales. The grid spacings were determined by map contour intervals. Spacings of 2 m.m., 5 m.m. and 10 m.m. were tested for possible improvements in accuracy and detail, but it was found that :

1. 2 m.m. spacings were too fine to be used at either scale, within any subcatchment.

2. 5 m.m. spacings were suitable for the most densely contoured parts of the upland catchment at both scales. A comparison of 5 m.m. and 10 m.m. slope value maps are shown later in figures 2.11, 2.12, 2.13 and 2.14 for subcatchments 6b and 4. Differences between them are not great as table 2.9 below shows.

Table 2.9 COMPARISON OF OVERALL SLOPES WITHIN SUB-CATCHMENTS, 1:250,000 SCALE

Subcatchment	6b		4		3a	28
Grid size	5 mm	10 mm	5 mm	10 mm	10 mm	10 mm
Basin slope	10.86°	11.20°	4.51°	4.59°	5.5°	<2°

3. 10 m.m. spacings were generally suitable for all circumstances.

4. Such was contour spacing, that even 10 m.m. boxes were necessarily amalgamated to cover areas of little relief on occasion.

5. Slope values should be weighted by box area where incomplete boxes are present at catchment boundaries, since slopes in these boxes tend to have extreme values.

6. Subcatchment 28 contour spacings were so great that the area was designated as having slopes $<2^o$, at both scales.

The F.S.R. groups basin slope values into three classes: low slope ($<2^o$), moderate (2^o-8^o) and high ($>8^o$) per combination with soil types.

Soil Types :

These were obtained from the 1:250,000 scale map and detailed descriptions are available(42). Five soil type groups were formed with reference to type, structure and depth as recommended by the F.S.R. and combined with the basin slope classes given above. This combination is illustrated below in table 2.10. Folded Map C shows soil type distributions within the Belize catchment, for types 1 to 5.

TABLE 2.10 COMBINATION OF BASIN SLOPES AND SOIL TYPES TO GIVE SOIL/SLOPE CLASSES

Soil Type	Slope Class $<2^o$	2^o-8^o	$>8^o$
1	I	I	II
2	I	II	III
3	II	III	IV
4	III	IV	V
5	IV	V	V

where soil/slope Class I indicates low run off

where soil/slope Class III indicates moderate run off

where soil/slope Class IV indicates high run off

In the case of each subcatchment the traced slope map was superimposed upon the 1:250,000 soil map that had been drawn to provide details of the five soil type groups. A combined tracing was then made which gave the soil/slope class distribution. This distribution was converted into a numerical index by using the following relationship:

$$\frac{0.15\,I + 0.35\,II + 0.40\,III + 0.45\,IV + 50\,V}{I + II + III + IV + V} \qquad (2.2.2.)$$

TABLE 2.11 OCCURENCE OF SOIL/SLOPE CLASSES WITHIN SUBCATCHMENTS (1:250,000 SCALE)

SUBCATCHMENT	I		II		III		IV		V		TOTAL AREA
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2
6b	12.56	2.9	59.68	13.8	69.16	16.0	80.38	18.6	211.21	48.8	432.99
3a	99.70	37.0	36.66	13.6	46.51	17.3	68.76	25.5	17.88	6.6	269.50
28	10.89	6.4	0.0	0.0	145.80	85.7	13.27	7.8	0.0	0.0	169.96
4	17.32	10.2	32.29	19.1	38.25	22.5	10.60	6.2	66.65	42.6	165.11

TABLE 2.12 SOIL INDICES FOR THE BELIZE RIVER CATCHMENT REGIONS

REGION 1 (SUBCATCHMENT 6b)					REGION 2 (SUBCATCHMENT 3a)				REGION 3 (SUBCATCHMENT 28)			
% AREA x CLASS					% AREA BY CLASS				% AREA BY CLASS			
48.8	x	0.5	V	24.40	6.6	x	0.5	3.30	0.0	x	0.50	0.0
18.6	x	0.45	IV	8.37	25.5	x	0.45	11.48	7.8	x	0.45	3.51
16.0	x	0.40	III	6.40	17.3	x	0.40	6.92	85.7	x	0.40	34.28
13.8	x	0.35	II	4.83	13.6	x	0.35	4.76	0.0	x	0.35	0.0
2.9	x	0.15	I	0.44	37.0	x	0.15	5.55	6.4	x	0.15	0.96
TOTALS				44.44				32.01				38.75

SOIL INDEX = 0.4444

SOIL INDEX = 0.3201

SOIL INDEX = 0.3875

It amounts to an areal weighting of different soil/slope classes, with a scaled influence depending upon the runoff potential of the class. Table 2.11 presents the proportions of soil/slope classes within the subcatchment areas.

With these proportion values available, they were applied to obtain regional values by the use of the percentages in table 2.11. The calculations of these regional values and the region's soil index values are given in table 2.12. These can be seen to be 0.4444, 0.3201 and 0.3875 for Regions 1, 2 and 3 respectively. Values for catchment areas above gauging stations were obtained by the application of percentage areas. For example the Benque Viejo soil/slope index = 0.3378 obtained in the following way: (43)

% of catchment comprised by	Region 1 +	Region 2 +	Region 3 +	Floodplain
	11.3%	83.3%	5.4%	0.0%
	0.4444x11.3 +	0.3201x83.3% +	0.3875 x 5.4 +	0.350x0.0%
= 33.78/100	soil/slope index	= 0.3378		

Thus for each gauging station the catchment soil/slope index was calculated with results as shown below in table 2.12. The floodplain index was not arrived at by subcatchment means. Slopes were seen to be low ($<2^{o}$) but with variable soil types similar to Region 3. It was attributed the soil/slope index of 0.350, consistent with the nature of soil slope class of II. Table 2.13 below gives the soil indices calculated for all catchment areas above gauging stations.

Table 2.13 SOIL/SLOPE INDICES FOR CATCHMENT AREAS ABOVE GAUGING STATIONS

	Gauging Stations	Soil/Slope index
1.	Benque Viejo	0.3378
2.	Cristo Rey	0.4343
3.	Iguana Creek	0.3695
4.	Banana Bank	0.3689

Figure 2.7. BASIN SLOPE CLASSES SUBCATCHMENT 3a (I:250,000 SCALE) TOPOGRAPHIC MAPS

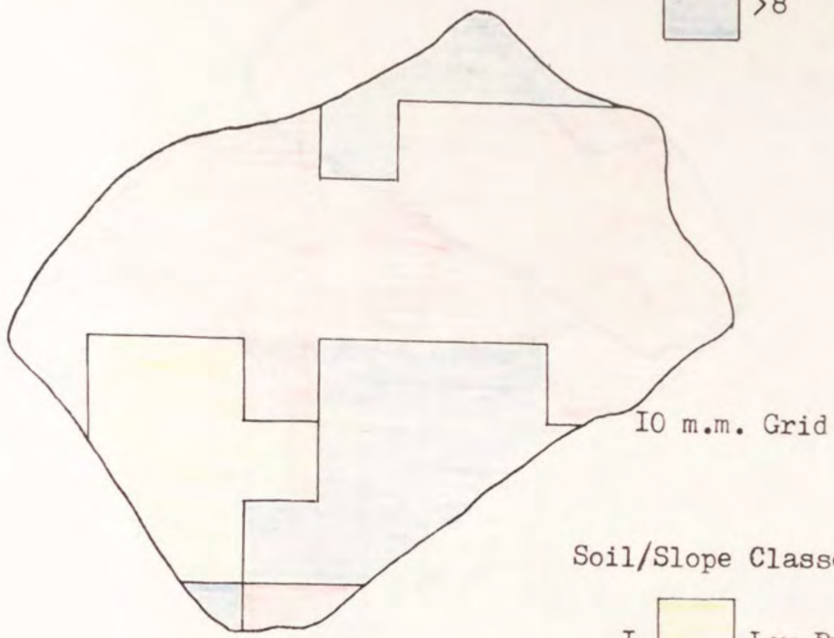


Figure 2.8. SOIL/SLOPE CLASSES SUBCATCHMENT 3a (I:250,000 SCALE) TOPOGRAPHIC MAPS

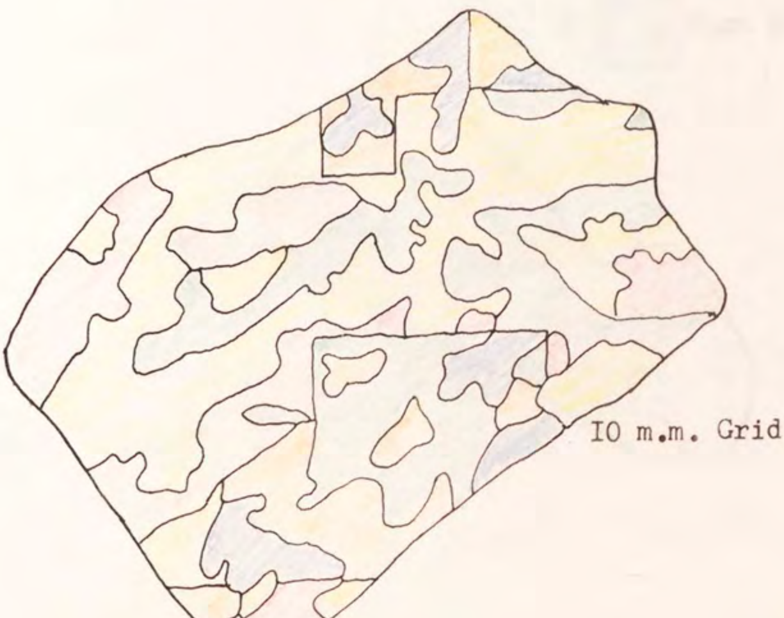
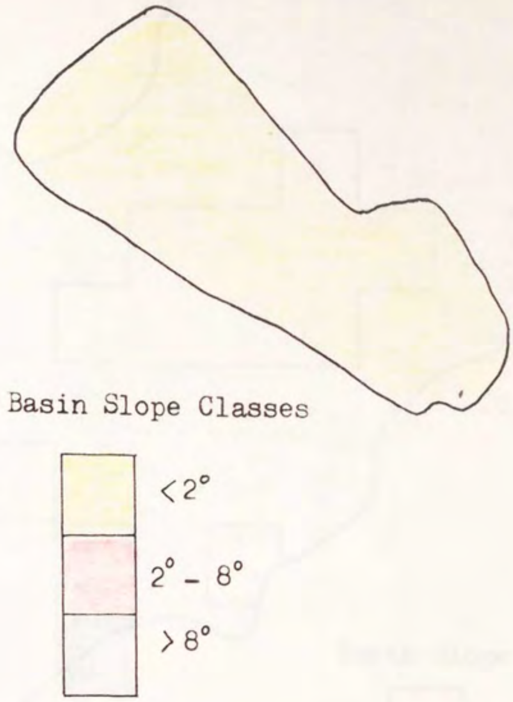


Figure 2.9 BASIN SLOPE CLASSES SUBCATCHMENT 28 (I:250,000 SCALE) TOPOGRAPHIC MAPS



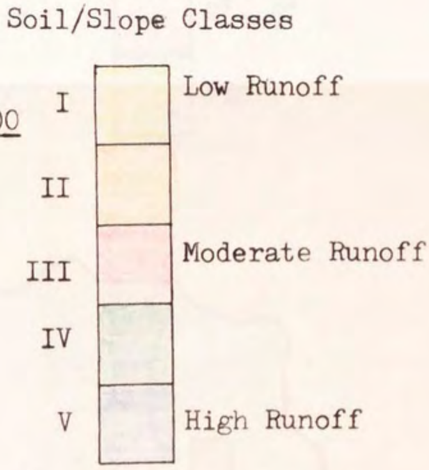


Figure 2.10. SOIL/SLOPE CLASSES SUBCATCHMENT 28 (I:250,000 SCALE) TOPOGRAPHIC MAPS

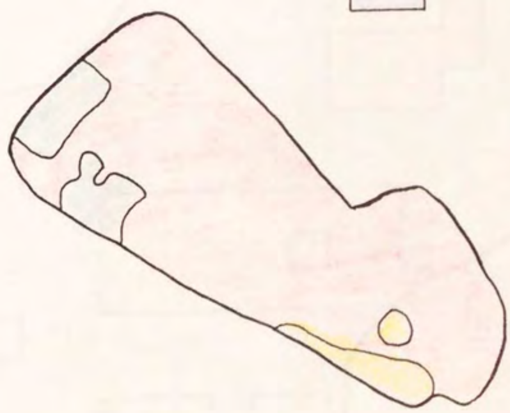
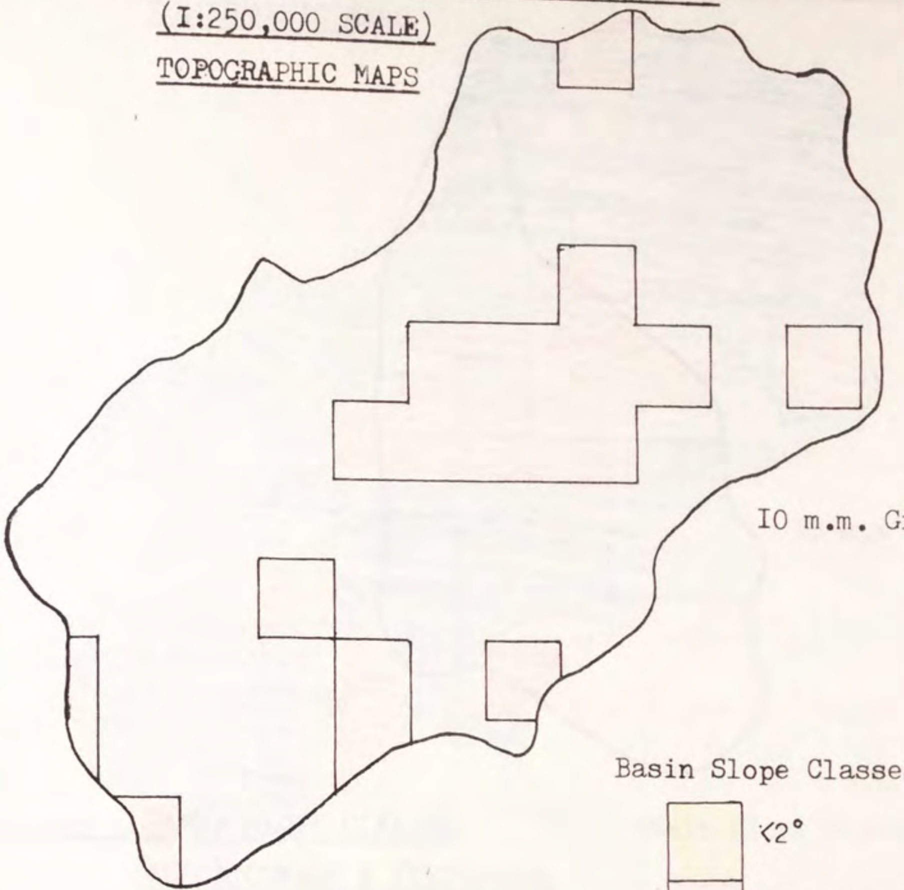


Figure 2.11 BASIN SLOPE CLASSES SUBCATCHMENT 6b. (1:250,000 SCALE) TOPOGRAPHIC MAPS



10 m.m. Grid

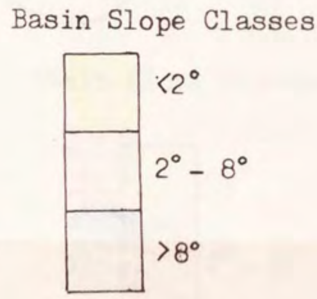
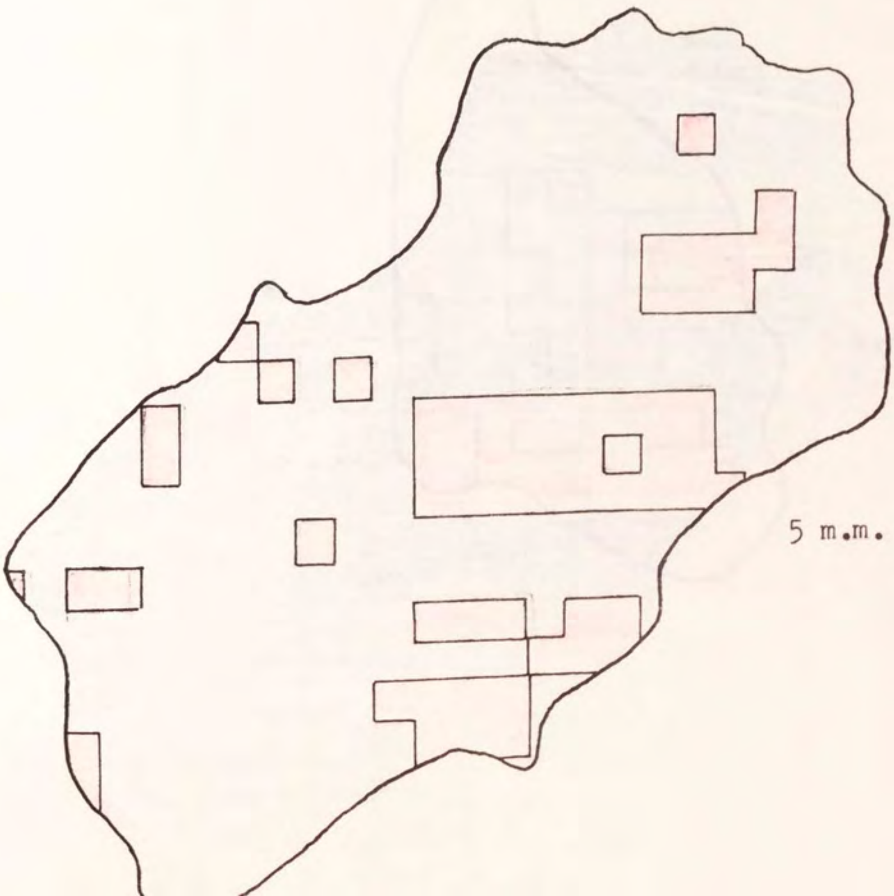


Figure 2.12 BASIN SLOPE CLASSES SUBCATCHMENT 6b (1:250,000 SCALE) TOPOGRAPHIC MAPS



5 m.m. Grid

Figure2.I3 BASIN SLOPE CLASSES SUBCATCHMENT 4 (I:250,000 SCALE) TOPOGRAPHIC MAPS

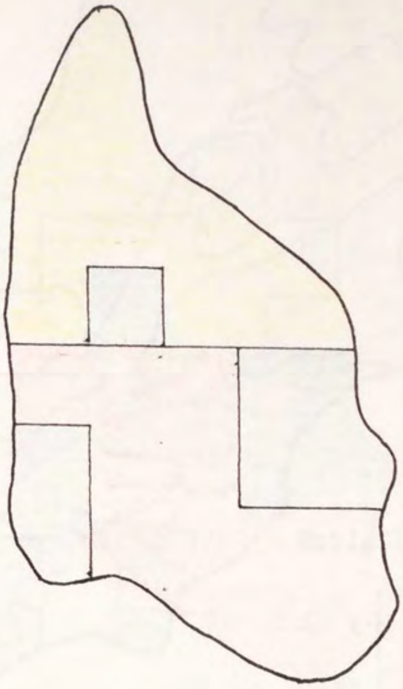


Figure2.I4 BASIN SLOPE CLASSES SUBCATCHMENT 4 (I:250,000 SCALE) TOPOGRAPHIC MAPS

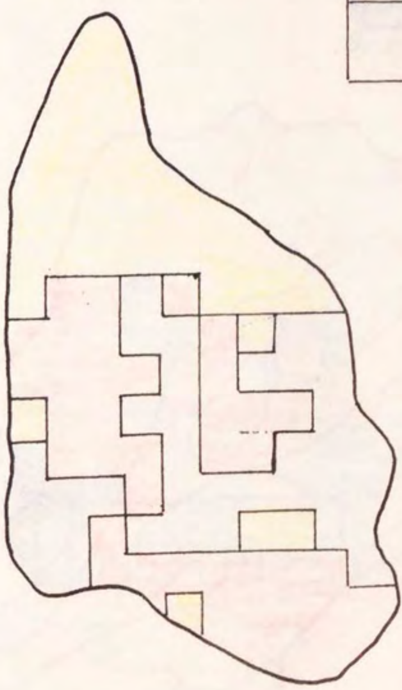
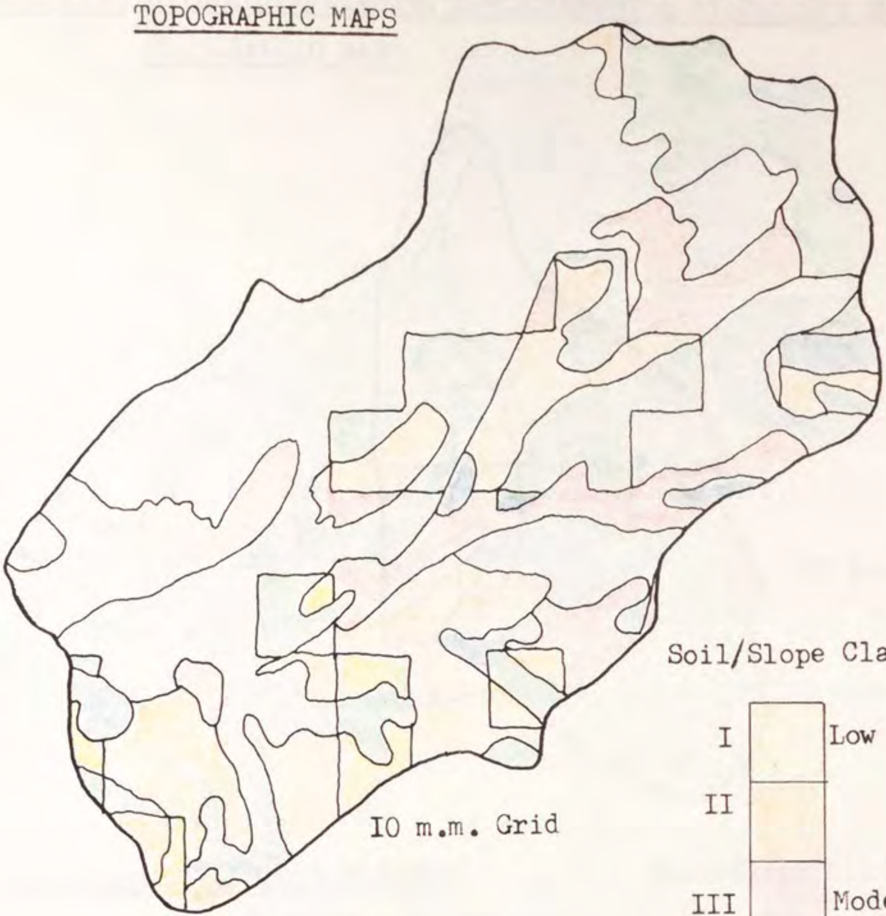


Figure 2.15 SOIL/SLOPE CLASSES SUBCATCHMENT 6b (I:250,000 SCALE) TOPOGRAPHIC MAPS



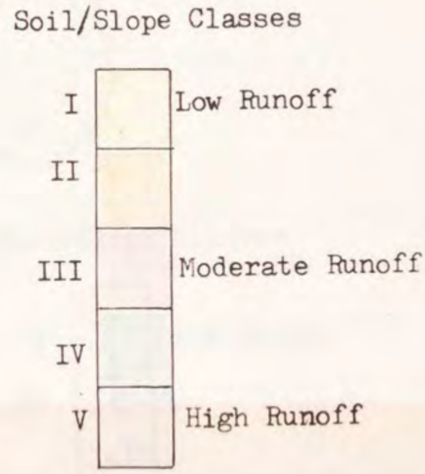
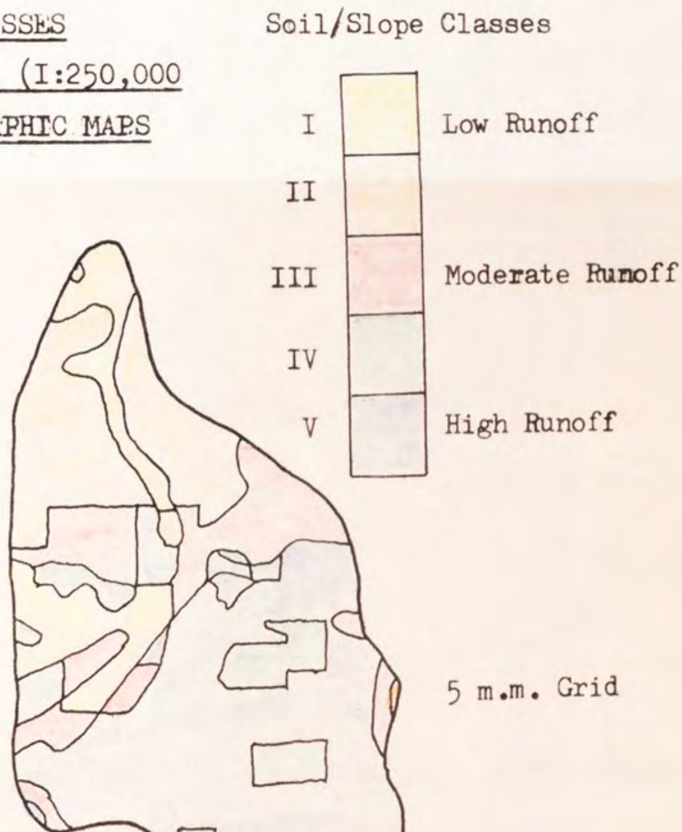


Figure 2.16 SOIL/SLOPE CLASSES (I:250,000 SCALE) TOPOGRAPHIC MAPS

Figure 2.17 SOIL/SLOPE CLASSES SUBCATCHMENT 4 (I:250,000 SCALE) TOPOGRAPHIC MAPS

10 m.m. Grid

Figure 2.18 SOIL/SLOPE CLASSES SUBCATCHMENT 4 (I:250,000 SCALE) TOPOGRAPHIC MAPS



5 m.m. Grid

Table 2.13 (continued)

5.	Big Falls Ranch	0.3679
6.	Burmudan Landing	0.3682
7.	Davis Bank	0.3663
8.	Gracie Rock	0.3785

2.2.v Floodplain Area

Urban and lake areas within the Belize catchment, are insignificant. However, the inclusion of a flood plain variable is important since it will relate to the attenuation of flood waves and the reduction of flood peaks. The floodplain variable is an easily and rapidly calculated variable from remotely sensed imagery(44), (45).

The measurement of the floodplain area was made in the two ways outlined in Chapter 1. Details on the 1:250,000 scale topographic maps were limited for the measurement by either definition. Little information other than large lagoons and swamps was present and the contour intervals (100 metres) were not included in the floodplain. Table 2.14 below gives values of floodplain area by the definitions of the gross (1) and specific (2) floodplains.

Table 2.14 FLOODPLAIN AREAS ABOVE GAUGING STATIONS (km^2)

Gauging Station	B.V.	C.R.	I.C.	B.B.K.	B.F.R.	B.L.	D.B.	G.R.
Method 1	0.0	0.0	0.0	0.0	391.0	434.0	1253.0	158.0
Method 2	0.0	0.0	0.0	0.0	51.6	77.4	209.2	66.0

2.2.vi Mainstream length

Mainstream length as defined by the F.S.R. was calculated as the length of the longest tributary shown by a blue line on the 1:250,000 scale map. To test the variables' behaviour in regression, both main tributaries were measured and averaged. Previous work(46) has shown high correlation between mainstream length and mainstream slope, thereby possibly removing the need for the latter in regression analysis, since it is not obtainable from LANDSAT imagery.

Table 2.15 MAINSTREAM LENGTHS ABOVE GAUGING STATIONS (km)

Gauging Station		Mopan branch	Macal branch	Average
1	B.U.	139.0	-	139.0
2	C.R.	-	90.0	90.0
3	I.C.	193.0	126.0	159.5
4	B.B.K.	225.0	158.0	191.5
5	B.L.	279.0	212.0	245.5
6	B.F.R.	294.00	227.0	260.5
7	D.B.	323.0	256.0	289.5
8	G.R.	-	-	99.8

2.2.vii Form Indices

Various workers(47) (48) have introduced a catchment form index into the relationship between runoff and catchment characteristics. The observation upon which this is generally based, is that elongated catchments attenuate peak flows. Significant correlations between a 'circularity index' and peak and mean flows have been found. This index is defined as being the area of a catchment divided by the area of a circle with the same perimeter. A ratio of catchment length to width has also been proposed(49).

The use of such indices in multiple regression is particularly useful where remotely sensed information is used and slope based variables of any kind are generally unobtainable. Measurements of the length:width ratio are made such that they give the maximum within the catchment, at right angles to one another. Table 2.16 gives their values for areas above gauging stations, to be used in regression.

Table 2.16 VALUES OF CIRCULARITY INDEX AND LENGTH:WIDTH RATIO

Gauging Station	B.V.	C.R.	I.C.	B.B.K.	B.F.R.	B.L.	D.B.	G.R.
Circularity index	0.496	0.527	0.568	0.603	0.530	0.479	0.350	0.519
Length:width ratio	0.97	1.24	1.32	1.60	1.95	2.07	2.28	1.038

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CHAPTER 3 CATCHMENT CHARACTERISTICS SELECTED AS INDEPENDENT FOR MULTIPLE REGRESSION ANALYSIS, LANDSAT BAND 7 PHOTOGRAPHIC PRINTS (NOMINALLY 1:250,000 SCALE)

3.1 INTRODUCTION

The sections of this chapter are similar to those of Chapter 2. However, since the medium from which information was obtained was photographic, modifications of method and omissions of some catchment characteristics were necessary. Details of methods are given with each variable.

LANDSAT imagery of the form of three photographic negatives in multispectral scanner(m.s.s.) band 7 (wavelength near infra red, 0.8 to 1.10 μm) were purchased from the EROS Data Center, Souix Falls, U.S.A., covering the Belize and Sibun catchment areas. Scene details are given below.

Table 3.1 LANDSAT SCENE DETAILS

Scene No.	Path/Row	Aquisition Date	Identification no.
1	020/48	25.3.75	8206215371500
2	020/49	25.3.75	8206215373500
3	020/48	26.12.79	83066115335XO

Scene No.	Band	Scene Centre
1	7	N17°14"08' W88°37"00'
2	7	N15°47"00' W88°59"00'
3	7	N17°17"00' W88°41"00'

Coverage of Belize is shown in text map figure 3.1 and the scenes are displayed in figures 3.2, 3.3 and 3.4. Appendix A gives LANDSAT Caribbean coverage and flight details.

These three images were selected as giving the most suitable coverage. Problems of image quality and cloud-cover limited the choice of scenes. Scenes 1 and 2 were chosen as a relatively cloud free 'same day' set and scene 3 because it post dated a severe flood, the main area of inundation being cloud

LANDSAT SCENE COVERAGE OF BELIZE

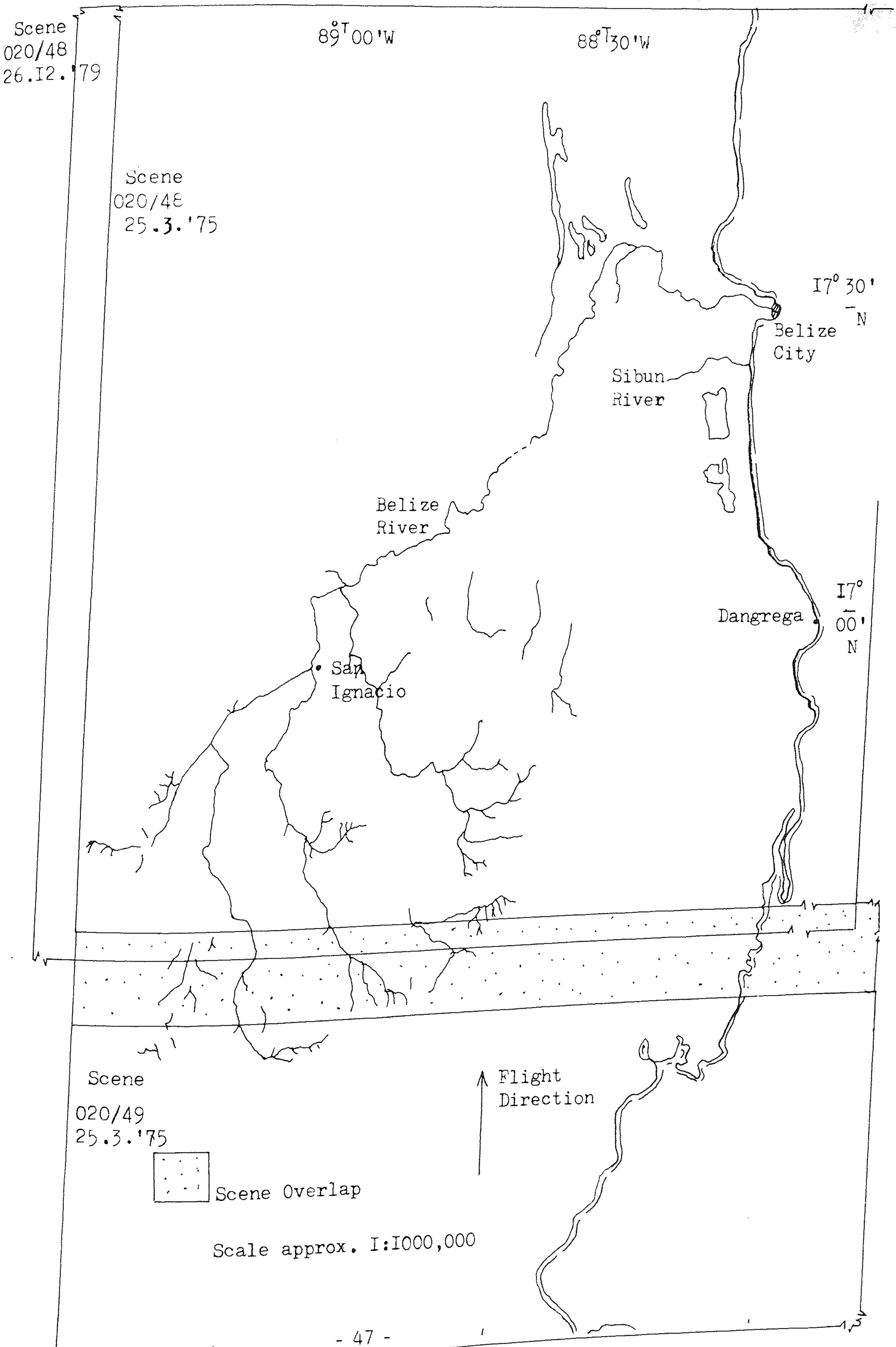


Figure 3.2 LANDSAT SCENE 020/48, 25 MAR 1975

BAND 7

Figure 3.3 LANDSAT SCENE 020/49, 25 MAR 1975

BAND 7

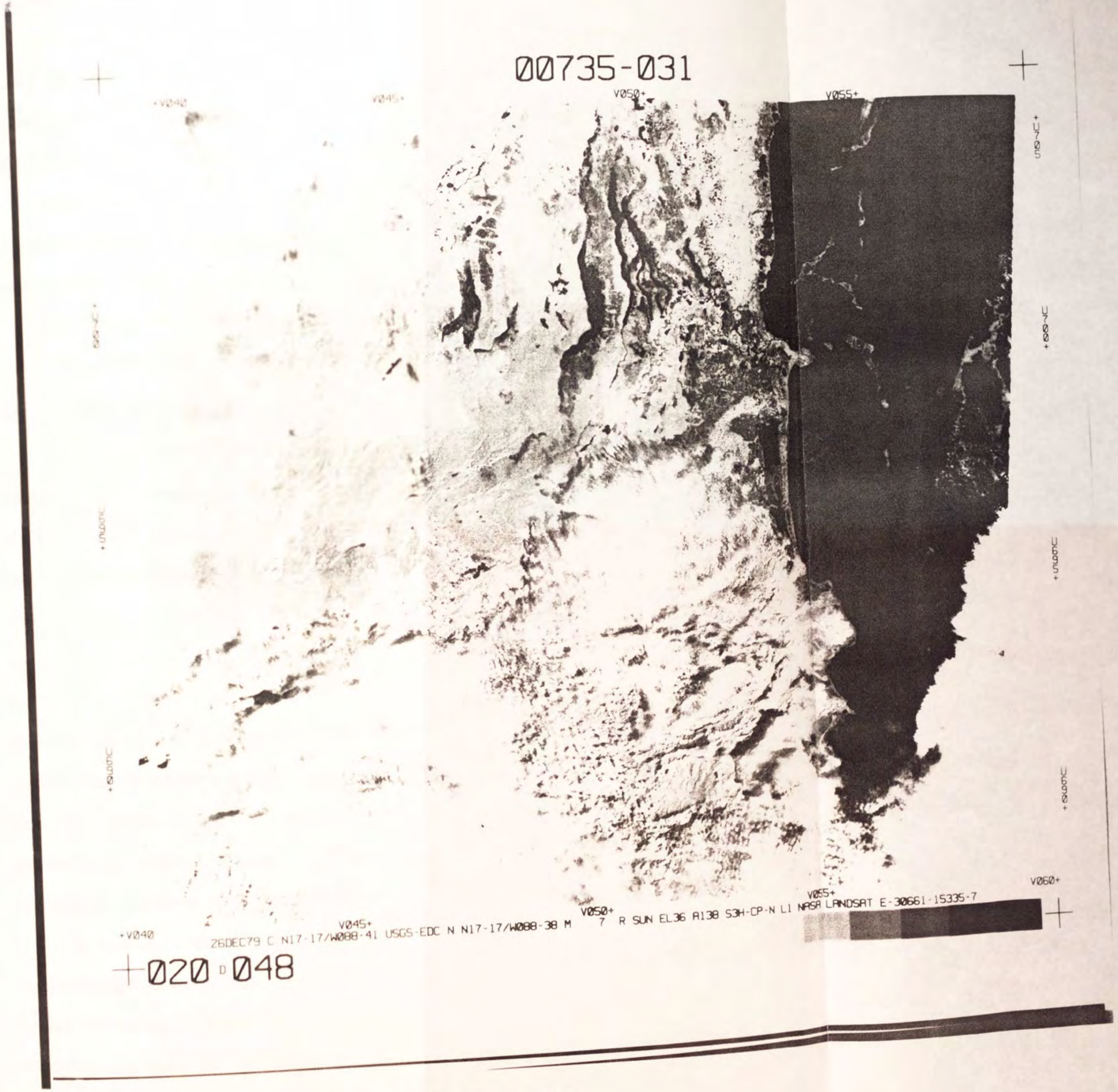


Figure 3.4 LANDSAT SCENE 020/48, 26 DEC 1979

BAND 7

free. Prior to purchase, the images were inspected on the microfilm files of the British Library, British Museum, London.

The use of these 1:1,000,000 scale images, to provide values for catchment variables for comparison with 1:250,000 scale maps, necessitated their enlargement. This enabled convenient, durable and nominally correct scale photographic prints to be aquired. Photographic degradation was preferred to the inconvenience of continual access to a zoom transferscope and the difficulties of its use over such large areas. Prints were made of each scene by enlargement based on the overall dimension of the negative image size. Personal control of the enlargement process was not possible. All scenes were corrected geometrically before purchase.

3.2 IMAGE DISTORTIONS

The distortions of the image enlargements were unknown and the assessment of these distortions, due to inaccuracies of printing, were calculated by the comparison of the positions of ground control points (g.c.ps.) on the prints and on 1:250,000 scale maps. This was done manually with the aid of an Oben precise rule, accurate to 0.1 m.m. Precision of this order was considered adequate, since on both maps and prints, g.c.p. features were rarely less than 0.3 m.m. in size. A total of 20 inter-g.c.p. distances were measured. Where possible, horizontal and vertical orientations were used to determine separate distortional elements but cloud cover and the lack of distinctive features made this very difficult. In all cases the maximum possible extents of the photographs were covered, though the N.W. quadrant of scene 1 proved to have few distinctive features and the south of scene 3 was largely cloud covered.

It was apparent that enlargement distortions would vary from photograph to photograph despite the use of consistent methods and equipment. Therefore it was necessary to calculate the distortions of each print individually. These distortions proved to be small and in this research they were considered insignificant. Had considerable distortions been encountered, modifications to

TABLE 3.2 DISTORTIONS OF LANDSAT PHOTOGRAPHIC ENLARGEMENTS AT 1:250,000 SCALE

SCENE NO. 3 020/48 26/12/79

No.	(a) LANDSAT DISTANCE m.m.	(b) MAP DISTANCE m.m.	RATIO (a)/(b)
1	305.0	305.5	0.99836
2	393.5	386.0	1.01943
3	235.0	234.5	1.00213
4	157.0	156.5	1.00319
5	378.8	377.5	1.00344
6	389.5	390.0	0.99872
7	201.5	202.5	0.99506
8	332.5	331.0	1.00453

* horizontal and vertical distortions could not be measured separately due to lack of suitable g.c.ps.

TABLE 3.3 PHOTOGRAPHIC DISTORTIONS OF LANDSAT PHOTOGRAPHIC ENLARGEMENTS AT 1:250,000 SCALE

SCENE No. 1 020/48 25/3/75

G.C.P. NO.	LANDSAT DISTANCE m.m. (a)	MAP DISTANCE m.m. (b)	RATIO (a)/(b)
		VERTICAL COMPONENT	
1	439.0	441.0	0.99546
2	205.6	206.5	0.99274
3	357.0	360.0	0.99167
4	268.5	270.2	0.99370
5	199.0	200.5	0.99252
6	518.0	520.2	0.99577
		HORIZONTAL COMPONENT	
7	259.5	260.0	0.99810
8	298.0	299.4	0.99532
9	352.0	353.0	0.99717
10	181.0	181.0	1.00000
11	344.2	339.6	0.99882
12	382.5	386.0	0.99093

the digitiser coordinates by the distortion of scale factor, would have enabled accurate measurements to have been calculated. The distortions of scene 1 and scene 3, those most used in this research, are given as linear regression formulae below, obtained from measurements given in tables 3.2 and 3.3.

Scene 1 : Vertical distortion

1:250,000 scale map value = 1.0032xLANDSAT value + 0.818

i.e. $y = 1.0032z + 818$

Scene 1 : Horizontal distortion

1:250,000 scale map value = 1.0115xLANDSAT value - 2.320

i.e. $y = 1.0115z - 2.320$

Scene 3 : Combined distortion

1:250,000 scale map value = 0.9877xLANDSAT value - 2.480

i.e. $y = 0.9877z - 2.480$

3.3 CATCHMENT CHARACTERISTICS AS INDEPENDENT VARIABLES FOR MULTIPLE REGRESSION ANALYSIS

The list of catchment characteristics presented in table 2.1, Chapter 2, were modified according to their suitability for extraction from LANDSAT photographic material. The variables of mainstream slope and the soil/slope index were omitted since LANDSAT prints contain no altitude or contour data. The amended list of catchment characteristics is given below.

Table 3.4 CATCHMENT CHARACTERISTICS MEASURED FROM LANDSAT 1:250,000 SCALE PRINTS

1. Area
2. Stream frequency
3. Flood plain area
4. Mainstream length
5. Circularity index
6. Length:width ratio

Tracings of the Belize catchment area were made on acetate film and then retraced onto matte tracing material to provide the final working maps. Cloud cover in certain areas of the images necessitated the combinations of tracings of all three prints. Despite this combination, cloud coverage was approximately 691 km^2 or 52% of the Sibun catchment. The proportion of the Belize catchment covered was only 5% or 460 km^2.

Regional division proceeded with the subdividing of the catchment areas in regions of homogenous topography, clearly corresponding to Regions 1, 2 and 3 of the topographic maps. The subcatchment equivalents of 6b, 3a, 28 and 4 were observable and were traced onto the overall catchment map, separate, more detailed maps were made for the analysis of each individual subcatchment (see figures 3.5 to 3.8). Subcatchment 28 was, to some extent, cloud covered.

All tracings were made strictly according to the limits of the hydrological and topographic features of the LANDSAT prints. Catchment and subcatchment divisions were made largely on the basis of the visual interpretation of drainage networks. Ridge and valley features, lagoonal areas and textural patterns were also used. The suggested manner(50) of image interpretation prior to that of the maps could not be adhered to due to delays in obtaining the LANDSAT imagery, however, image interpretation took place six months after that of the maps. It should be noted that folded map B, showing the overall catchment and subcatchment boundaries, does not attempt to display the complete drainage network of the Belize and Sibun rivers, only those necessary to illustrate catchment boundaries.

3.3.i Catchment and Subcatchment Areas

The catchment areas were obtained as detailed above. Two main difficulties were found to be the fact that the extreme western tip of the overall catchment was not covered by the imagery. The extent of this closing tip was estimated and is shown by dashed lines on Map B. Also, a small part of the Belize and Sibun joint boundary was obscured by cloud, over the eastern part of Region 2. The boundary here was estimated with regard to the surrounding topographical features and river drainage. All major river tributaries were extended to their headwaters, as far as the interpretation of topographic features allowed, to define the catchment divides. Only highest order rivers were visible. Areas of different topographical natures presented different difficulties in interpretation for catchment boundaries. These difficulties may be outlined thus:

1. Areas of high relief present clearly defined ridge and valley systems, but their complexity sometimes may lead to problems of defining the smaller streams and rivers and consequently inhibit the accurate placing of boundaries.
2. Karst areas proved difficult to subdivide internally, due to their lack of drainage features.
3. Flatter, densely vegetated areas proved more easy to subdivide since valleys, though forest covered, displayed drainage by textural differences and shading patterns.
4. The accurate recognition of the floodplain was difficult due to the lack of topographic features generally, but in areas of lagoon and marsh, hydrologically determined boundaries were more easily obtained.
5. It is important to note that while no quantification was possible, the variation of sun angle upon topographic features is important in their interpretation, even though these variations are small. The effect is integrally connected to the orientation of topographic features especially those of a linear nature. The resulting areas of shadow and high reflectance may emphasize or hide these features.

Regional division was essentially the same as for the topographic maps. Region I was defined as an area of strong relief and predominantly linear features, marked by major faulting and some indications of a central igneous massif. Valley density was high, indicating a high drainage density. Region 2 appeared to be generally flat with a uniform texture and lacking the lineations of Region I. Large river valleys could be defined easily, interpretation aided by the lighter tones of dense vegetation. One underground river feature was evident (see subcatchment 3a, map B). Drainage density was apparently low. Region 3 was identified as having the greatest textural uniformity, broken only by low ridges trending S.S.W. - N.N.E., well displayed by the low sun angle. The floodplain area was by the interpretations discussed in Chapter I, using such features that were available. Changes in structural and lithological geology may be inferred from these regional subdivisions.

Cloud cover is one of the most limiting factors of LANDSAT usage in tropical areas and even the use of multi-scene combinations left 15% of the map unobservable. Precise subcatchment boundaries were drawn with some difficulties even though the overall subcatchment drainage systems were compatible. It was found that while the boundaries of regions of different types can easily be defined, the subdivision of homogenous regions into smaller areas is more difficult. The boundaries of subcatchment 28 are in part estimated due to cloud cover. Tables 3.5 and 3.6 below, present values for areas measured from LANDSAT 1:250,000 scale prints.

Table 3.5 REGIONAL AND SUBCATCHMENT AREAS OBTAINED FROM LANDSAT PRINTS

Belize River, Region	Area (km^2)	Subcatchment	Area (km^2)
1	1861	6b	342.1
2	3686	3a	312.7
3	1307	28	72.3 (part cloud covered)
		4	137.5

Floodplain method 1 1597

Floodplain method 2 210.6

TOTAL CATCHMENT AREA 8451 km^2

Table 3.5 (continued)

Sibun River, Region	Area (km^2)
1	415
2	466
3	0
Floodplain method 1	454
Floodplain method 2	103
TOTAL CATCHMENT AREA	1335 km^2

Table 3.6 AREAS ABOVE GAUGING STATIONS BY REGION, LANDSAT PRINTS

Gauging Station	Regions 1	2	3	Floodplain method 1	TOTAL AREA (km^2)
B.V.	415	3071	0	0	3486
C.R.	1250	66	0	0	1316
I.C.	1723	3413	323	0	5459
B.Bk.	1860	3616	561	0	6037
B.F.R.	1860	3686	1307	333	7186
B.L.	1860	3686	1307	384	7237
D.B.	1860	3686	1307	1326	8179
G.R.	415	454	0	140	1009

Stations were located by direct reference to 1:250,000 scale maps.

3.3.ii Stream Frequency

Defined as the number of stream junctions per unit area, stream junctions were calculated from figures 3.5 to 3.8 inclusive. Area values used are those derived from table 3.5. The drainage networks were defined by distinct valley features. Interpolated river courses were used to close breaks in the network due to the complexity of some valley networks, though not in areas suspected of underground drainage.

Figure 3.5 DRAINAGE NETWORK SUBCATCHMENT 28 (1:250,000 SCALE) LANDSAT PRINTS

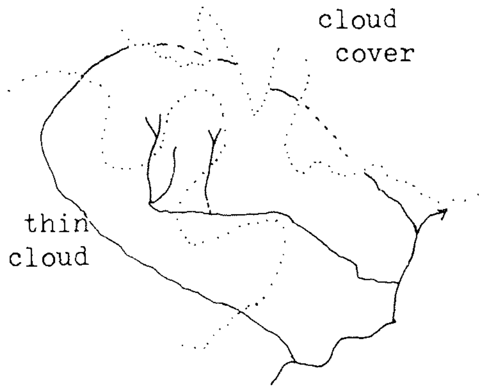


Figure 3.6 DRAINAGE NETWORK SUBCATCHMENT 4 (1:250,000 SCALE) LANDSAT PRINTS

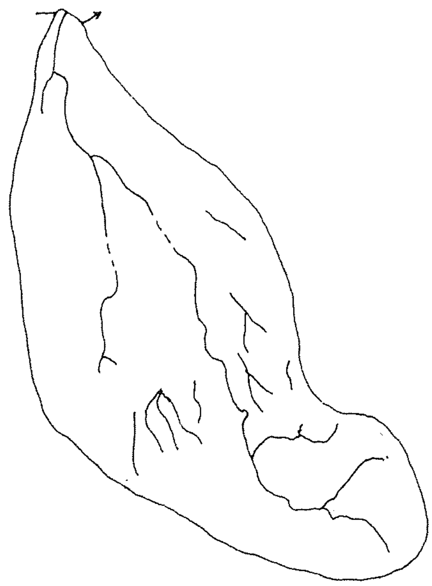


Figure 3.7 DRAINAGE NETWORK SUBCATCHMENT 3a (1:250, 000 SCALE) LANDSAT PRINTS

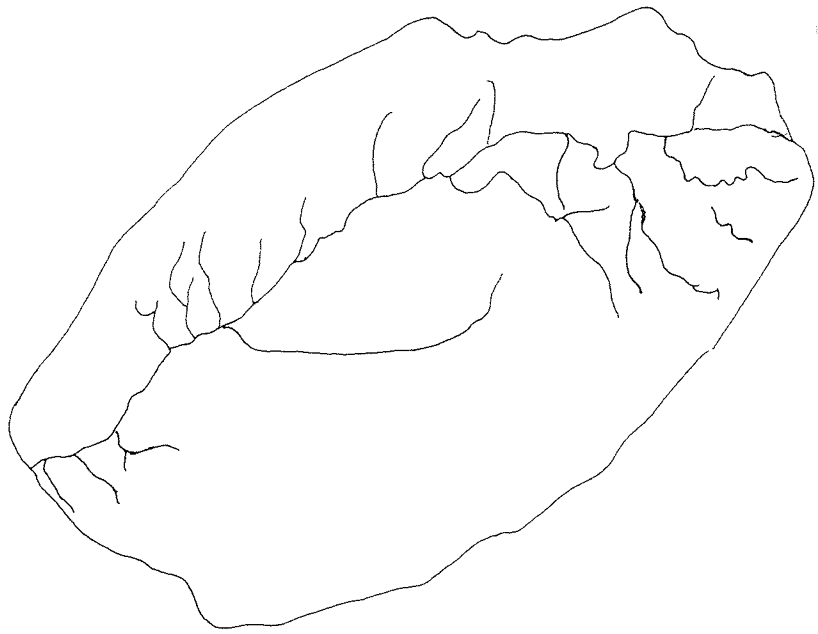


Figure 3.8 DRAINAGE NETWORK SUBCATCHMENT 6b (1:250,000 SCALE) LANDSAT PRINTS

Table 3.7 STREAM FREQUENCY OF REGIONAL SUBCATCHMENTS, LANDSAT PRINTS

Region	Subcatchment	No.junctions	Area (km^2)	Stream frequency
1	6b	168	342.1	0.4910
2	3a	23	312.7	0.0736
3	*28	5	72.3	0.0690
1 + 2	4	11	137.5	0.0800

* significant cloud cover

Stream frequencies for the subcatchments above were applied on a proportional basis for areas above gauging stations, they are given below in table 3.8.

Table 3.8 STREAM FREQUENCIES ABOVE GAUGING STATIONS, LANDSAT PRINTS

Gauging Station	B.V.	C.R.	I.C.	B.BK.	B.F.R.	B.L.	D.B.	G.R.
Stream frequency	0.112	0.147	0.205	0.202	0.181	0.180	0.167	0.245

3.3.iii Floodplain Areas

Floodplain areas above gauging stations were measured according to the two alternative methods given in Chapters 1 and 2. Tracings were made from LANDSAT Scene 3, 020/48, 26.12.79.

Table 3.9 FLOOD PLAIN AREAS GAUGING STATIONS, LANDSAT PRINTS

Gauging Stations	Floodplain method 1 (km^2)	Floodplain method 2 (km^2)
B.V.	0	0
C.R.	0	0
I.C.	0	0
B.BK.	0	0
B.F.R.	333.0	45.0
B.L.	384.0	64.4
D.B.	1326.0	210.6
G.R.	140.0	cloud covered

3.3.iv Mainstream Length

Mainstream length values were measured for both major tributaries, to their upstream extent as defined by topographic features. Values are given below.

Table 3.10 MAINSTREAM LENGTHS, LANDSAT PRINTS

Gauging Station	B.V.	C.R.	I.C.	B.BK.	B.F.R.	B.L.	D.B.	G.R.
Mopan length (km)	123	-	174	206	254	269	299	-
Macal length (km)	-	88	124	156	204	219	249	-
Average length (km)	123	88	148	180	228	243	273	66

3.3.v Form indices

Both circularity indices and the length:width ratio were calculated for the catchment areas above gauging stations, according to methods used in Chapter 2. The values of these indices are given overleaf in table 3.11.

TABLE 3.11 CIRCULARITY INDICES AND LENGTH:WIDTH RATIOS DERIVED FROM 1:250,000 LANDSAT PRINTS

STATION	CIRCULARITY INDEX: PERIMETER (km)	AREA OF O = PERIMETER (km^2)	ACTUAL AREA (km^2)	INDEX	LENGTH:WIDTH RATIO: LENGTH (km)	WIDTH (km)	RATIO L:W
B.V.	251.6	5037.5	3486	0.692	60.0	36.0	0.86
C.R.	165.6	2182.3	1316	0.603	73.4	85.5	1.67
I.C.	306.4	7470.8	5459	0.731	92.8	82.3	1.13
B.BK.	317.8	8037.1	6037	0.751	111.5	75.0	1.49
B.F.R.	375.7	11232.4	7186	0.640	144.0	75.3	1.91
B.L.	398.1	12611.7	7237	0.574	150.8	75.0	2.01
D.B.	490.4	19137.8	8179	0.427	166.5	75.1	2.22
G.R.	143.9	1647.8	1009	0.612	NA	NA	NA

For the purpose of the ratio above, length and width are defined as the greatest dimensions within the catchment taken at right angles

CHAPTER 4 EVALUATION OF CATCHMENT CHARACTERISTICS, LANDSAT COMPUTER COMPATIBLE TAPES

4.1 INTRODUCTION

Computer campatible tapes (c.c.ts.) presenting LANDSAT imagery, have previously been used in hydrology(51). While research(52) has shown that in some circumstances band 7 prints are as useful as computer assembled and manipulated images, investigations(53) also show that advantages may be obtained from these sophisticated techniques.

Three c.c.ts. were purchased from the EROS Data Center, identical to the band 7 images used to give photographic prints. The processing of these tapes was undertaken on the Dipex Image Processing System of the Open University, using Aries II software. Image details are those given at the beginning of Chapter 3, additional information being that each tape contained wavelengths 4, 5, 6 and 7 covering the wavelength range 0.50 um to 1.10 um. Scenes 1 and 2 had a band interleaved format, scene 3 band sequential.

The objectives of the image processing analysis were :

1. To make a comparison of basic catchment characteristic evaluation with those from maps and LANDSAT prints.
2. To make a comparative study of the floodplain of the Belize and Sibun rivers, using both prints and c.c.ts. (see Chapters 11 to 14).
3. To determine the most suitable processing methods to achieve objectives 1 and 2.
4. To put these analyses on the basis of the relative cost of each - a cost effective comparison. It will be seen in this chapter that the cost of c.c.t processing and the large quantity of information generated, has restricted the area of investigation to the flood plain and subcatchment areas of the Belize river catchment. A full investigation of the whole

catchment was beyond the financial resources and time available for this research. However, the important characteristics of area, stream frequency, mainstream length and form indices of the catchments, were investigated.

An outline of the methods used in preparing the c.c.ts. to obtain photographic slides from which information was ultimately extracted, is given below. Tapes 020/48, 25.3.75 and 020/48, 26.12.79 were used in these investigations.

1. Tape 020/48, 25.3.75 was loaded with an automatic stretch of fixed brightness values.

2. Bands 4, 5 and 7 were used to provide the false colour composite (f.c.c.) and monochrome single band images which were given operator designated pixel brightness values, to provide the most visually useful image.

3. An area designated 3A, excluding cloud cover, of the subcatchment areas was loaded for inspection.

4. Area 3A was inspected for dropped lines (caused by sensor malfunction) on all bands separately, without decimation of the image. No dropped lines were found.

5. Some sectors of the image displayed striping, especially on band 4, and so a filter, averaging pixel values on each side of the dropped line was used to visually smooth the image.

6. The destriped image 3A was renamed 3R and bands 4, 5, 6 and 7 were renamed DST 4, 5 + 7.

7. The dynamic range of the pixel brightness values was not altered.

8. The resampled image 3R was geometrically corrected for earth rotation and satellite velocity and altitude changes by the method of registration to ground control points, selected from 1:50,000 scale maps. This

process utilised a split screen monitor image and a large scale precise location image, with the images registered to UTM coordinates.

DST 7 was used for registration since it provided the best quality undecimated image. The use of DST 4 which provides the best display of cultural features(54) was considered, but it proved to be of relatively poor quality and the number of observable cultural features available was small. DST 7 provided 23 g.c.ps. which were used in registration providing a standard deviation (accuracy of location) of somewhat less than 100 metres. A preliminary correction of the image, after 10 points were registered enabled a crude transformation to be made, thereby aiding the location of further g.c.ps. and shortening the time involved.

The most serious problems encountered were :

I. Cloud over the northern part of the image.

II. Large proportion of sea within the image.

III. Unsuitability of g.c.ps. obtained from 1:250,000 scale maps, used to supplement those obtained from the 1:50,000 scale maps.

The image was sampled overnight to 50 x 50 metre pixels for fine resolution of the image. Scene 020/48, 26.12.79 was pre-processed in the same way for radiometric connections, but the scene was geometrically corrected prior to purchase and its correction by the use of ground control points was not necessary. This provided images in all bands suitable for processing on the monitor screen but does not provide a durable image and even where possible, direct analysis from the screen is very costly. Slide photography is the usual method of collecting hard copies from such imagery.

In this research, colour slide photographs were taken by a tripod mounted 35 m.m. camera, fitted with a 135 m.m. telescopic lens. The use of such a lens was intended to counter some of the curved distortion of the monitor screen. Appendix A lists the total number of slides taken, with photographic and scene details. The camera was mounted square to the monitor, with lens and screen centres aligned to minimise distortion of the photograph. Distortions were expected to be the same for each session, with possible variations between sessions. Exposure (aperture) settings were varied from 8 to 5.6 to give relatively slow shutter speeds ($^1/_{8th}$ or $^1/_{15th}$ of a second), too rapid a speed leading to the photographing of the rasta scan of the monitor.

Projections of the developed slides were shown as below in figure 4.1 using an inclined mirror for projection of the glass screen.

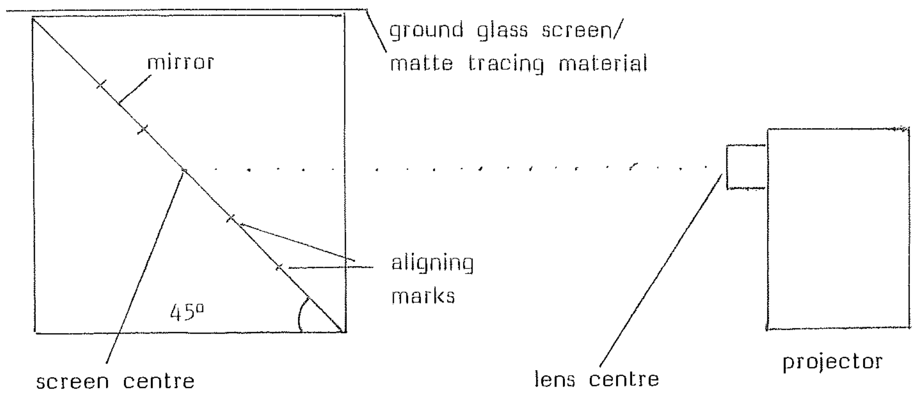


Figure 4.1 CONFIGURATION OF SLIDE PROJECTION

4.2 DISTORTIONS OF SLIDE IMAGES

The preliminary study of one scene (B3R f.c.c. 020/48, 25.3.75) showed negligible vertical distortion across the screen but variations in image width were evident. Measurements were made every 25 m.m. to assess this variation and determine the need for comprehensive assessment of image distortion. The maximum distortion was seen to be approximately 0.9%.

Selected ground control points were taken and distances between them compared to those on 1:250,000 scale maps. The distortions of the image are shown below in table 4.1, with measurements taken directly from the projected image.

Table 4.1 PROJECTED IMAGE DISTORTIONS, SLIDE B3R
f.c.c. 020/48, 25.3.75

G.c.p. No.	Slide distance (m.m.) (a)	Map distance (m.m.) (b)	Ratio (a)/(b)
1	87.6	87.4	1.0023
2	61.0	61.0	1.0000
3	90.8	91.6	0.9913
4	80.4	80.2	1.0025
5	92.5	93.0	0.9946
6	77.4	78.2	0.9898
7	87.5	87.4	1.0011
8	67.7	67.8	0.9985
9	95.6	95.8	0.9979
10	94.6	94.0	1.0064
11	51.4	51.0	1.0078

The distortions are relatively small and the correlation of map and LANDSAT slide material was considered acceptable for this research.

The separation of the vertical and horizontal components was not possible. The regression formula for the data above, for the conversion of linear measurement is :

1:250,000 map value = 0.9989 x LANDSAT slide value + 0.00283

i.e. $y = 0.9989z + 0.0283$ (4.2.1)

4.3 EVALUATION OF CHARACTERISTICS, LANDSAT 1:250,000 SCALE SLIDES

To cover the entire catchment of the Belize river, sixteen undecimated images in band 7 and false colour composites would be necessary. Additional images in band 4 and 5 in areas of cultural interest would be needed. The presentation of perhaps forty images, their manipulation and photographic record, was beyond the financial resources of this research. The whole area of the Belize and

Sibun catchments could not be investigated and therefore data was collected and later will be compared, on a subcatchment basis. It was hypothesised that if the determination of subcatchment characteristics could be reasonably achieved, by methods involving computer compatible tapes, no problems would be found in determining those of the large regional areas. Since previous research has shown that band 7 print material can be successfully used for hydrological investigations(55), it is necessary to determine what further information can be obtained from image manipulation, both in terms of the physical nature of catchment areas and the behaviour patterns of flooding. The list of quantifiable catchment characteristics, determined for comparison, not multiple regression analysis, was as follows in table 4.2 below.

Table 4.2 SELECTED CHARACTERISTICS FOR INVESTIGATION

1. Area
2. Stream frequency
3. Mainstream length
4. Circularity index and length:width ratio

Direct tracings of the projected images in false colour composite (bands 4, 5 and 7) were made on acetate then transferred to matt tracing material. Band 7 images (monochromatic) were also tried, but it was found that f.c.c. images presented more and clearer detail. This was particularly true where the presence of vegetation was an important indicator of water courses.

Edge enhancement by the use of a 3 x 3 pixel 'box car' filter. The steps involved in this procedure are as follows:

1. The local average pixel brightness value (in all bands), surrounding the central pixel, is computed.
2. The deviation of the central pixel from the surrounding average is noted.
3. This deviation is doubled.

LANDSAT Scene 020/48 25.3.'75

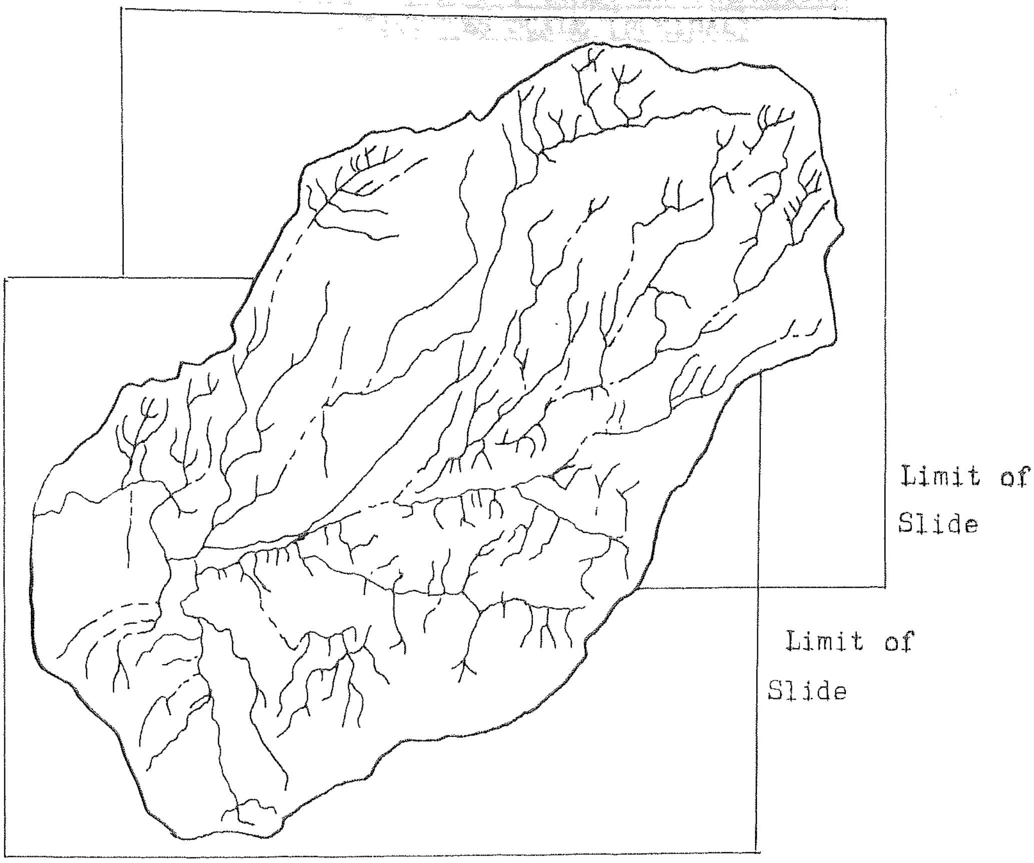
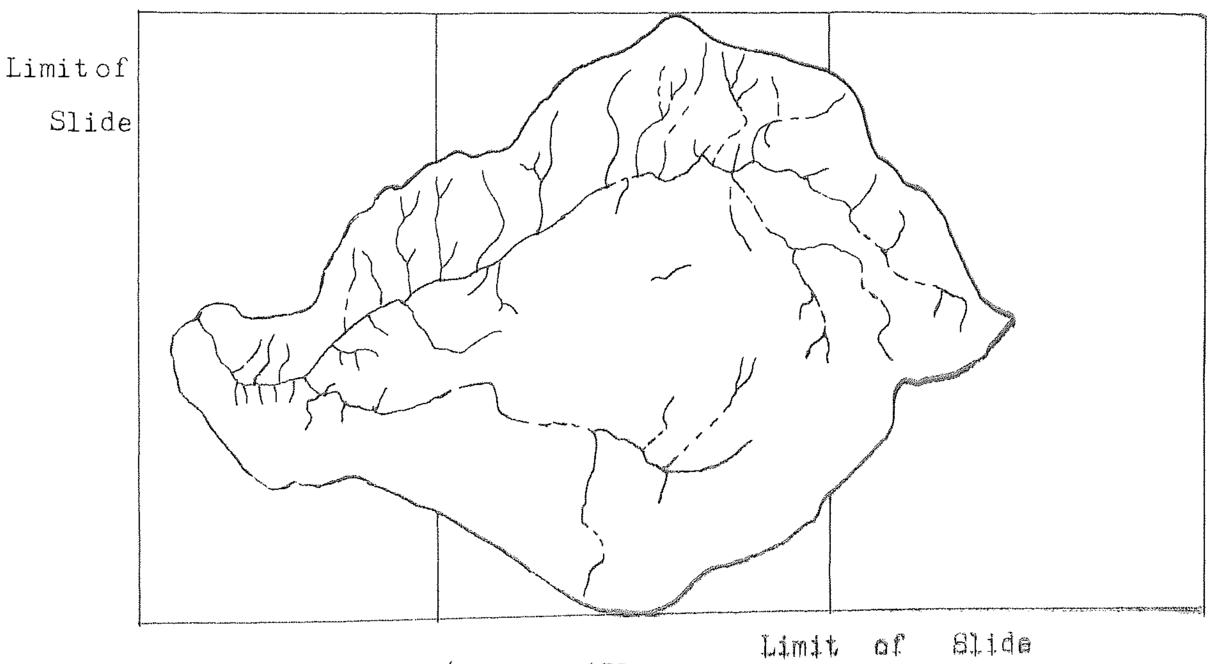


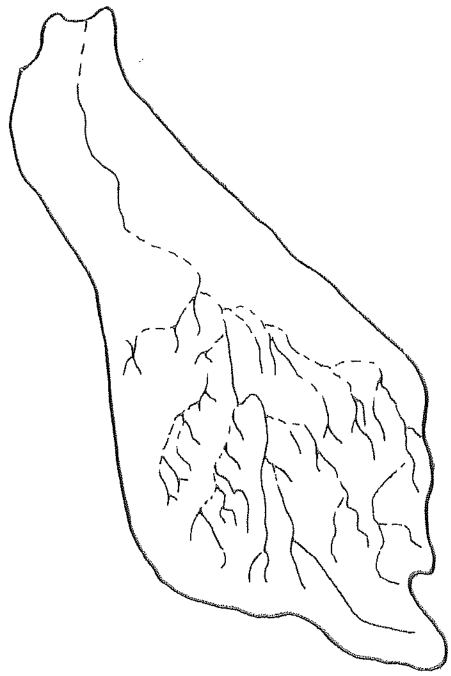
Figure 4.2 DRAINAGE NETWORK SUBCATCHMENT 6b COMPUTER COMPATIBLE TAPES:FALSE COLOUR COMPOSITES SCALE (NOMINAL) 1:250,000

Figure 4.3 DRAINAGE NETWORK SUBCATCHMENT 3a COMPUTER COMPATIBLE TAPES:FALSE COLOUR COMPOSITES SCALE (NOMINAL) 1:250,000



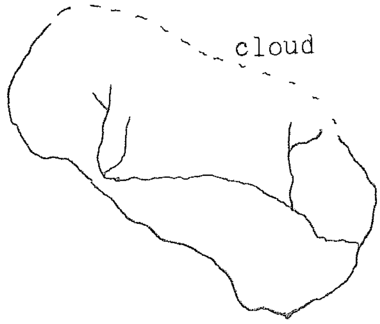
LANDSAT Scene 020/48 25.3.'75

Figure 4.4 DRAINAGE NETWORK SUBCATCHMENT 4 COMPUTER COMPATIBLE TAPES:FALSE COLOUR COMPOSITES SCALE (NOMINAL) I:250,000



LANDSAT Scene 020/48 25.3.'75

Figure 4.5 DRAINAGE NETWORK SUBCATCHMENT 28 COMPUTER COMPATIBLE TAPES:FALSE COLOUR COMPOSITES SCALE (NOMINAL) I:250,000



LANDSAT Scene 020/48 25.3.'75

4. The filter box moves along the line one pixel and the process is repeated until the image is resampled.

This process emphasises the inherent differences between dark and bright tones and displays greater detail of physical features. However. the differences between the edge enhanced images and those not enhanced was not significant and this technique was not adopted. Principal components analysis was not used because it was not expected to provide extra hydrological information and its extensive use of computer time, and therefore cost, was beyond the financial support of this research.

Unmanipulated f.c.c. scenes were used with the operator specified brightness values given below in table 4.3. It was necessary to use two slides to cover each of subcatchments 6b and 3a. Subcatchment 28 was partly cloud covered on both 020/48 scenes.

Table 4.3 BRIGHTNESS VALUES FOR F.C.C. IMAGES, TAPE 020/48, 25.3.75

Band	Cut off b.v.	Saturation b.v.
DST 7	14	30
DST 5	4	44
DST 4	10	30

4.3.i Subcatchment areas

Areas were measured by digitiser from the maps presented in figures 4.2 to 4.5. The areas of the subcatchments are given below.

Table 4.4 SUBCATCHMENT AREAS, LANDSAT SLIDE (km^2)

Subcatchment	6b	3a	28	4
Area (km^2)	396.4	277.5	64.8	146.9

4.3.ii Stream frequency

Only the highest order rivers, the main courses of the Belize and Sibun were visible as integral features. The concentration of low pixel values in all three bands, about the rivers' actual position defined them clearly, though width estimates could not be accurately made. In their upper courses, their tone width was less than that of a pixel, but they remained reasonably well defined.

More and better detail was seen with regard to terrain and vegetation, compared to the LANDSAT band 7 prints, but 1st order and 2nd order streams were obtained, by necessity, from topographic and vegetational features. In some cases (subcatchments 3a and 28), vegetational densities highlighted river courses, in other areas (6b and 4) they merely obscured direct observation. It was evident, even from preliminary observation, that areas of differing vegetational density, topographic nature and textural patterns each possess significant information and often in contrasting forms.

It has been suggested(56) that all ponds and streams where not visibly connected to an identifiable river, should be connected directly, where mapping from such images is undertaken. This method was followed, understanding that while the precise location of some parts of tributaries might be inaccurate, stream frequency values in terms of junction/unit area, would be more truly reflected. These interpolations are represented by dashed lines on figures 4.2 to 4.5. Table 4.5 presents stream frequency values for all subcatchments.

Table 4.5 STREAM FREQUENCIES, LANDSAT SLIDES

Subcatchment	No.stream junctions	Area (km^2)	Stream frequency
6b	196	396.4	0.494
3a	60	277.5	0.216
*28	4	64.8	0.062
4	39	146.9	0.265

* partly cloud covered

4.3.iii Mainstream length

Mainstream length, from catchment boundaries to gauging stations could not be measured because of the limited coverage of the computer compatible tape imagery chosen. An attempt to use decimated images for the mapping of the major rivers' courses and thereby reduce image processing costs, was not successful. However, the definition of mainstream lengths within the sub-catchments, provides a useful comparison with map information.

Table 4.6 MAINSTREAM LENGTHS WITHIN SUBCATCHMENTS, LANDSAT SLIDES

Subcatchment	Mainstream lengths(km) 1:250,000 scale map	Mainstream lengths (km) LANDSAT Slides	% difference
6b	36.5	34.5	-5.5
3a	30.0	31.0	+3.3
28	17.5	18.3	+4.3
4	28.0	27.0	-3.6

Such a comparison clearly indicates that slide material, if used on a major river in undecimated form, can give very accurate assessments of mainstream length, where facilities and time permit.

4.3.iv Form indices

The importance of form indices, as stated before, is that such characteristics are linked to flood flow times of concentration and flood peak attenuation. The cost of covering the whole of the Belize and Sibun catchments, by undecimated images was prohibitive but subcatchment form indices are presented below in table 4.7.

Table 4.7 FORM INDICES DERIVED FROM LANDSAT C.C.T. SLIDES

Subcatchment	length (km)	width (km)	length:width ratio
6b	31.0	17.0	1.82
3a	27.5	19.0	1.45
28	14.3	7.4	1.93
4	24.3	11.0	2.21

Table 4.7 (continued)

Subcatchment	Perimeter (km)	Area (km^2)	Area of circle	Circularity Ratio
6b	80.5	396.4	515.7	0.769
3a	69.3	277.5	382.2	0.726
28*	33.0	64.8	86.7	0.747
4	55.7	146.9	247.3	0.594

* partly cloud covered

Overall, computer manipulated images were felt to give more and better detail of hydrological and terrain features, though it was found to be costly in terms of both computer and operator time.

CHAPTER 5 EVALUATION OF CATCHMENT CHARACTERISTICS, METRIC CAMERA PHOTOGRAPHY

5.1 INTRODUCTION

The Metric Camera, developed for use by the European Space Agency, was launched on November 28th 1983 on board the 9th N.A.S.A. Space Shuttle flight, taking black and white and colour infra red stereoscopic photographs of the Earth's surface. Among these photographs, were several of the coast zones of Belize, including much of the lower floodplain of the Belize and Sibun rivers and the mountain areas peripheral to their headwaters. Two photographic diapositives, with 60% overlap, were purchased from D.F.V.L.R.* The details of these photographic diapositives are given below in table 5.1. Diapositive scale was approximately 1:820,000.

Table 5.1 METRIC CAMERA BELIZE DIAPOSITIVE DETAILS

Flight no.	Scene no.	Time of aquisition G.M.T.	Date	Sun Elevation
9/29	01-0900-29	13-19-12 - 310	5.12.83	15º
9/29	01-0901-29	13-19-22-205	5.12.83	15º

Sun azimuth	Scene Centre	Cloud cover (tenths by quadrant)
120	N.16º9' W.88º0'	3162
119	N.17º4' W.87º60'	6321

Details relating to film type, exposure and flight details are given in Appendix B.

Metric Camera imagery differs from LANDSAT information in two important ways; first it is photographic (using high resolution kodak double x aerographic film 2405) and second stereoscopic overlap of up to 80% (tropical

* Deutsche Forschungs - und Versuchsanstalt fur Luft und Raumfahrt e.V., Wessling, F.D.R.

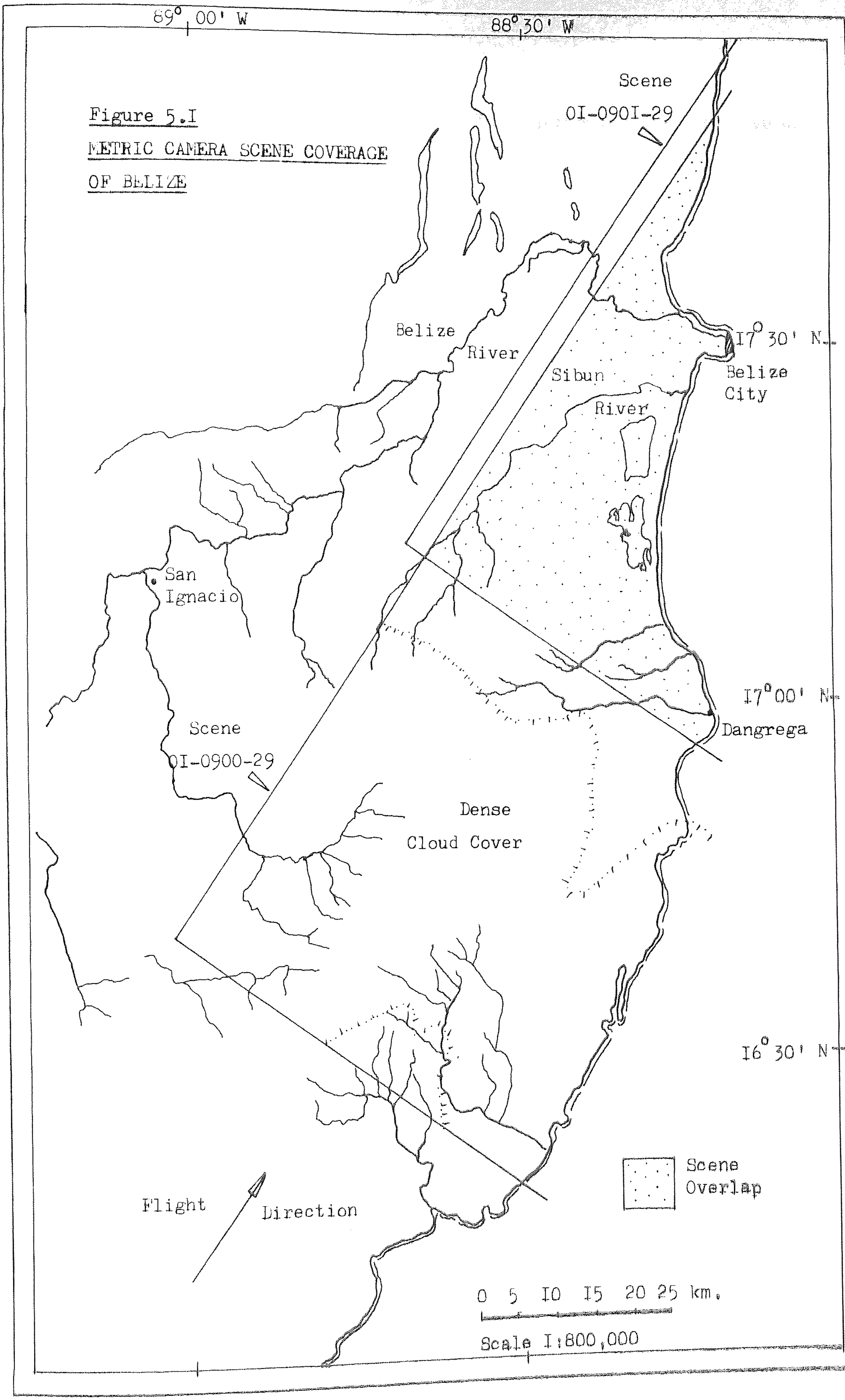


Figure 5.I
METRIC CAMERA SCENE COVERAGE
OF BELIZE

areas) and 60% (higher latitudes) is present. These differences lead to several important aspects of application compared to LANDSAT data, which are listed below.

1. Far greater stereoscopic investigation is possible, slopes and altitudes may be determined.
2. Resolution of the images is greater, as little as 25 metres.
3. Imagery is not recorded in digital form.
4. At present, global coverage is limited.

The applications of Metric Camera information have hardly been extended to practical fields of investigation, beyond those of its primary use as a map generating data source(57), when comparison is made with other sources of space remotely sensed information, such as LANDSAT. While the comparison with data elicited from LANDSAT imagery is important, Metric Camera with its relatively fine resolution and familiar photographic format, indicates a direction of development where one information source may be used as ground truth for a second. The regional nature of Metric Camera coverage, linked to this high resolution and photographic simplicity, make its development and that of the Large Format Camera, very important. While research(58) (59) has indicated the usefulness of the Metric Camera in determining observable water courses and the drainage of large rivers, little work has been done on the wide range of useful applications of such an important instrument in hydrology.

The use of photographic prints obtained from the Metric Camera is described by similar limitations as for LANDSAT print enlargement. The use of the original diapositives can be exploited through zoom transferscope magnification or more elaborate stereoscopic viewing equipment. This, unlike photographic enlargement, does not involve direct degradation of the imagery but requires expensive equipment for the accurate definition of planimetric and altitude measurement. This research investigates both methods of investigation. Most of the catchment characteristics studied in earlier chapters were assessed by the use of photographic prints, enlarged to a nominal 1:250,000 scale. Slope, altitude and topography were investigated by the use of computer aided stereoscopic equipment.

5.1.i Image distortions of photographic prints

A total of eleven interground control point distances measured between discreet features were made to establish the distortion of scene 900. The lack of cultural or distinct physical features gave some difficulties. Table 5.2 below gives inter g.c.p. distances relating to both the image and 1:250,000 scale maps. The regression formula relating these distances, averaged over as great a proportion of the scene as possible was found as being :

1:250,000 scale map distance = 1.0706 Metric Camera distance - 7.56

i.e. $y = 1.0706z - 7.56$ (5.1.1)

Table 5.2 DISTORTIONS OF METRIC CAMERA 1:250,000 SCALE PRINTS

	Metric Camera distance (m.m.) (a)	Map distance (m.m.) (b)	Ratio (a)/(b)
1.	257.3	264.3	0.9735
2.	55.6	55.0	1.0109
3.	231.8	242.0	0.9579
4.	157.1	158.5	0.9912
5.	90.0	91.5	0.9836
6.	262.8	265.5	0.9887
7.	39.0	40.0	0.9750
8.	71.1	72.2	0.9848
9.	117.5	118.5	0.9916
10.	218.5	220.5	0.9909
11.	74.5	75.2	0.9907

5.2 EVALUATION OF CATCHMENT CHARACTERISTICS

The area of Belize covered by the Metric Camera and illustrated in figure 5.1, includes only a small part of the Belize and Sibun catchments. The collection of data to be used in the multiple regression analysis and in comparison with some of the parameters obtained from LANDSAT coverage, is therefore not possible. To make comparisons it was necessary to select a group of subcatchments, not located within the Belize catchment and marginal to the Sibun catchment from both the Metric Camera images and the 1:250,000 scale topographic maps. The catchment characteristics assessed from these sub-catchments cannot, in any case, be applied to the regression formulae analysis presented later in Chapter 10, but the comparative accuracies of the Metric Camera values places its importance in the range of remotely sensed information.

The subcatchments were self contained river basins selected to represent the best available examples of high, moderate and low relief areas as well as the coastal floodplain zone. Comparisons with other information sources are made in Chapter 7.

5.2.i Area

The catchment boundaries were drawn from the Metric Camera prints according to the topographical and hydrological features observed, as were the river networks. Table 5.3 gives details.

Table 5.3 AREAS OF CATCHMENTS, METRIC CAMERA PRINTS

Catchment	Area (km^2)
Mahogany Creek	118.1
Big Creek	183.6
Plantation Creek	62.5

5.2.ii Stream frequency

It has been stated(60) rivers of widths greater than 35 metres are clearly visible on Metric Camera photography. No rivers were directly observable in these cases, and the interpretation of drainage networks was based on terrain and vegetational features, as in the work on LANDSAT prints. Table 5.4 gives stream frequency values using area values from table 5.3.

Table 5.4 STREAM FREQUENCY VALUES, METRIC CAMERA PRINTS

Catchment	Stream Junctions	Area (km^2)	Stream frequency (j/km^2)
Mahogany Creek	4	118.1	0.034
Big Creek	40	183.6	0.218
Plantation Creek	42	62.5	0.672

5.2.iii Mainstream Slope

The main river courses, shown in illustration figure 5.3 were superimposed upon the contour map of the area derived from the stereoscopic investigations of the diapositives. Figure 5.3 presents the catchment drainage networks which may be compared to those obtained from 1:250,000 scale topographic maps, figure 5.2. Details regarding these stereoscopic investigations are given later in this chapter, in section 5.3.

Mainstream slope values were calculated by the 1085% method. Small inaccuracies in placing the rivers over the contour map were present but rarely exceeded 250 metres. The reason for these inaccuracies was not only due to possible inaccurate estimates of contour location, but also deep valley shadow that made, in certain places, the precise location of river courses impossible. Figures 5.4 and 5.5 show the measurement of mainstream slope values for topographic maps and Metric Camera diapositives respectively.

Table 5.5 1085% MAINSTREAM SLOPE VALUES, METRIC CAMERA

Catchment	1085% slope
Mahogany Creek	N.A.
Big Creek	0.0098
Plantation Creek	0.0174

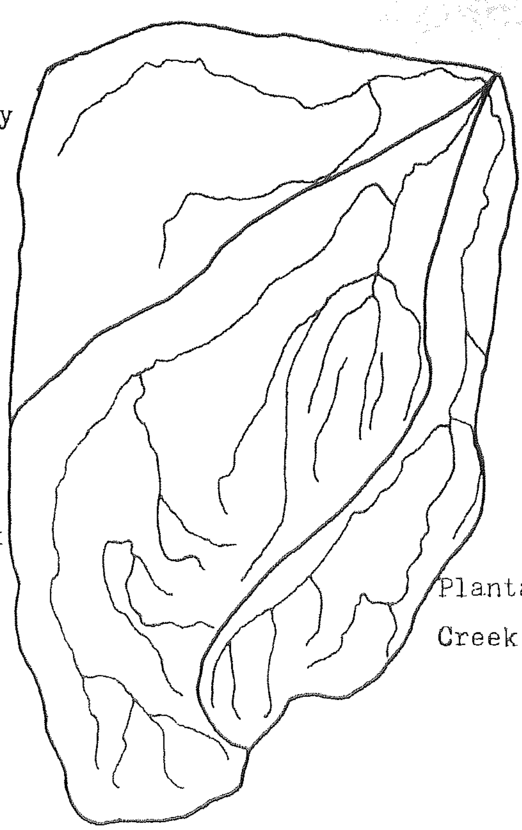
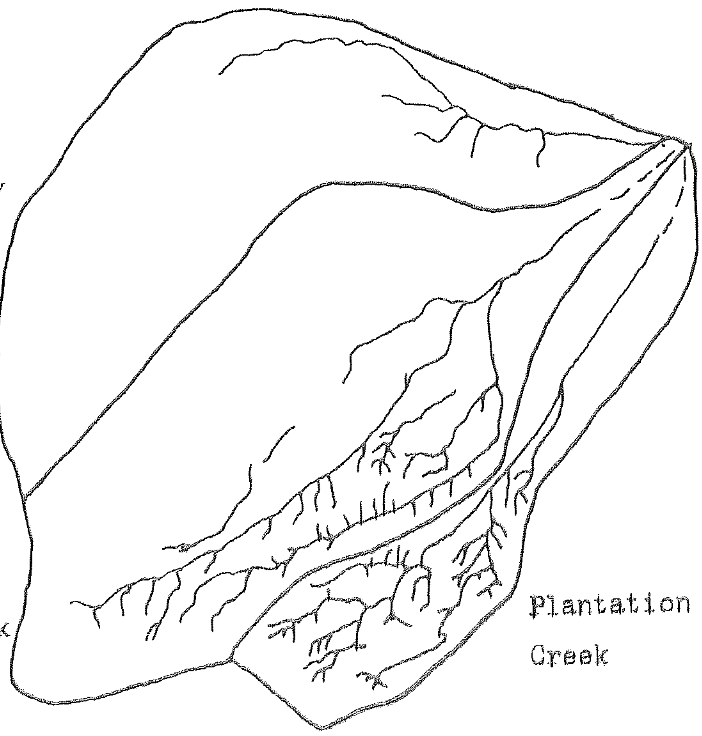


Figure 5.2 DRAINAGE OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK
I:250,000 SCALE TOPOGRAPHIC MAP

Figure 5.3 DRAINAGE OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK
I:250,000 (NOMINAL) SCALE METRIC CAMERA PHOTOGRAPHIC PRINTS



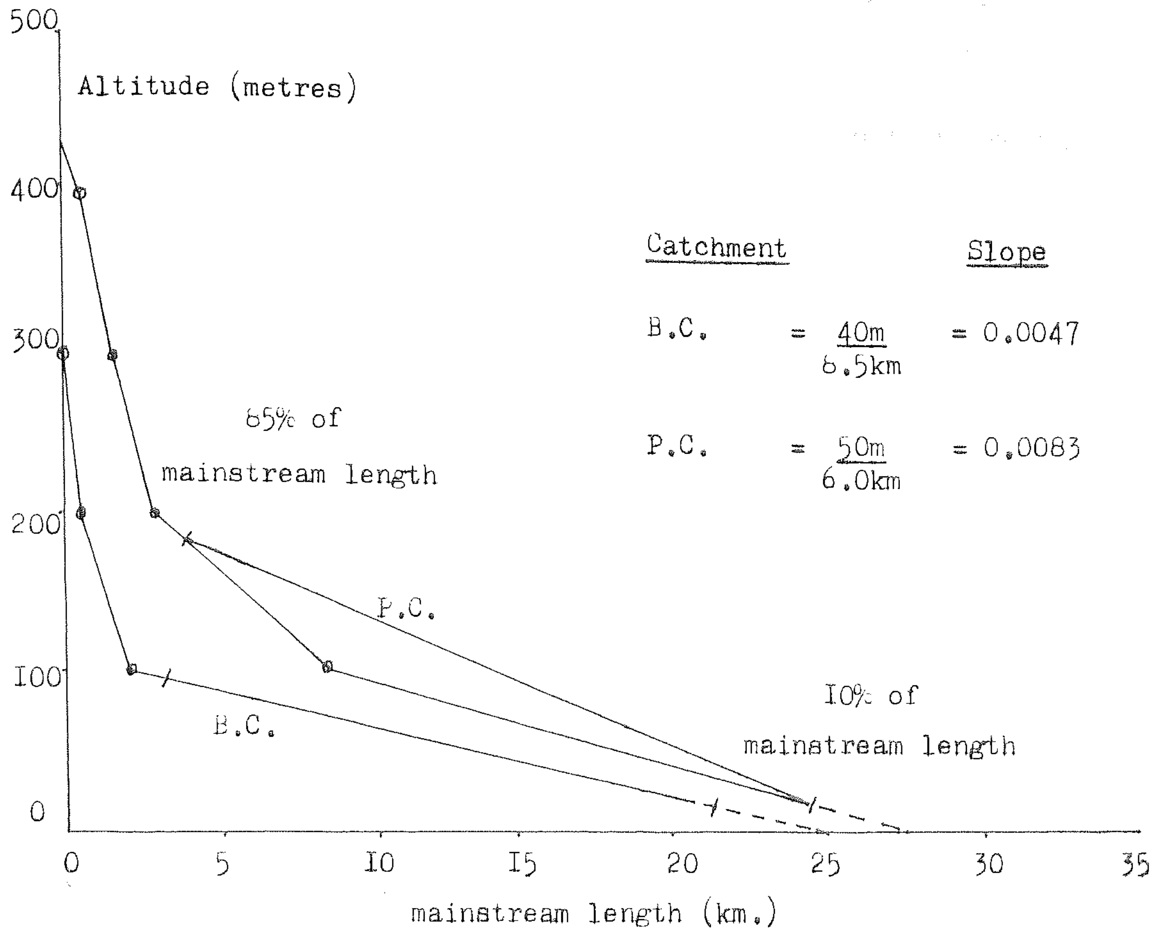
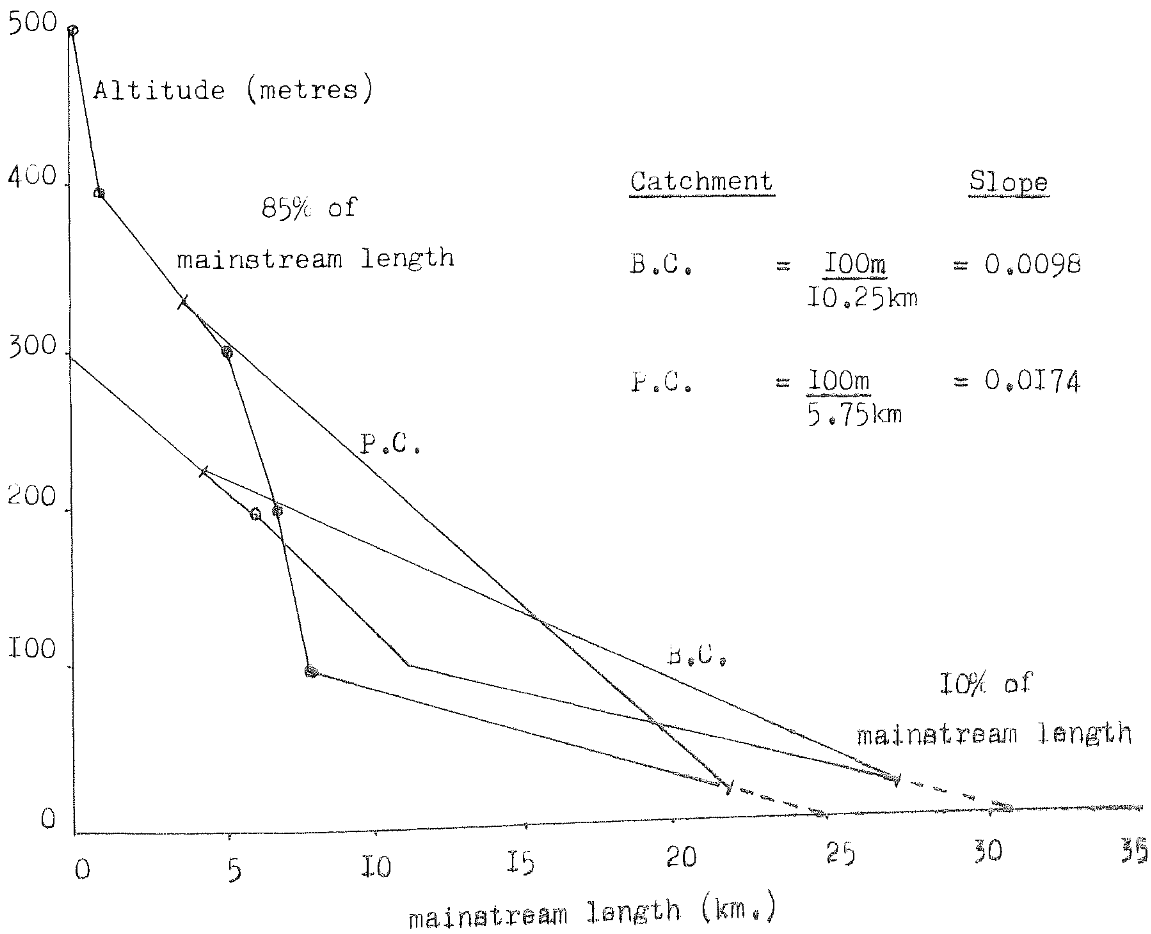


Figure 5.4. 1:250,000 MAP 1085% MAINSTREAM SLOPE

Figure 5.5. METRIC CAMERA 1085% MAINSTREAM SLOPE



The course of Mahogany Creek was not observed to cross any of the contour lines (100 metre intervals) thus a slope value was not calculable from either maps, or Metric Camera images.

5.2.iv Soil/slope index

The derivation of the soil/slope index is fully described in Chapter 2. Soil class types are obtained from soil maps and other documentary information and then combined with basin slope class information. Thus the comparison between Metric Camera photography and maps lies in the quality of the basin slope information that can be obtained. Figures 5.6 and 5.7 give contour information for the subcatchments for maps and Metric Camera photography upon which the calculation of basin slope is based. Calculations of basin slope were made using the 10 m.m. box method and the distributions of these basin slopes, for both information sources, may be seen in figures 5.8 and 5.9. Weighting by area was applied at catchment boundaries where basin slopes are often high and where fractions of 10 m.m. boxes were commonly present.

Table 5.6 below gives values of Metric Camera basin slopes.

Table 5.6 OVERALL BASIN SLOPES, METRIC CAMERA

Catchment	Overall basin slopes (^{o})
Mahogany Creek	$< 2^o$
Big Creek	2.9^o
Plantation Creek	5.7^o

5.2.v Floodplain areas

Significant floodplains relating to the small rivers draining the sub-catchment could not be identified. It was expected that, given the ground resolution of Metric Camera photography, major floodplain areas such as those of the Belize and Sibun rivers could be identified with accuracies at least as great as those of LANDSAT imagery.

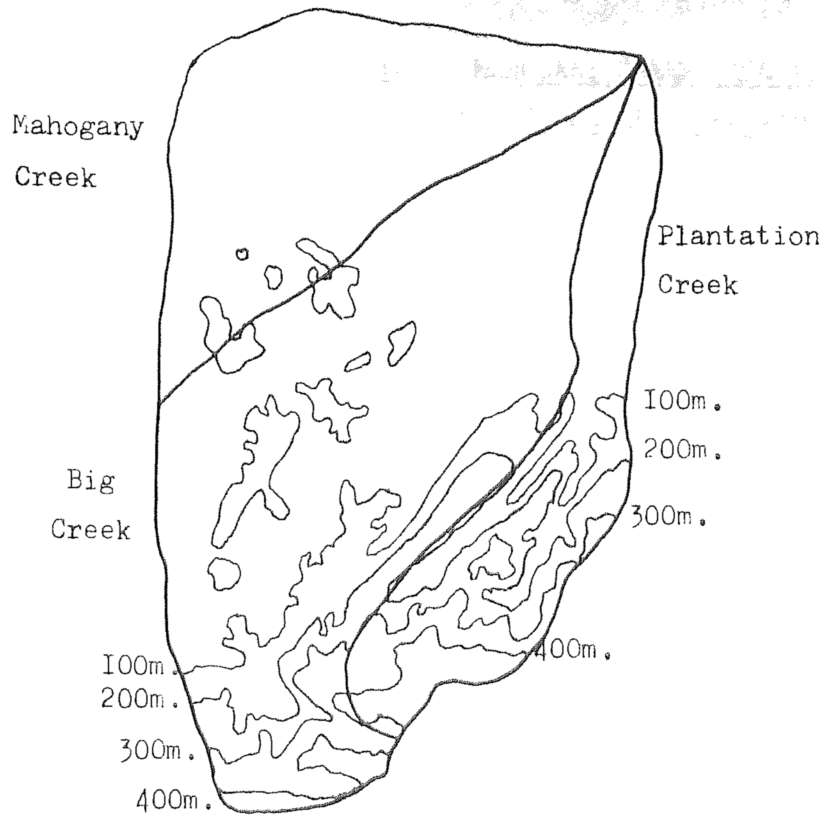


Figure 5.6 ALTITUDE CONTOURS OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK : 1:250,000 SCALE TOPOGRAPHIC MAP

Figure 5.7 ALTITUDE CONTOURS OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK : METRIC CAMERA PHOTOGRAPHIC STEREO DIAPOSITIVES : 1:250,000 SCALE

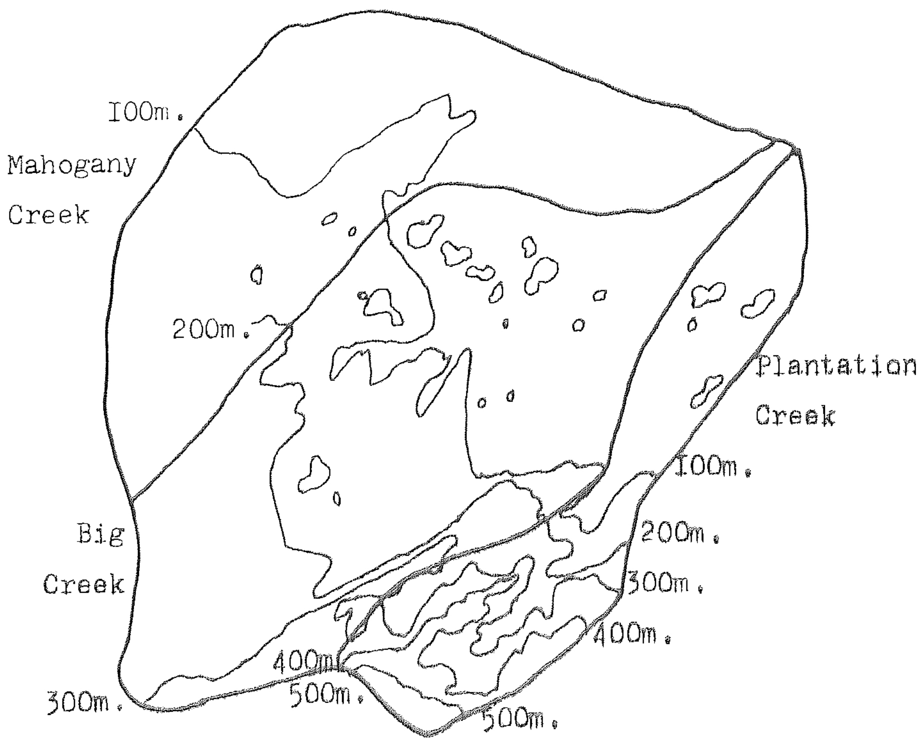
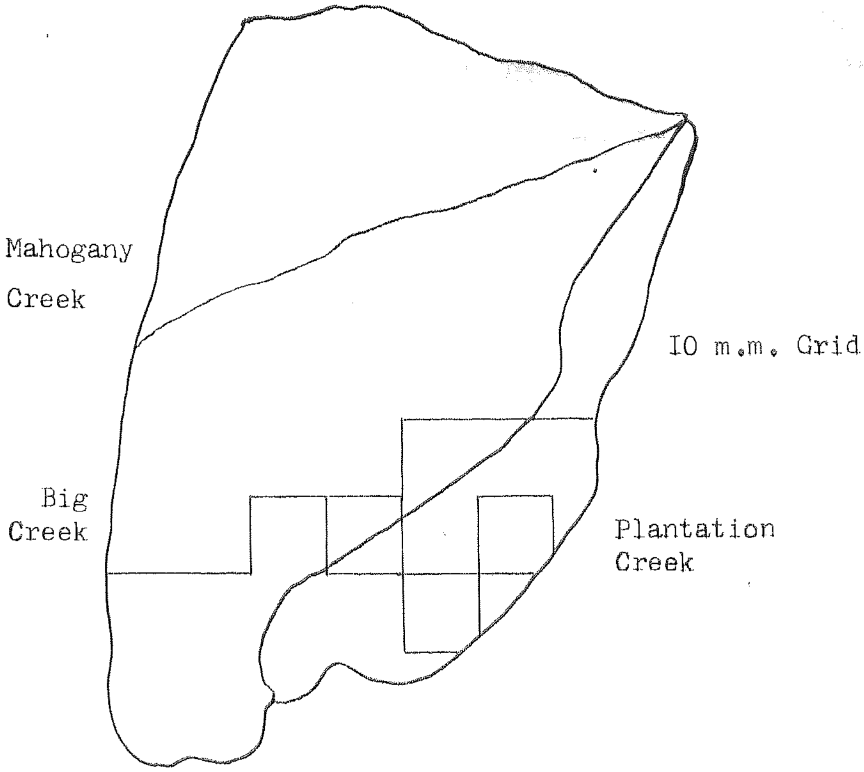


Figure 5.8 BASIN SLOPE CLASSES OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK : I:250,000 SCALE TOPOGRAPHIC MAPS



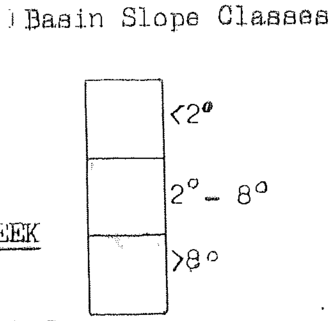
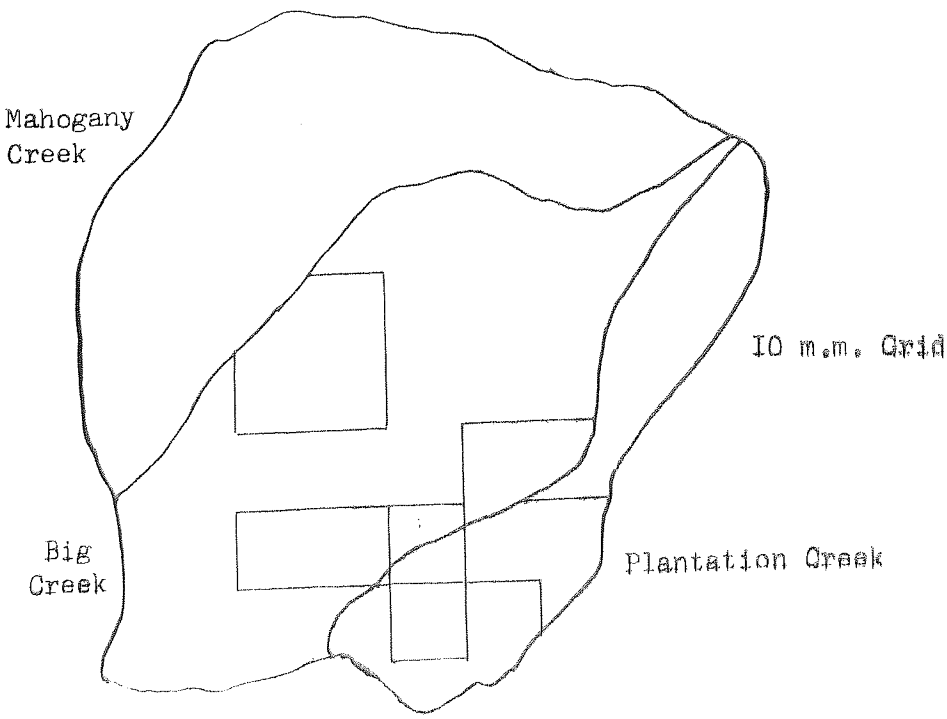


Figure 5.9 BASIN SLOPE CLASSES OF MAHOGANY CREEK, BIG CREEK AND PLANTATION CREEK : METRIC CAMERA PHOTOGRAPHIC DIAPOSITIVES : I:250,000 SCALE



5.2.vi Mainstream length

Measurements of the longest river courses were made as far as the headwaters of each were observable by topographic features. The longest branch of Mahogany Creek was in fact Cornhouse Creek. Stream lengths are given below in table 5.7.

Table 5.7 MAINSTREAM LENGTH, METRIC CAMERA PRINTS

Catchment	Mainstream length (km)
Mahogany Creek	14.75
Big Creek	23.75
Plantation Creek	19.25

5.2.vii Form Indices

Table 5.8 below presents the form indices of each catchment as described in Chapter 2.

Table 5.8 FORM INDICES, METRIC CAMERA PRINTS

Catchment	Perimiter (km)	Area of O of = perimeter (km^2)	Actual area (km^2)	Circularity Index
Mahogany Creek	56.25	251.3	118.1	0.4700
Big Creek	60.25	288.9	183.6	0.6355
Plantation Creek	50.00	198.9	62.5	0.3142

Catchment	Length (km)	Width (km)	Length/width ratio
Mahogany Creek	20.00	8.25	2.42
Big Creek	27.50	9.50	2.89
Plantation Creek	23.38	5.75	4.07

5.3 STEREOSCOPIC INVESTIGATIONS TO OBTAIN PLANIMETRIC ACCURACIES AND ALTITUDE INFORMATION, 1:820,000 SCALE DIAPOSITIVES PLOTTED TO 1:250,000 SCALE

5.3.i Introduction

Various workers(61), (62) have investigated the planimetric accuracies of Metric Camera information and their usefulness in altitude data generation. To some extent the results of this work have been contradictory but generally the consensus indicates the presence of vertical inaccuracies of up to 25 metres and similar planimetric accuracies. These appear to be closely related to the quantity and quality of ground control points, and the terrain type.

While simple desk stereoscopes can illustrate three dimensional features of high relief and enhance vegetational boundaries when used with Metric Camera photographic prints, more elaborate equipment is essential to draw contours and determine spot height values. This necessity can be illustrated by defining the parameters of calculation as follows.

The scale of the diapositives is equal to the focal length of the camera lens ÷ by the camera altitude, that is 305 m.m. ÷ 244 km or 1:800,000. Thus 1 m.m. on the diapositives is equal to 800 metres.

The image shift or absolute parallax, is illustated below in figure 5.10 and is equal to distance 'a' + distance 'b'. The convergence of the angle of camera axes is = 0.3052° and is negligible.

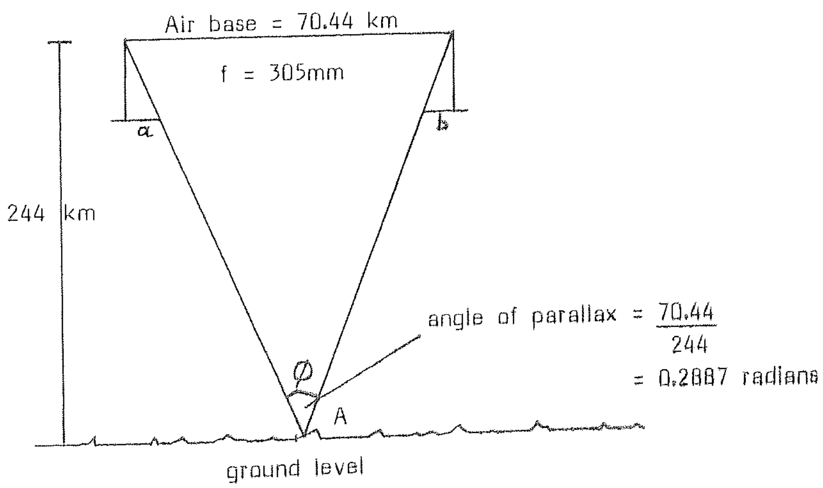


Figure 5.10 PARALLAX RELATIONSHIPS

Therefore the absolute parallax of any point A, 244km from the camera base

$$= \frac{305\times10^{-6}\text{km} \times 70.44 \text{ km}}{244\text{km}} = 8.81\times1\text{-}^{-5} = 88.1 \text{ m.m.}$$

Thus for the calculation of height difference of 100 metre contours (-dh) then

$dh = \frac{(H - h)^2}{f\ B}.\ dp$, where dp = the difference in parallax and h is negligible

compared to H $\therefore$ $dh = \frac{(H)^2}{f\ B}\ dp = \frac{(244\times10^6)^2}{0.305\times70.44\times10^6}$ m. dp

$= 2.7712 \times 10^6.\ dp$

When both dh and dp are in millimetres, then the difference in parallax (dp) is

$$dp = \frac{10^5 \text{ m.m.}}{2.7712 \times 10^6} = 0.036 \text{ m.m.}$$

Thus, a difference of 0.036 m.m. of the stereoscope floating mark would necessarily be detectable for the drawing of 100 metre contours. This is clearly beyond the accuracy of desk stereoscopes.

Facilities afforded by University College (London), Department of Photogrammetry were used for detailed stereoscopic investigations. The stereo diapositives were viewed using a KERN K5R-1 stereo viewer linked to a KERN GP1 plotting table. The basic steps followed are listed below.

1. A data file name (Belize Dat.) was entered into the interactive computer terminal of the K5R-1.
2. Interior orientation of the two diapositives was achieved by the alignment of the feducial marks, visible on the viewing screen.
3. A correction for Earth curvature was necessary considering the air base separation of the two scene centres, of 70 km. This was accomplished by imposing a camera lens distortion correction, radial from the scene centre, at intervals of 10 m.m. across the images.
4. Relative orientation was achieved by using 24 parallax points on the images. It was found that cloud features gave a good rough estimate of

correct relative orientation. These orientation points, once the rough estimated had been achieved, were discarded to obtain the final orientation.

5. Absolute orientation was achieved by the selection of suitable ground control spot height points. They were obtained from 1:50,000 scale map series using U.T.M. coordinates. Only 5 distinct ground control points could be used for this orientation. 13 altitude control points, 11 of which were sea locations, were used. The standard deviations of the control points were : 91.14 metres (planimetric) and 14.49 metres (altitude). While the former was disappointingly large, it was not surprising perhaps, considering the limited ground data.

5.3.ii Assessments of altitude and topographic information

Contours were drawn by observing the shift of the floating mark on the stereo viewer. Each contour was drawn, at 100 metre elevation differences, by the plotting table, at a scale of 1:250,000. Map C presents details of contour lines, spot heights and topographic features.

Large scale features :

The main forms of the mountainous area under study (about 15 by 20 km in extent) were well defined and a good correlation was seen with those evident on 1:250,000 scale maps in the following ways:

1. The location of gradient change from flat coastal plains to hilly areas was clearly and accurately defined.
2. Large valley features (5-10 km long, 1 km wide) were accurately and clearly defined.
3. Smaller valley features (1 km long and as little as 250 m wide) were clearly defined.
4. Small hills (less than 500 m in diameter) were accurately placed.

Contour line accuracies :

Previous work has used regression analysis to determine the relative precision of boundary and contour locations; it has been done with a limited number of observations and using simple configurations. The complex nature of the contour information obtained from both topographic maps and Metric Camera imagery prevents this sort of analysis. A generalised description, illustrated by typical maximum deviations is more appropriate. Details of each contour line are given below and limited comparisons can be made between figures 5.6 and 5.7 regarding contours within the catchments.

1. 100m contour line: Approximately 40% of this contour agrees well with that of the map, but differences of placings of 750m occur. In the N.W. and S.E. portions of the images, it agrees better with the 200m map contour. The maximum misplacement (3.75 km) occurs in the S.E.
2. 200m, 300m, 400m, contour lines: Accuracy varies widely in a manner similar to the 100m contour. It appears that an extra, interpolated contour may occur in this group. While contour accuracy is not always good, topographic features, on the whole, are well defined.
3. 500m contour line: No areas on the topographic maps are seen to exceed 500 metres, but the Metric Camera analysis presents a 500m contour line very similar to the 400m contour of the map.

It is evident that given the difficulties of image orientation due to the lack of control points and the necessity of a wide experience in dealing with subtle stereoscopic characteristics, Metric Camera altitude information must be treated with care, where absolute values are needed. However, the information relating to topographic features and general slopes is of high quality when compared to such information sources as LANDSAT and extremely useful in hydrological investigations.

CHAPTER 6 EVALUATION OF CATCHMENT CHARACTERISTICS FROM SIR-A RADAR IMAGERY

6.1 INTRODUCTION

The launch of the second flight of the space shuttle took place on the 12th November 1981 and during its flight, the side imaging radar, Earth resources programme was initiated. A series of data takes, covering about 10 million square kilometres and including every continent except Antarctica, were made. The imagery was processed onto strip negative in black and white at a scale of 1:500,000 (63). Part of this imagery covers the central area of Belize and although it does not include the whole of the Belize and Sibun river catchments, it does provide another source of remotely sensed information. Map figure 6.1 shows the coverage of the imagery, with reference to the catchments, figure 6.2 shows the scene by contact print.

The operation of radar (active microwave) systems is totally different to systems using passive, high resolution backscattered radiation from external illumination, such as LANDSAT m.s.s. Radar is able to penetrate cloud cover and may also be used to collect information at night. This is advantageous, particularly in tropical regions where cloud cover is a frequent problem. A resumé of the technical details relating the nature of radar systems is beyond the scope of this thesis and these details are freely available in text books of remote sensing(64), (65). However, technical aspects of radar imagery that are directly concerned with this research will be discussed.

SIR-A is a synthetic aperture system, operating in the L band of the microwave spectrum, with a wavelength of 25 cms. and giving ground resolution of approximately 25 metres(66). The ground swath of the imagery is approximately 50 kilometres. Image distortions are variable within the radar scene, decreasing at the edges (the range direction) as resolution becomes finer,

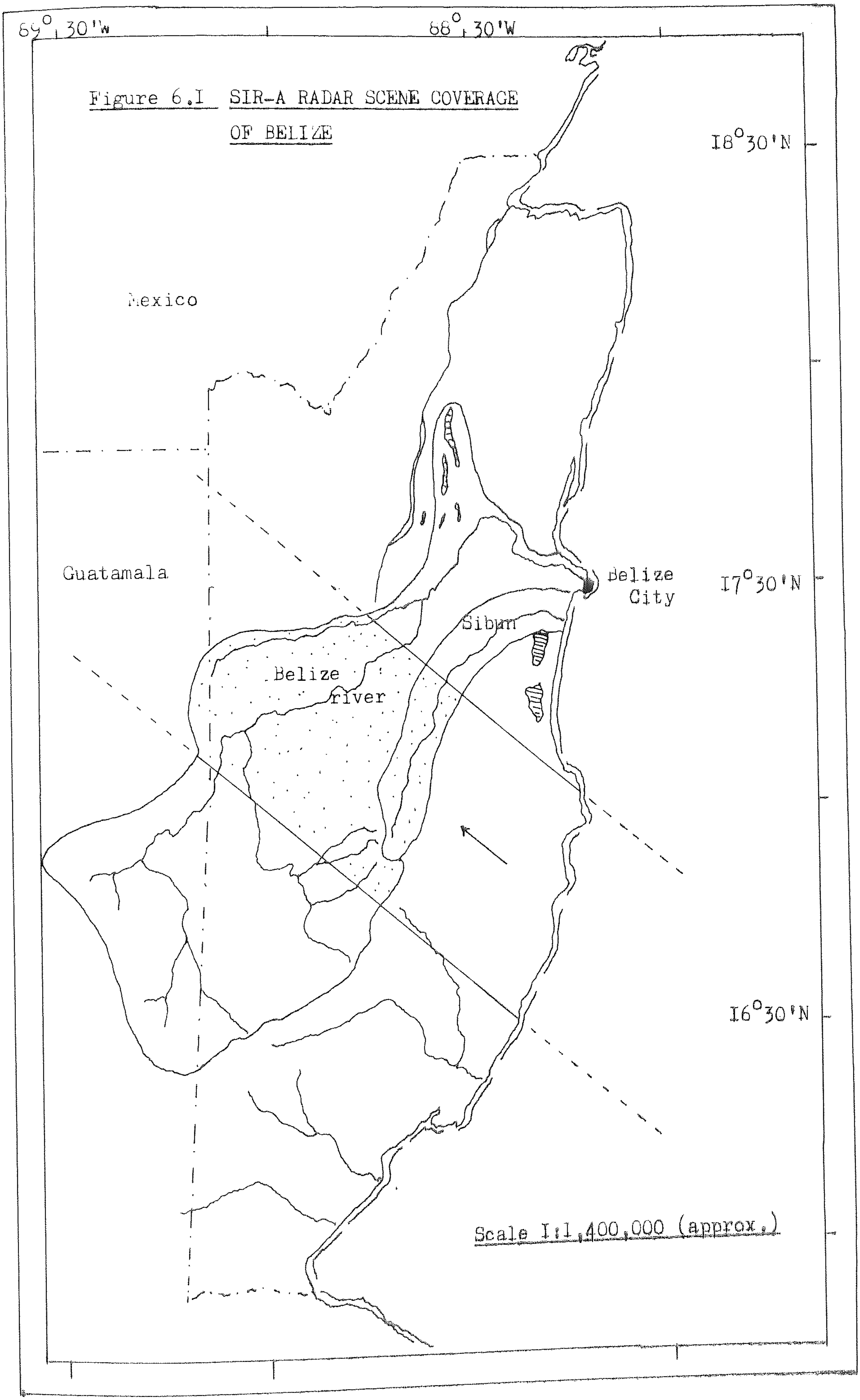


Figure 6.I SIR-A RADAR SCENE COVERAGE OF BELIZE

Figure 6.2 SIR-A COVERAGE OF BELIZE

conversely, distortions increase in the azimuth direction, the greater the distance from the radar source as resolution becomes coarser. The relationship is determined by the formulae:

$$\text{Ground resolution in the range direction} = \frac{CT}{2\ \text{COS}X} \qquad (6.1.1)$$

$$\text{Ground resolution in the azimuth direction} = GR.B \qquad (6.2.2)$$

(where C = the speed of light, T = the pulse duration, X = the depression angle, GR. = distance from radar source and B = the angular beam width). Figures 6.3 and 6.4 overleaf illustrate the nature of the relationships.

Since the ground swath of SIR-A imagery is relatively narrow compared to altitude and the angle of depression is high (50°), distortional resolution size changes throughout the scene are reduced. Also as the depression angle is high, areas of radar shadow (where all illumination is prevented by land slopes being greater than the depression angle) are few, except in the most rugged of terrains.

As for the Metric Camera imagery, investigations in this chapter are limited by the area of coverage. Photographic prints were made to a nominal 1:250,000 scale from which the quantification of catchment characteristics was undertaken. Investigations were possible relating to subcatchments 4 and 28 and all the regions except the floodplain area. Assessments of distortions were made. Stereoscopic investigations are not applicable to this imagery.

6.2 LARGE SCALE FEATURES OBSERVABLE FROM SIR-A IMAGERY

6.2.i Distortions

This section relates to the identification of regional features and the ability of SIR-A imagery to provide sufficient evidence for regional differentiation, based on drainage and topographical characteristics.

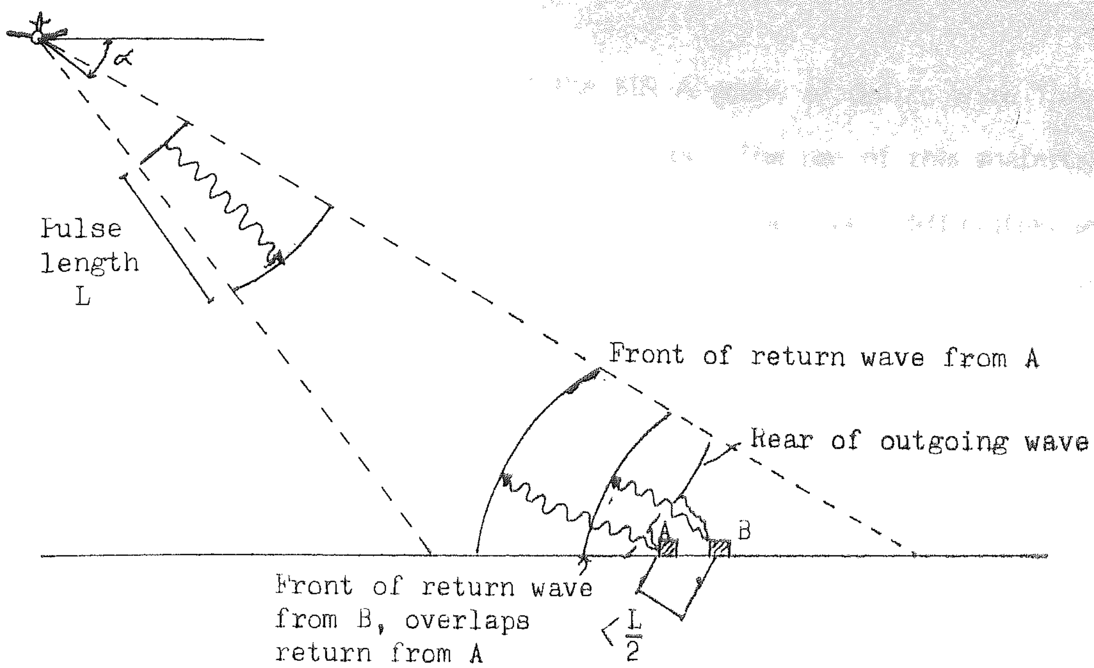


Figure 6.3 DEPENDENCE OF RANGE RESOLUTION ON PULSE LENGTH

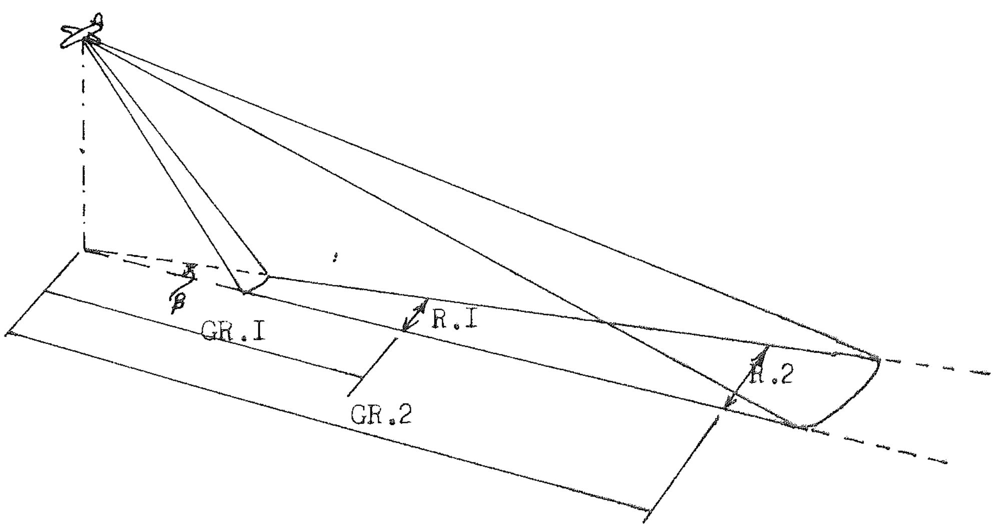


Figure 6.4 DEPENDENCE OF AZIMUTH RESOLUTION (Ra) ON ANTENNA BEAMWIDTH (β) AND GROUND RANGE (GR.)

Both figures reproduced from Remote Sensing and Image Interpretation, Lillesand T.M. and Kiefer R.W., Wiley & Sons, New York, 1979.

The distortional characteristics of the SIR-A scene of Belize were first investigated by the use of 1:500,000 contact prints. The use of this material negated distortions from photographic enlargement. However, difficulties in measurement at such a scale were considerable and generally such contact prints were less suitable for use than those of 1:250,000 scale. These were produced by selecting a portion of the scene suitable for the processing of a 10 x 8 inch inter-negative, the largest possible for enlargement use. An area of the Maya Mountains and the middle reach of the Belize river was selected as the most relevant to this research.

A series of ground control points, limited by available features, was selected to calculate the true scale of the enlargements. The values of these inter-g.c.p. measurements are given below in table 6.1

Table 6.1 SCALE SIZE OF (NOMINAL) 1:250,000 SCALE SIR-A PRINTS

Ground Control points	SIR-A distance (m.m.) (a)	1:250,000 (m.m.) (b)	Ratio (a)/(b)	SIR-A Scale
1 and 2	61.5	58.5	1.0513	1:237,901
1 and 5	344.0	336.0	1.0238	1:244,188
5 and 6	92.1	90.1	1.0222	1:244,571
1 and 6	285.7	275.5	1.0370	1:241,080
2 and 5	362.6	355.0	1.0214	1:244,762
3 and 4	371.0	356.4	1.0410	1:240,154
1 and 3	84.3	79.0	1.0671	1:234,280

Mean scale = 1:240,977, maximum difference = 6.3%, minimum difference = 2.1%

The mean scale difference is 3.6% larger than the nominal enlargement scale of 1:250,000 including inherent distortions of the scene, enlargement and measurement inaccuracies. This was not regarded as an impediment to the evaluation of catchment characteristics. The linear regression formulae linking this relationship was determined as being :

1:250,000 scale map = 0.9758 x SIR-A scale - 1.7045

i.e. $y = 0.9758z - 1.7045$

6.2.ii Regional identification

The task of regional identification and catchment characteristic evaluation was undertaken using the photographic enlargement giving an approximate coverage of the Belize and Sibun river catchments of 50%.

Distinctions in regional type were determined from observable differences in relief and textural pattern. Regional boundaries were clearly defined in greater detail than LANDSAT imagery. Descriptions of the distinctive characteristics of regional types are given below.

Region 1 :

This region was identified by large scale topographical features of a mountainous nature. The predominant trend of its geological structure was N.E.-S.W., approximately parallel to the radar 'look' direction. Despite this, sufficient small valleys at right angles to the overall trend supplied high reflectance to identify its alighment. Radar shadow effects were rare with little effective influence on interpretation, indicating that the general terrain had slope values well below 50°. Several large river valleys were easily identified, but on the whole the area appears as one of deeply incised terrain with many small river valleys, identifiable to 250 metres wide. The textural identity of the area was seen to be overwhelmed by the complex nature of the topography.

One sub region, significantly different from the rest of the area was identified, lying on the S.W. edge of the scene. Apparently of plateau-like structure, it was not highly incised and had a fine, homogenous textural nature. Topographic, vegetational and geological information relating to the area confirmed its flat nature with low slopes and shallow river valleys. Its granitic composition, in contradistinction with surrounding highly folded, metamorphic lithologies, provided the massif plateau topographic form. Vegetational differences indicated by reference(67) between it and surrounding areas, were concordant with the textural pattern of the area.

Region 2 :

It was clearly identifiable that this region is of lower altitude, from the photographic enlargements. Several large river valleys, including the Belize and the Sibun, were seen to enter the area from Region 1. However, by contrast, small river valleys clearly terminate abruptly at the regional boundary, indicating a marked change of lithology, emphasised by a distinct change of relief and structural pattern. The area is dominated by large rounded hills of 500 m to 1.5 km in diameter. Generally, drainage features were seen to be few, except in the presence of the largest of rivers.

Cultural features, while known to be present in this area, were not visible. 'Corner' reflectance - extremely high reflectance associated with cultural features - was not identified(68). However, areas of cultivated land, distinguished by clearly delineated boundaries were very visible in darker tones. The influence of the vegetation structure and relative dieletric nature of the differing vegetation types was probably the distinguishing factor in this differentiation(69).

Region 3 :

This region was clearly identified as a relatively flat, uniformly vegetated lowland area with no prominent relief and a texturally homogeneous nature. The Belize river, close to the Region 2/3 boundary, could be seen as the most obvious drainage feature, with only Labouring Creek and the streams of the Yalbac hills being also clearly visible. Smaller drainage features of this region were indistinct within the dense vegetation. Some cultivated areas were evident, though population centres were not. A few small lagoons (black due to specular reflectance) were evident.

6.2.iii Drainage Networks

Of the numerous drainage networks seen on the images, only three rivers - the Belize, Sibun and Labouring Creek - were directly observable, appearing black in contrast to their banks which presented relatively high back-scattered radiation. River widths, estimates possible only for the Belize river, were in the range 35-50 metres.

Four major river valleys were seen to descend from Region 1 to Region 2, by virtue of their size (up to 1 km. in width) and incised nature. Generally, drainage networks were implied by topographic features rather than direct observation. Map figure 6.5 illustrates the regional division of the scene, drainage patterns and subcatchment areas investigated.

Two main problems of interpretation were recognised:

1. While major river valley directions could be clearly identified, those of small rivers could not, resulting in the misplacing of tributaries from one drainage system into another.
2. Photographic grain size became a problem when identifying small streams, though this does reflect the comparatively detailed nature of information presented by SIR-A imagery.

6.3 EVALUATION OF CATCHMENT CHARACTERISTICS, SIR-A radar

As only 50% of the Belize and Sibun catchments was represented by SIR-A imagery, sufficient information for direct use in multiple regression analysis was not possible. However, as with Metric Camera information, a direct comparison by subcatchment could be made with 1:250,000 scale maps and LANDSAT imagery.

While the distortional aspects of radar imagery and its photographic treatment inevitably compromise the accuracy of measurement(70), it is unlikely that such inaccuracies are greater than those of other information sources. In addition, radar imagery overcomes problems of cloud cover.

FIGURE 6.5

Aston University

Illustration removed for copyright restrictions

6.3.i Area of subcatchments

Areas were digitised for subcatchments 4 and 28, regional areas were not completely covered by the imagery and therefore were not measured.

Table 6.2 AREA OF SUBCATCHMENTS

Subcatchment	4	28
Area (km^2)	176.9	92.2

6.3.ii Stream frequency

Stream frequency values were quantified as for other remotely sensed information sources. In the case of subcatchment 4, a large number of tributary valleys were truncated on entry into Region 2. Such valleys and their implied rivers were not extrapolated to evaluate stream frequencies.

Table 6.3 STREAM FREQUENCIES, SIR-A PRINTS

Subcatchment	4	28
Area (km^2)	176.9	92.2
Stream frequency	0.158	0.043

6.3.iii Mainstream lengths of subcatchments

Mainstream lengths, extended to the catchment boundaries by the observation of topographical features, are given below:

Table 6.4 SUBCATCHMENT MAINSTREAM LENGTHS

Subcatchment	4	28
Mainstream lengths (km)	25.5	11.4

6.3.iv Form indices

Both circularity indices and length:width ratios are given below.

Table 6.5 FORM INDICES OF SUBCATCHMENTS

Subcatchment	Perimeter (km)	Area (km^2)	Area of O of = perimeter (km^2)	circularity index
4	59.75	176.9	284.1	0.623
28	39.25	92.2	122.6	0.752

Subcatchment	Length (km)	Width (km)	Length:Width ratio
4	102.5	41.5	2.470
28	68.0	36.0	1.889

Values of floodplain area were not possible to evaluate due to its exclusion from the imagery. Mainstream slope and basin slope were also not available from monoscopic SIR-A imagery. Previous research has shown that the examination of radar imagery with reference to feature slope:length geometry and the identification of grazing angles can provide slope information(71) but serious problems are encountered with SIR-A images. The former method involves the use of more than one image viewed from different locations. The latter is of limited use since the depression angle of SIR-A is very high(50°) and to obtain a range of slope values it is necessary to vary the depression angle of the radar source, whereas SIR-A information is obtained from a source with a fixed depression angle.

CHAPTER 7 COMPARISON OF CATCHMENT INFORMATION FROM DIFFERENT REMOTE SENSING SOURCES AND TOPOGRAPHIC MAPS

7.1 INTRODUCTION

Chapters 2 to 6 of this thesis describe the methods of evaluation of catchment characteristics from the following information sources:

1. (Chapter 2) 1:250,000 scale topographic maps
2. (Chapter 3) 1:250,000 scale LANDSAT prints
3. (Chapter 4) 1:250,000 scale LANDSAT c.c.t. slides
4. (Chapter 5) 1:250,000 scale Metric Camera prints and diapositives
5. (Chapter 6) 1:250,000 scale SIR-A radar prints

This chapter compares the results of each of these sources, indicates their relative accuracy of measurement. Chapter 15 'Conclusions' provides an estimate of cost of purchase and use. The results of the measurements obtained from 1:250,000 scale maps are used as 'ground truth' against which remotely sensed values are judged. These comparisons are made in the context of certain characteristics of the information sources, which may conveniently be presented here :

1. LANDSAT provides the greatest areal coverage per scene.
2. The quality of data from each of the information sources may be highly variable with time and location.
3. Global coverage varies widely, LANDSAT coverage is almost world-wide, while others are much more limited.
4. The nominal ground resolution of each source is different and therefore scene detail varies greatly. LANDSAT resolution is about 80m, Metric Camera 25m, and SIR-A 25m. (72), (73), (74).
5. Different sources may present information in different formats - photographic or digital tapes - and thus may have different inherent ease and cost of utilisation. Conversion from one format to another is possible however.

The advantages and disadvantages of these facts is difficult to estimate, since the balance between coverage, resolution size and format will depend largely upon the use to which the information is to be put. Wide global coverage is, however, an indisputable advantage.

7.1.i Distortions of Remotely Sensed Imagery

Distortional inaccuracies are an important basic characteristic of all remotely sensed imagery that can be obviated only by the use of facilities such as laser-line printers, which locate each picture element precisely on the overall image(75). These distortions, however, may be of little significance where regional studies are made and where precise cartographic accuracy is not essential.

Comparisons made in this research indicate that where reasonable care is taken in the use of the imagery, these distortional inaccuracies will be small, especially when compared to errors of measurement and interpretation. Photographic prints will have distortions fixed at the time of enlargement. Paper shrinkage/expansion is regarded as very small. Slide projection will inevitably lead to different distortions at each projection. Vertical and horizontal distortions may well be different, and where possible must be assessed separately. Table 7.1 below presents the regression formulae linking remote sensing sources to topographic map linear measurement.

Table 7.1 REGRESSION FORMULAE LINKING REMOTELY SENSED IMAGES TO MAPS

	Source	Regression Formula	Scene Components
1.	LANDSAT PRINTS	MAP = 0.9877 PRINTS + 2.480	Scene 3, combined vertical and horizontal
	LANDSAT PRINTS	MAP = 1.0032 PRINTS + 0.818	Scene 1, vertical component only
	LANDSAT PRINTS	MAP = 1.0115 PRINTS - 2.320	Scene 1, horizontal components only
2.	LANDSAT SLIDES	MAP = 0.99898 SLIDES + 0.0028	combined horizontal and vertical
3.	Metric Camera	MAP = 1.0706 PRINTS - 7.560	combined horizontal and vertical
4.	SIR-A Radar	MAP = 0.9758 PRINTS - 1.705	combined horizontal and vertical

Thus, if 1,000 metres on the map is measured, the eqivalent distance determined by the remote sensing sources would be :

1.	LANDSAT PRINTS	-	990 metres	(i.e. - 1.0%)
	LANDSAT PRINTS	-	1004 metres	(i.e. + 0.4%)
	LANDSAT PRINTS	-	1009 metres	(i.e. + 0.9%)
2.	LANDSAT SLIDES	-	999 metres	(i.e. - 0.1%)
3.	Metric Camera	-	1063 metres	(i.e. + 6.3%)
4.	SIR-A Radar	-	974 metres	(i.e. - 2.5%)

In the cases above, the LANDSAT images provide the smallest distortions, and only those of the Metric Camera approach a significant level. It is important to note that this was the imagery with fewest suitable ground control features for measurement and this may be reflected in the percentage distortion. The comparison shows that none of these distortions would lead to serious problems of regional hydrological analysis, but to problems in the accurate location of features not actually visible on the images. The availability of good quality maps is important in the calculation of distortions, but the values above give a range of distortions that may be expected.

7.2 COMPARISONS OF CATCHMENT CHARACTERISTIC EVALUATION

7.2.i Area

Only LANDSAT print data provided sufficient coverage to evaluate the regional and total areas of the Belize and Sibun river catchments. They are compared to the equivalent 1:250,000 scale map areas in Table 7.2 below.

Table 7.2 REGIONAL AREAL MEASUREMENT (km^2)

Belize River	Map Area	LANDSAT Area	Difference
Region 1	1923	1861	-62 km^2 (-3.2%)
2	3428	3686	+258 km^2 (+7.5%)
3	1368	1307	-56 km^2 (-4.1%)
Floodplain	1528	1597	+69 km^2 (+4.5%)
TOTAL	8242	8451	+199 km^2 (+2.4%)

Table 7.2 continued

Sibun River	Map Area	LANDSAT Area	Difference
Region 1	371	415	+44 km2 (+11.9%)
2	341	466	+125 km^2 (+36.7%)
3	0	0	0 km^2 (0%)
Floodplain	511	454	-57 km^2 (-11.2%]
TOTAL	1223	1335	+112 km^2 (+9.2%)

Table 7.3, overleaf, gives a similar comparison for areas above gauging stations, with a breakdown of regional proportions for these areas.

Consideration of tables 7.2, 7.3 and 7.4 indicates several important aspects concerning the capacity of LANDSAT print material to provide accurate areal measurement, they are :

1. Where cloud cover is not a significant problem, LANDSAT prints can provide relatively accurate evaluations of regional areas, by defining drainage networks and topographic features. In the case of the Belize river, accuracies of measurement ranged from +7.5% to -4.1%. The Sibun river catchment values are less accurate (+36.7% to -11.2%) but this catchment was extensively cloud covered, and boundaries were in part estimates.
2. Regions of high relief, with distinctive landforms (e.g. Region 1) will be most accurately defined.
3. The photographic details of LANDSAT prints compensate, in drawing catchment boundaries, for the lack of contour information.
4. The overall accuracy of the areal measurement of large river catchments may be very high, in the case of the Belize river catchment, the difference was only +2.4%.

It can be seen that generally, the larger the region being defined, the greater the accuracy, where difficulties of definition due to the lack of topographical features (e.g. Region 2), are not exceptional.

TABLE 7.3 AREAS ABOVE GAUGING STATIONS BY REGION (km^2)

MAP AND LANDSAT PRINT COMPARISON

...ation	Map				LANDSAT											
	Region				Region 1			Region 2			Region 3			Floodplain		
	1	2	3	Floodplain	Area	Difference	% Diff.	Area	Difference	% Diff.	Area	Difference	% Diff.	Area	Difference	% Diff.
...V	378	2792	181	0	415	+37	+9.8	3071	+279	+10.0	0	-181		0	0	0
...CR	1366	118	8	0	1250	+126	+9.2	66	-52	-44.0	0	-8		0	0	0
...C	1792	2911	510	0	1723	-69	-3.8	3412	+502	-17.2	323	-187	-36.7	0	0	0
...B BK	1922	3258	860	0	1860	-62	-3.2	3616	+358	+10.9	561	-299	-34.8	0	0	0
...BFR	1922	3422	1345	391	1860	-62	-3.2	3686	+264	+7.7	1307	-38	-2.8	333	-58	-14.8
...BL	1922	3422	1345	434	1860	-62	-3.2	3686	+264	+7.7	1307	-38	-2.8	384	-50	-11.5
...DB	1922	3422	1345	1253	1860	-62	-3.2	3686	+264	+7.7	1307	-38	-2.8	1326	+75	+5.8
...GR	371	340	0.0	158	415	+44	+11.9	466	+126	+37.1	0	0	0	454	+296	+187

The % standard errors of estimate at the 68% and 95% confidence levels are ±7.2% and ±14.4% respectively, as averages.

TABLE 7.4 TOTAL AREAS ABOVE GAUGING STATIONS : MAP AND LANDSAT COMPARISONS

Gauging Station	1:250,000 Total Area km^2	LANDSAT Prints Total Area km^2	(Difference) (km^2)	% Difference
BV	3351	3486	(+ 135)	+ 4.0
CR	1492	1316	(- 176)	- 11.8
IC	5213	5459	(- 336)	+ 6.4
B.BK	6040	6037	(- 3)	- 0.05
BFR	7080	7186	(+ 106)	+ 1.5
BL	7123	7237	(+ 116)	+ 1.6
DB	7942	8179	(+ 237)	+ 3.0
GR*	878	1009	(+ 131)	+ 14.9

* significant cloud cover

The standard errors of LANDSAT regional measurement were calculated using $s.e. = \sqrt{\frac{\sum d^2}{n - 2}}$ where d = the deviation of LANDSAT from map data and n = the number of measurements

The results are given below in table 7.5.

Table 7.5 STANDARD ERRORS OF LANDSAT REGION MEASUREMENT

Confidence level	Standard error	Region 1	Region 2	Region 3	Floodplain	Total area
68%	1 s.e.	±6.9%	±22.9%	±29.3%	±8.8%	±6.5%
95%	2 s.e.	±13.8%	±45.9%	±58.6%	±17.6%	±13.0%

Table 7.6 overleaf presents subcatchment measurements of areas for all information sources and indicates the following important factors:

1. LANDSAT c.c.t. images gave more accurate results than any of the other remote sensing sources, though generally, the accuracy is not very much greater.

2. That it is more difficult to identify small subcatchments in homogeneous regions, than to identify regions of different types. This is especially true where cloud cover interference is encountered.

3. Metric camera prints provide more accurately interpretable images than similar LANDSAT prints.

The standard errors of the subcatchment measurements is given below in table 7.7.

Table 7.7 STANDARD ERRORS OF SUBCATCHMENT MEASUREMENT

Confidence level	LANDSAT Prints	LANDSAT c.c.t.	Metric camera	SIR-A
68% (1 s.e.)	± 45% (±29%)	± 16.0%	± 24%	N/A
95% (2 s.e.)	± 90% (±56%)	± 32.0%	±48%	N/A

These standard errors are generally greater than those for regional measurement, but those of LANDSAT prints, may be reduced by the removal of values for subcatchment 28 which was largely cloud covered. The standard errors in this case are given in parenthesis in table 7.7., for LANDSAT prints.

TABLE 7.6 AREAS OF SUBCATCHMENT (km^2), COMPARISON OF ALL SOURCES

Sub catchment	Map	LANDSAT Prints			LANDSAT c.c.t			Metric Camera			SIR-A		
		Area	Difference	% Diff.	Area	Difference	% Diff.	Area	Difference	% Diff.	Area	Difference	% Diff.
6b	432.2	342.1	-90.1	-20.8	396.4	-35.8	-8.3		NA			NA	
3a	271.2	312.7	+41.5	+15.3	277.5	+6.3	+2.3		NA			NA	
28	79.7	72.3	-7.4	-9.3	64.8	-14.9	-18.8		NA		92.2	+12.5	+15.7
4	161.2	137.5	-23.7	14.1	146.9	14.3	-8.9		NA		176.9	+15.7	+9.7
Mahogany Creek	103.9		NA			NA		118.1	+14.2	+13.7		NA	
Big Creek	153.1		NA			NA		183.6	+30.5	+19.9		NA	
Plantation Creek	61.6		NA			NA		62.5	+0.9	+1.5		NA	

7.2.ii Mainstream slope

Only Metric Camera information is directly convertible through stereo photographic methods, to obtain altitude values and thereby slope values. A comparison with LANDSAT data cannot be made, though it remains to be seen if mainstream slope is an essential component of the regression equations defining flood values. Values for mainstream slope obtained by the 1085% method are given below in table 7.8, for comparison.

Table 7.8. MAINSTREAM SLOPES, 1085% METHOD

Catchment	Maps	Metric Camera
Plantation Creek	0.0083	0.0174 (+109.6%)
Big Creek	0.0047	0.0098 (+108.5%)

In the cases above, Metric Camera values are consistently higher than those obtained from the 1:250,000 scale maps, but the 1085% method appears not to account for high slope values at the river headwaters. This is illustrated by Big Creek, where the position of the 85% mainstream length point of the map data lies below 100 metres, leaving slope values from 100 to 400 metres unaccounted for and giving a low mainstream slope value. Because of this, a second slope measurement investigated by the F.S.R.(76) was used to give a separate estimate of slope values. The formula for this, the Tayslo method, is as follows :

$$\text{Tayslo} = \left(\frac{\sum L_i}{\sum \frac{L_i}{\sqrt{S_i}}} \right)^2$$

where L_i = distance between contours (metres)

S_i = contour interval (metres)

while this method is more lengthy in calculation, it does take into account all contour intervals. Table 7.9 below gives results for the subcatchments.

Table 7.9 MAINSTREAM SLOPES, TAYSLO METHOD

Catchment	Maps	Metric Camera
Plantation Creek	0.0076	0.0090 (+18.4%)
Big Creek	0.0052	0.0064 (+23.1%)
Mahogany Creek	N/A	N/A

The use of this method does bring map and Metric Camera slope values closer to agreement, partly by increasing the map slope value of Plantation Creek, but largely by decreasing Metric Camera values. This latter effect was unexpected. The most significant factor in this discussion of mainstream slope, beyond the fact that Metric Camera values indicate a clear order of magnitude, is that the use of *one* slope method compared to another, can lead to differences almost as large as those between information sources. For instance, the difference between Plantation Creek 1085% slope and Tayslo is 93%, while the differences between the slope values of map and Metric Camera are 109% for the 1085% method and only 18.4% for the Tayslo method. With such examples, it is clear that information source is no more important than slope calculation method, and will probably lead to no greater inaccuracies of measurement.

7.2.iii Stream Frequency

Stream frequencies within the Belize river catchment were obtained from LANDSAT prints and c.c.ts. and SIR-A radar, Metric Camera information provided values adjacent to the Sibun river. All are compared to values from 1:250,000 scale maps. Table 7.10 presents these with 1:50,000 scale map values also.

Table 7.10 STREAM FREQUENCY VALUES

Sub-catchment	Map 1:250,000	Map 1:50,000	LANDSAT Prints	LANDSAT c.c.ts.	SIR-A radar
6b	0.180	1.780	0.491	0.494	NA
3a	0.066	0.380	0.074	0.216	NA
28	0.063	0.472	0.069	0.062	0.043
4	0.056	0.530	0.080	0.265	0.158
		Map	Map	Metric Camera	
Mahogany Creek		0.130	NA	0.672	
Big Creek		0.085	NA	0.218	
Plantation Creek		0.0096	NA	0.034	

The relationship of these values can, perhaps, be most clearly seen by giving stream frequency values of 1:250,000 scale maps a value of 1.0 and relating other information sources to this base. Table 7.11 below does this.

Table 7.11 STREAM FREQUENCY RELATIONSHIPS

Sub-catchment	Map 1:250,000	Map 1:50,000	LANDSAT Prints	LANDSAT c.c.ts.	SIR-A Radar
6b	1.0	9.89	2.73	2.74	NA
3a	1.0	5.76	1.12	3.27	NA
28	1.0	7.49	1.10	0.98	0.68
4	1.0	9.46	1.43	4.73	2.82
		Map	Map	Metric Camera	
Mahogany Creek		1.0	NA	5.15	
Big Creek		1.0	NA	2.59	
Plantation Creek		1.0	NA	3.54	

Several points of interest are raised by these tables:

1. In almost all cases, remote sensing sources provide higher stream frequencies than 1:250,000 scale maps. None give higher values than 1:50,000 scale maps.

2. These values vary by information source and type of regional subcatchment.

3. Almost all sources provide higher relative values for high relief subcatchments and lower values for subcatchments of lower relief.

4. While inter-source comparison is difficult, Metric Camera and LANDSAT c.c.t slides provide the greatest information of river courses.

5. Linking regression formulae can be devised and are provided below.

Table 7.12 REGRESSION FORMULAE LINKING 1:250,000 MAPS TO REMOTE SENSING SOURCES, STREAM FREQUENCY

LANDSAT Prints	MAP = 0.3036 print + 0.0310
LANDSAT c.c.t	MAP = 0.2862 slide + 0.01717
Metric Camera	MAP = 0.1722 print + 0.0217
SIR-A Radar	Sufficient values not available.
1:50,000 Scale Maps	MAP = 0.0899 map + 0.226

While the bifurcation ratio - an indicator of stream ordering and terrain type - is not used as a regression variable, stream orders and numbers are useful indicators of the drainage network information available from data sources. The number of streams found from each data source considered in this way (see each relevant chapter) indicate that the following conclusions may be drawn.

1. LANDSAT prints determined between 180% and 144% more first order streams than the same scale maps.2.

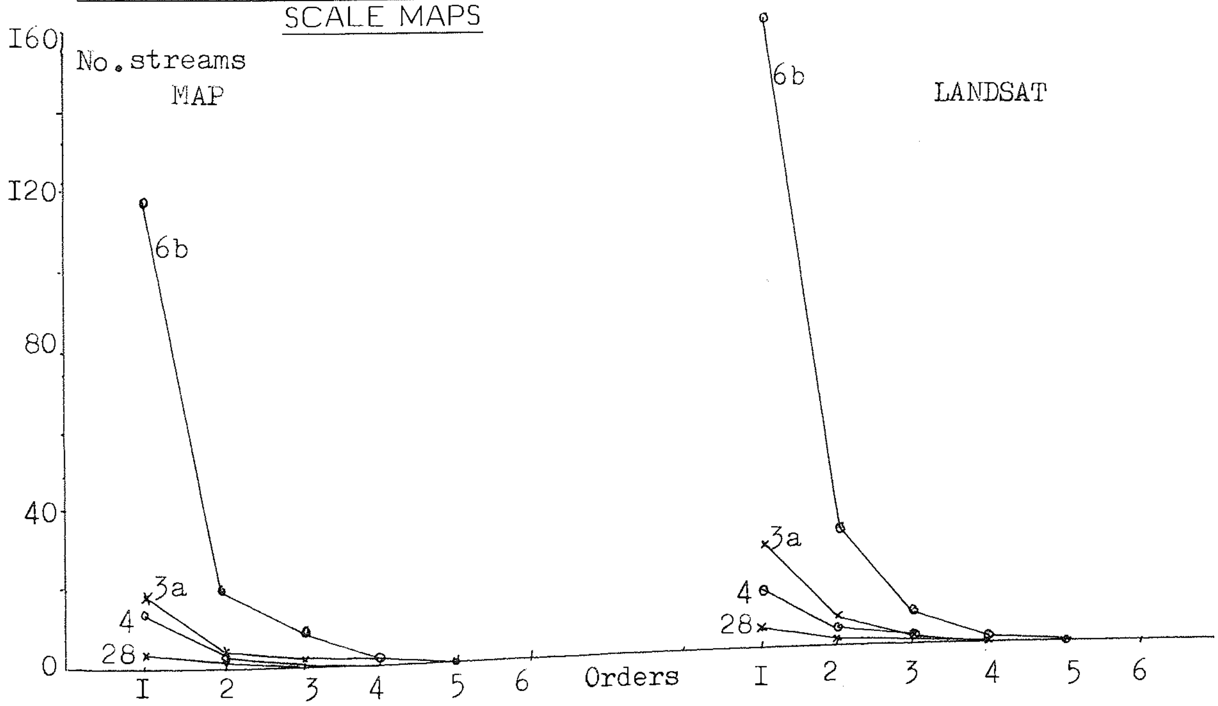
2. LANDSAT c.c.t slides indicated between 388% and 133% more first order streams.

3. When checked against 1:50,000 scale maps, 98% of LANDSAT print and 99% of LANDSAT slide derived river courses were seen to be correctly interpreted.

4. LANDSAT print data did display a one order shift up within subcatchment 28 and a one order shift down in subcatchment 3a, as found by certain research(77). LANDSAT slide data displayed a 1 order shift in subcatchment 28.

5. Both LANDSAT sources provided significantly less information than 1:50,000 scale maps.

Figure 7.1 STREAM ORDERS OF LANDSAT PRINTS AND 1:250,000 SCALE MAPS



7.2.iii Soil/Slope Index

Comparisons with any other information source than Metric Camera was not possible. From Metric Camera information (see Chapter 5) basin slope values were determined by stereoscopic investigation. Since the soil component of the index is obtained from soil maps and documentary data, only the basin slope component need be compared.

Table 7.13 COMPARISONS OF BASIN SLOPES, METRIC CAMERA AND 1:250,000 SCALE MAPS

Catchment	Map Basin Slope	Metric Camera Slope	Difference	
Mahogany Creek	2°	2°	0.0°	0.0%
Big Creek	2.8°	2.9°	0.1°	+3.6%
Plantation Creek	5.9°	5.7°	0.2°	-3.4%

Metric Camera information can be seen to give highly accurate basin slope values.

7.2.iv Floodplain areas

Floodplain areas for 1:250,0o00 scale maps and same scale LANDSAT prints were measured and for comparison are presented below in table 7.14.

Table 7.14 COMPARISON OF FLOODPLAIN AREAS, MAPS AND LANDSAT PRINTS (km^2)

Measurement	1:250,000 Scale Maps				LANDSAT Prints							
Method	BFR	BL	DB	GR	BFR	% Diff.	BL	% Diff.	DB	% Diff.	GR	% Diff.
1	391.0	434.0	1253.0	158	333	-14.8	384	-11.5	1326	+5.8	140	-11.4
2	51.6	77.4	209.2	66.0	45.0	-12.8	64.4	-16.8	210.6	-0.7	NA	-

Accuracies, based on both methods of floodplain definition, with the exception of the part cloud covered Sibun catchment, can be seen to be accurate for the purposes of regression analysis for the catchments.

7.2.v Mainstream Lengths

Mainstream lengths for the use of multiple regression analysis can only be supplied by LANDSAT print material, but comparisons can be made between river lengths within subcatchments, taken from the different remotely sensed sources. Table 7.15 overleaf gives mainstream lengths above gauging stations.

Table 7.16 below gives comparative values for subcatchments.

Table 7.16 RIVER LENGTHS WITHIN SUBCATCHMENTS (km)

Sub-catchment	Maps	LANDSAT c.c.ts.		LANDSAT prints.		SIR-A	
6b	36.5	34.5	(-5.5%)	35.5	(-2.7%)	NA	
3a	30.0	31.0	(+3.3%)	32.0	(+6.6%]	NA	
28	17.5	18.3	(+4.6%)	19.0	(+8.6%)	11.4	(-34.9%)
4	28.0	27.0	(-3.6%)	26.7	(-4.6%)	25.5	(-8.9%)

	Maps	Metric Camera	
Mahogany Creek	15.5	14.75	(-4.8%)
Big Creek	28.5	23.75	(-16.7%)
Plantation Creek	21.5	19.25	(-10.5%)

In almost all cases, the remote sensing sources underestimate mainstream lengths. The SIR-A values were particularly inaccurate, though LANDSAT print values for the main Belize river are largely accurate. Difficulties in observation of the actual river course within subcatchment areas undoubtedly led to higher inaccuracies, especially in SIR-A, subcatchment 28. Once more it is clearly recognised that terrain type is a strong influence on accurate measurement. It is also apparent that different remote sensing courses will perform well to different degrees, with varying terrain type.

Distortional inaccuracies were investigated with regard to the measurement of mainstream lengths above gauging stations, but the effect of correction for these distortions was negligible. Improvements were recognised, but these averaged an improvement of only 0.77%. Obviously distortion plays little part in any inaccurate measurement of mainstream length.

TABLE 7.15 MAINSTREAM LENGTHS ABOVE GAUGING STATIONS (km), MAPS AND LANDSAT PRINTS

Gauging Station	1:250,000 Maps			LANDSAT Prints					
	Mopan Branch	Macal Branch	Average	Mopan Branch	% Difference	Macal Branch	% Difference	Average	% Difference
BV	139	-	139	123	- 11.5	-		123	- 11.5
CR	-	90	90	-	-	88	- 2.2	88	- 2.2
IC	193	126	159.5	174	- 9.8	124	- 1.6	149	- 6.6
B.BK	225	158	191.5	206	- 8.4	156	- 1.3	181	- 5.5
BFR	279	212	245.5	254	- 9.0	204	- 3.8	229	- 6.7
BL	294	227	260.5	269	8.5	219	- 3.5	244	- 6.3
DB	323	256	289.5	299	- 7.4	249	- 2.7	274	- 5.4
* GR	-	-	99.8	-		-		66	-34.0

* Mainstream length estimated due to cloud cover

7.2.vi Form Indices

The relationships between the circularity index and length:width ratio, for catchment areas above gauging stations, is presented below in table 7.17 and these values are used in Chapter 10, 'Multiple Regression Analysis'. The pattern of a general increase in accuracy with increasing area may once again be noted.

Table 7.17 FORM INDICES COMPARISONS, MAPS AND LANDSAT PRINTS

Gauging Station	Circularity Index		Length:Width Ratio	
	Map	LANDSAT	Map	LANDSAT
B.V.	0.496	0.692	0.97	0.86
C.R.	0.527	0.603	1.24	1.67
I.C.	0.568	0.731	1.32	1.13
B.BK.	0.603	0.751	1.60	1.49
B.F.R.	0.530	0.640	1.95	1.91
B.L.	0.479	0.574	2.07	2.01
D.B.	0.350	0.427	2.28	2.22
G.R.	0.519	0.612	1.038	NA

Table 7.18 FORM INDICES COMPARISONS (SUBCATCHMENTS)

Sub catchment	Map		LANDSAT c.c.t.		SIR-A	
	C.I.	L:W.R.	C.I.	L:W.R.	C.I.	L:W.R.
6b	0.708	2.01	0.769	1.82	NA	NA
3a	0.800	1.44	0.726	1.45	NA	NA
28	0.342	2.88	NA	1.93	0.623	2.47
4	0.756	2.04	0.594	2.21	0.752	1.89

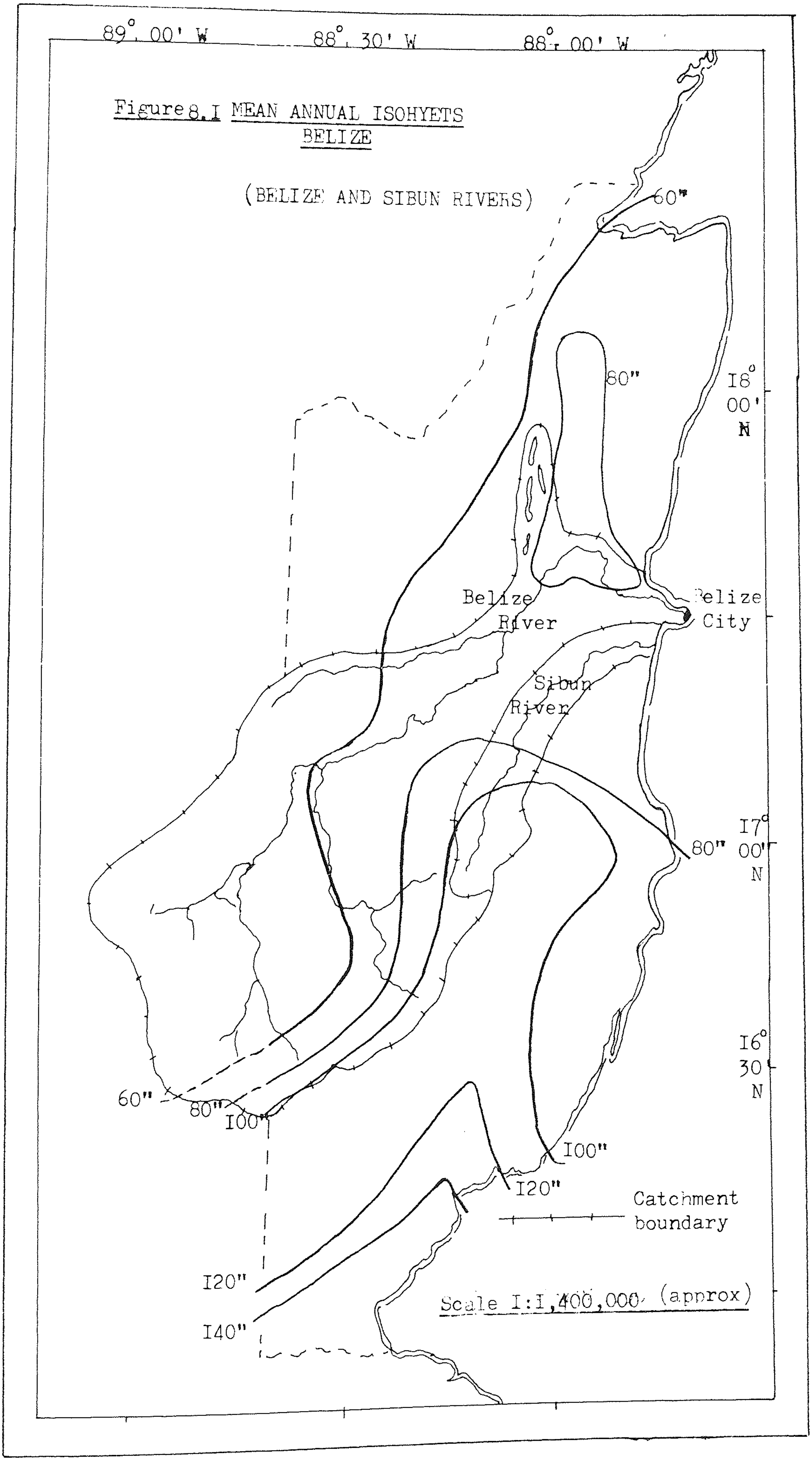
	Map		Metric Camera	
Mahogany Creek	0.465	3.21	0.470	2.42
Big Creek	0.485	2.28	0.636	2.89
Plantation Creek	0.366	4.45	0.314	4.07

CHAPTER 8 THE DERIVATION OF AN INDEPENDENT VARIABLE FOR CLIMATE

8.1 INTRODUCTION

The data upon which this chapter is based is taken from two main sources, 'Land in British Honduras' (78) and 'A Summary of Climatic Records for Belize' (79). In most respects, the latter publication extends the coverage of the former, but both deal in terms of monthly rainfall and temperature values. Data for daily rainfall analysis and the estimation of Penman evapo transpiration values was obtained from a supplementary report to the Summary of Climatic Records(80) and by direct approach to the National Meteorological Service of Belize, based at Belize International Airport.

The overall climatic regime of Belize may be described as subtropical. Atmospheric humidity is variable from 75% in the west to 83% on the east coast to 88% in the south east. Temperatures vary from about 50°F. to 95°F. with a mean annual figure of 79°F. November to January is the coolest period (average 75°F.), May to September the hottest (average 81°F.). While temperatures may drop to as low as 46°F., shade temperatures of 100°F. or more are not uncommon. A large variation of rainfall from year to year and from region to region is also noticed. The north of the country has a 3 to 4 month dry season (usually January to April), though the onset of the rains is not strictly predictable. The south of the country may have a dry season of only 3 or 4 weeks. Generally, the predictability of dry season rainfall amount is straightforward whereas during the wet season the general rule is the higher the rainfall, the greater the possible departures from normal(81). The distribution of mean annual rainfall over Belize is shown in map figure 8.1, taken from the Summary of Climatic Records. The map is compiled from widely differing periods for 76 rainfall stations(82). The variation of periodic cycles in rainfall is quite marked and is illustrated overleaf in figure 8.2 by a compilation of 87 years' data at Belize City.



89° 00' W
88° 30' W
88° 00' W
Figure 8.I MEAN ANNUAL ISOHYETS
BELIZE
(BELIZE AND SIBUN RIVERS)
60"
80"
18° 00' N
Belize River
Belize City
Sibun River
17° 00' N
80"
16° 30' N
60"
80"
I00"
I00"
I20"
Catchment boundary
I20"
I40"
Scale I:I,400,000 (approx)

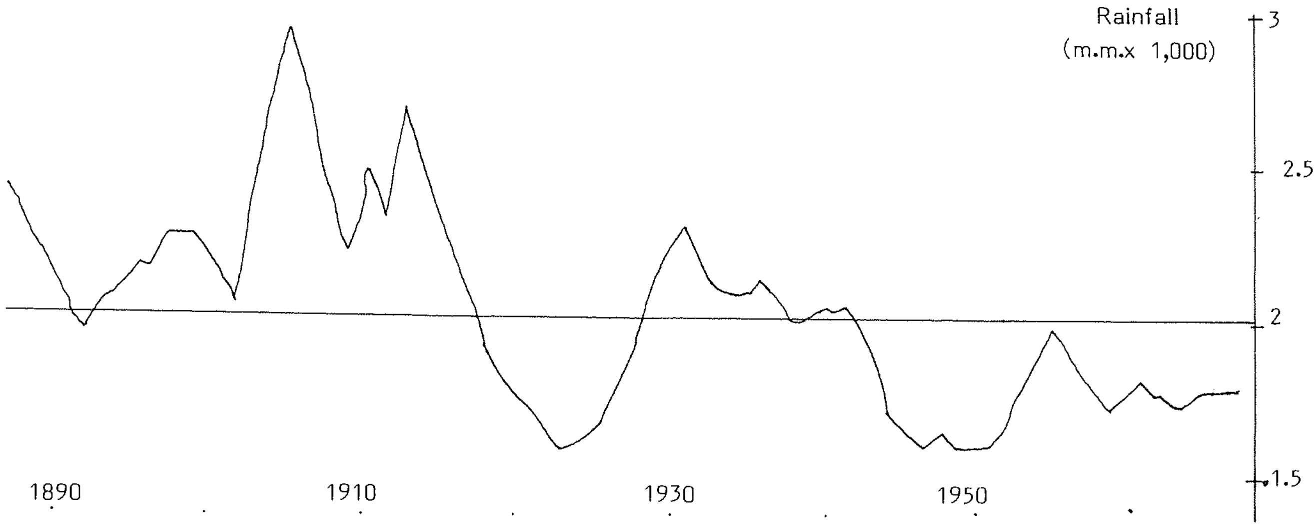


Figure 8.2. LONGTERM VARIATION OF RAINFALL, BELIZE CITY. (Walker 1973)

The average above is smoothed by a 3 year moving mean in the form:

$xs = (x - 3) + 2(x - 2) + 3(x - 1) + 4x + 3(x + 1) + 2(x + 2) + (x + 3) \div 16$

where : xs = annual total for specific year x, x - 3 = annual total for three years previous to x.

The irregularity of meteorological records in Belize is a serious problem. Many stations have only a few years' data, many records are intermittent and the location of some rainfall gauges is unknown. Their distribution throughout the country is uneven, depending more on location accessibility than meteorological suitabilty. Winds are predominantly the 'S.E. Trades' with average velocities of 10 m.p.h., blowing from February to September. Stronger winds are relatively rare and associated with anticyclonal areas over N.America. During August to September, Belize is exposed to the uncommon event of the passage of hurricanes from the Atlantic.

8.2 THE CLIMATE INDEPENDENT VARIABLE

The use of climate (usually rainfall) variables in multiple regression analysis is based on the observation that rainfall is a decisive factor contributing to river flow. A variety of independent variables describing climatic effect have been used in the development of formulae predicting or describing probable river discharge. These variables range from simple values of average annual rainfall(83), rainfall less evaporation(84) to the complex treatment of data proposed by the Flood Studies Report(85).

The use of these different variables may be justified in each specific case and each type of variable has advantages supporting its use. For instance, average annual rainfall provides a factor that is easily and rapidly calculable, that is available for any region of the world and may be easily correlated with examples of dependent discharge. However, it takes no account of the fact that flood flows are the result of causative process involving rainfall amount, intensity and antecedent conditions within the catchment. This influence of catchment and rainfall dimensions upon flood response has been widely recognised in previous research(86), (87), (88), (89). That analysis by multiple regression does not assume a cause and effect basis does not invalidate its use and studies of rainfall, evapotranspiration and soil moisture are widespread. This work involves the application of specific data to specific locations and may not be transferable to other regions. It is also dependent upon the availability of detailed meteorological information. The use of methods based on sound hydrological principles and suggested by the F.S.R. are assessed for their useful application to Belize data.

The F.S.R. method proposes the use of the 1 day 5 year return rainfall event, rainfall directly related to high flows(90). Antecedent conditions, controlling the amount of rainfall that runs off, are taken into account by subtracting the antecedent soil moisture deficit of the catchment from the storm rainfall(91), (92) and defining the rainfall excess in the general terms:

$$Q = R - SMD \qquad (8.2.1)$$

where R = 1 day 5 year rainfall and SMD = the soil moisture deficit

where rainfall is equal or greater than soil moisture deficit.

The rainfall excess is termed "effective rainfall" by the F.S.R.

In this research, the effective rainfall is assessed with regard to Belize data and is compared in regression analysis (see Chapter 10), with its simplest alternative, average annual rainfall. THE F.S.R.(93) found little significant difference in regression analysis between these alternative variables. Section 8.3 below describes the calculation of average annual rainfall (A.A.R.) and 8.4 the calculation of effective rainfall, termed R.S.M.D.

8.3 CALCULATION OF THE CLIMATE VARIABLE A.A.R.

8.3.i Background

The data from which A.A.R. values are obtained are taken from the Summary of Climatic Records, in the form of mean annual isohyets; values determined by the Theissen method(94) are also discussed.

Generally speaking, estimates of areal precipitation increase in accuracy with increasing density of the rainfall gauge network. The network in Belize does not conform strictly to a predetermined pattern, but in many respects is a response to the accessibility of location and the availability of responsible readers. The total number of existing stations is reasonable though the distribution for national coverage is deficient(95). Analysis by the U.S. Weather Bureau(96) provides density-area-error relationships, indicating probably inaccuracies. Figure 8.3 below describes this relationship and provides estimates of the probable accuracies of Belize data. Since the density of the rainfall gauge network in Belize is highly variable and since these errors are not accounted for within the isohyetal distribution data, it is not possible to modify the information used in this research, but table 8.1 presents standard errors likely to be encountered.

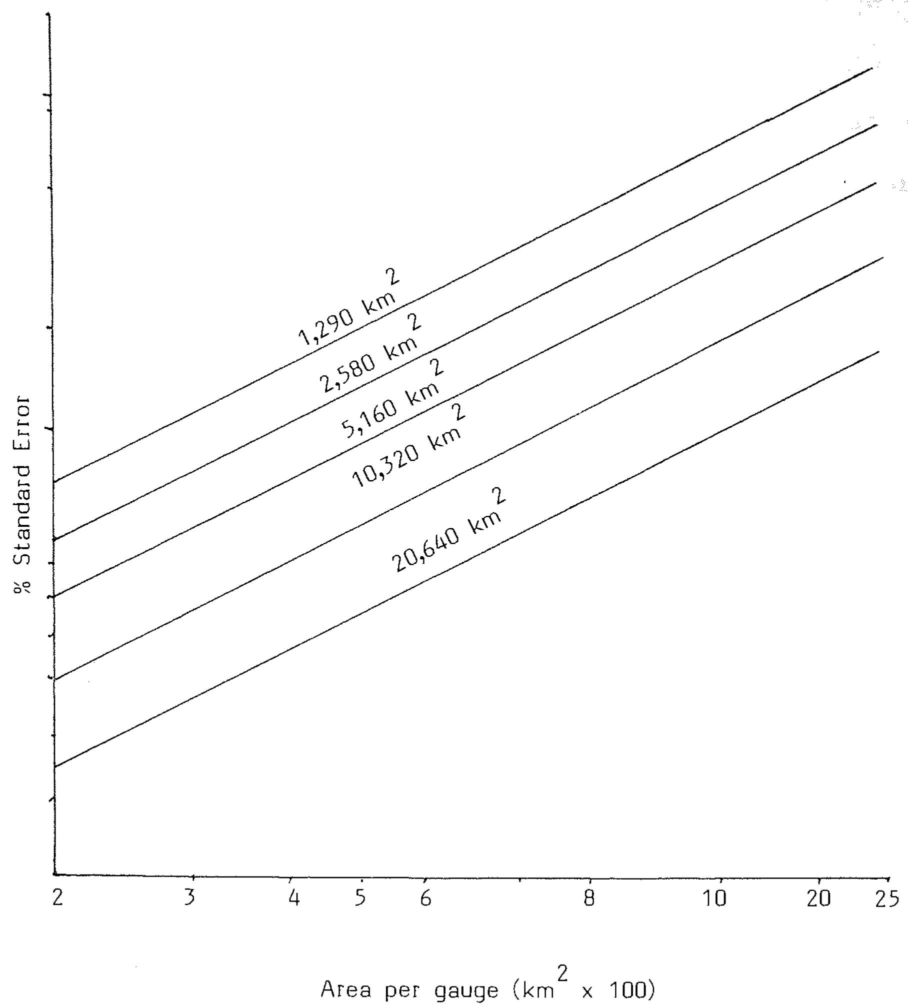


Figure 8.3 RAIN GAUGE NETWORK DENSITY PERCENTAGE ERROR RELATIONSHIPS

Table 8.1 EXAMPLES OF PERCENTAGE ERRORS FOR SELECTED STATIONS

Rainfall Station	Areal Coverage (km)	% Standard error
Belize Airport	245	± 10%
Big Falls Ranch	441	± 12%
Belmopan	147	± 7%
Norland Farm	145	± 7%
San Ignacio	75	± 4%

The calculation of A.A.R. values presents certain problems in distribution weighting, many of which have been conveniently summarised(97). Arithmetic averages give no weighting, the two most usual methods used being the isohyetal and polygonal methods. The latter, developed by Theissen and extended by some workers to include altitude effects(98) bases weighting upon the areas of constructed polygons around the gauging stations. Some workers have suggested the use of applying a polynomial surface to evaluate rainfall trends, suitable for computer analysis(99). However, the provision of a comprehensive A.A.R. isohyetal map(100), the small quantity of data to be analysed and the proven worth of the isohyetal method, overwhelmingly suggested its use in this research. It was expected that this map, drawn using the fullest amount of Belize data and considering the local variations of rainfall distribution, would provide the most accurate evaluation of A.A.R. values.

8.3.ii Calculation of A.A.R.

The isohyets shown on map figure 8.1 were transferred to a 1:250,000 scale map of the Belize and Sibun river catchment. Map figure 8.4 shows the location of all rainfall stations with regard to the river catchments and lists the station name abbreviations.

Inter-isohyetal areas were measured for each catchment area above hydrological gauging stations to obtain weighting percentages. Values are presented overleaf in table 8.2, in inches.

The lengths of each respective isohyet were used to weight the area distribution of rainfall values and determine the weighted mean values shown in table 8.3 below. Weighting was achieved by applying the following formula(101).

$$r = B + \left(\frac{i}{3} \times \frac{2(a)+b}{a+b} \right) \qquad (8.3.1)$$

where r = weighted average rainfall, B = value of the lower value isohyet, A the higher, b = the length of isohyet B, a = the length of isohyet A.

The 120" isohyet does not enter the catchment and no average annual rainfall as low as 40" is recorded. Some localised extrapolation of the 100", 80" and 60" isohyets was necessary at the extreme western part of the catchments, but the regular conformity of the isohyets with topographical features provided little difficulty in this. Table 8.3 below gives overall A.A.R. values weighted and converted into millimetres for use in regression analysis. Unweighted values are also given for comparison.

TABLE 8.2 INTER-ISOHYTEL AREAS FOR THE BELIZE AND SIBUN RIVER CATCHMENTS (km^2)

Gauging	120"-100" (mean 102")		100"-80" (mean 90")		80"-60" (mean 70")		60" (mean 50")		Total
Station	Area	% Area	Area	% Area	Area	% Area	Area	% Area	Area
B.V.	146	4.3	658	19.3	660	19.4	1941	57.0	3405
C.R.	220	14.8	790	53.3	452	30.5	21	1.4	1483
I.C.	366	7.0	1513	29.0	1235	23.6	2110	40.0	5228
B.BK	366	6.1	1678	27.9	1855	30.8	2119	35.2	6018
B.F.R.	366	5.2	1707	24.1	2589	36.6	2419	34.2	7081
B.L.	366	5.2	1707	24.0	2609	36.7	2419	34.1	7101
D.B.	366 (mean 105")	4.6	1707	21.5	2653	33.5	3203	40.4	7929
G.R.	380	43.8	194	21.8	295	34.4	-	-	869

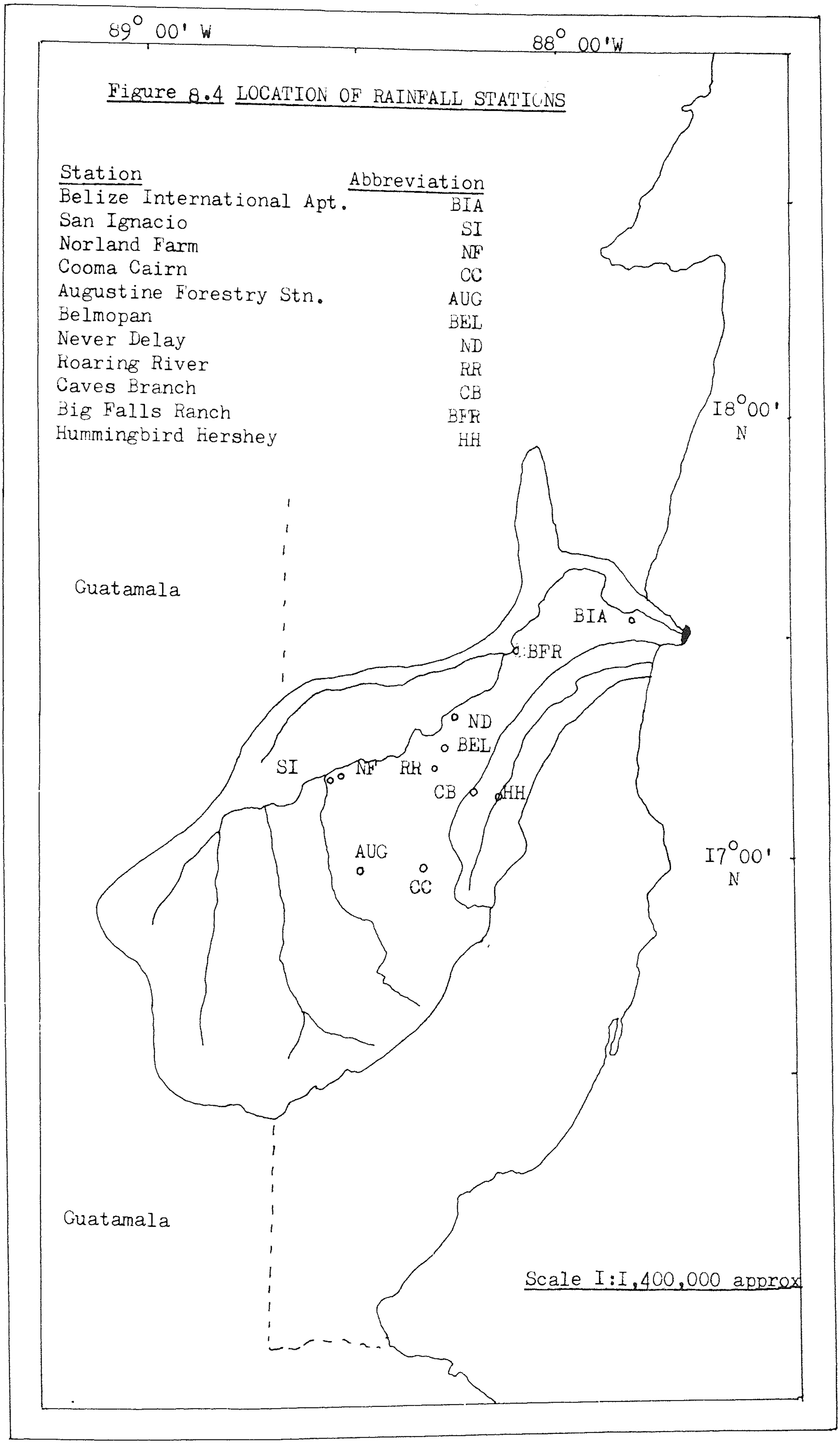


Figure 8.4 LOCATION OF RAINFALL STATIONS

Table 8.3 A.A.R. VALUES FOR CATCHMENT AREAS ABOVE GAUGING STATIONS

Gauging Station	Unweighted A.A.R. (m.m.)	Weighted A.A.R. (m.m.)	% Difference
B.V.	1621	1671	+3.0
C.R.	2162	2177	+0.7
I.C.	1777	1814	+2.0
B.BK.	1790	1821	+1.7
B.F.R.	1769	1808	+2.2
B.L.	1769	1808	+2.2
D.B.	1787	1816	+1.6
G.R.	2278	2299	+1.0

In all cases, the effect of weighting can be seen to increase values of A.A.R., but the implication is that in areas of isohyetal simplicity, differences will be very small.

8.4 CALCULATION OF CLIMATE VARIABLE R.S.M.D.

8.4.i Background

Faced with the problem of comparing stations where rainfall and soil moisture deficit information covered different periods, or where this information did not match, the F.S.R. attempted to describe these factors by separate statistical distributions and then combine them to deduce their differences(102). The work undertaken in the F.S.R. showed several important features of the rainfall-soil moisture deficit relationship.

1. That raw, end of the month S.M.D. values could be used to represent conditions on any particular day.
2. That the 5 year return level of S.M.D. could be taken as representative for the range of annual to 100 year event.
3. The 5 year return level could be viewed as an effective S.M.D. representative of typical conditions at any site(103).

These conclusions are useful to this research. The statistical analysis of rainfall/S.M.D. relationships are not entered into in this research - only one meteorological station being able to provide the data necessary. The outline procedures recommended by the F.S.R. for the evaluation of the R.S.M.D. variable were adapted for Belize data and are listed below.

1. To evaluate the 2 day 5 year rainfall event.
2. To calculate the 1 day 5 year event from this by tabulating the 1 day/2 day relationship.
3. To modify the 1 day 5 year event for point rainfall by the use of an areal reduction factor (A.R.F.).
4. To subtract the end of the month S.M.D. value from the 1 day 5 year event, to provide a value of R.S.M.D. for regression.

While Belize International Airport is the meteorological station to provide data for the calculation of evapo-transpiration and thereby the soil moisture deficit, basic rainfall data is collected throughout Belize at various stations. The selection of useful data was limited by their lengths of record. Table 8.4 below lists the most suitable for analysis.

Table 8.4 RAINFALL RECORDS USED IN ANALYSIS

Rainfall Station	Period of records (dates inclusive)
Belize International Airport	1960 - 1981
San Ignacio	1930 - 48, 1951 - 55, 1965 - 81
Cooma Cairn	1965 - 1981
Norland Farm	1954 - 1970

Daily totals of records longer than ten years' duration were used. Breaks in records were inconvenient but such circumstances reflect the limitations commonly found in developing countries and in such circumstances, it is necessary to use the maximum amount of data.

8.4.ii The calculation of 1 day and 2 day 5 year return rainfall events

Using nearly 7,000 rainfall stations, the F.S.R. is able to determine linking relations between various durations of rainfall, some of which are

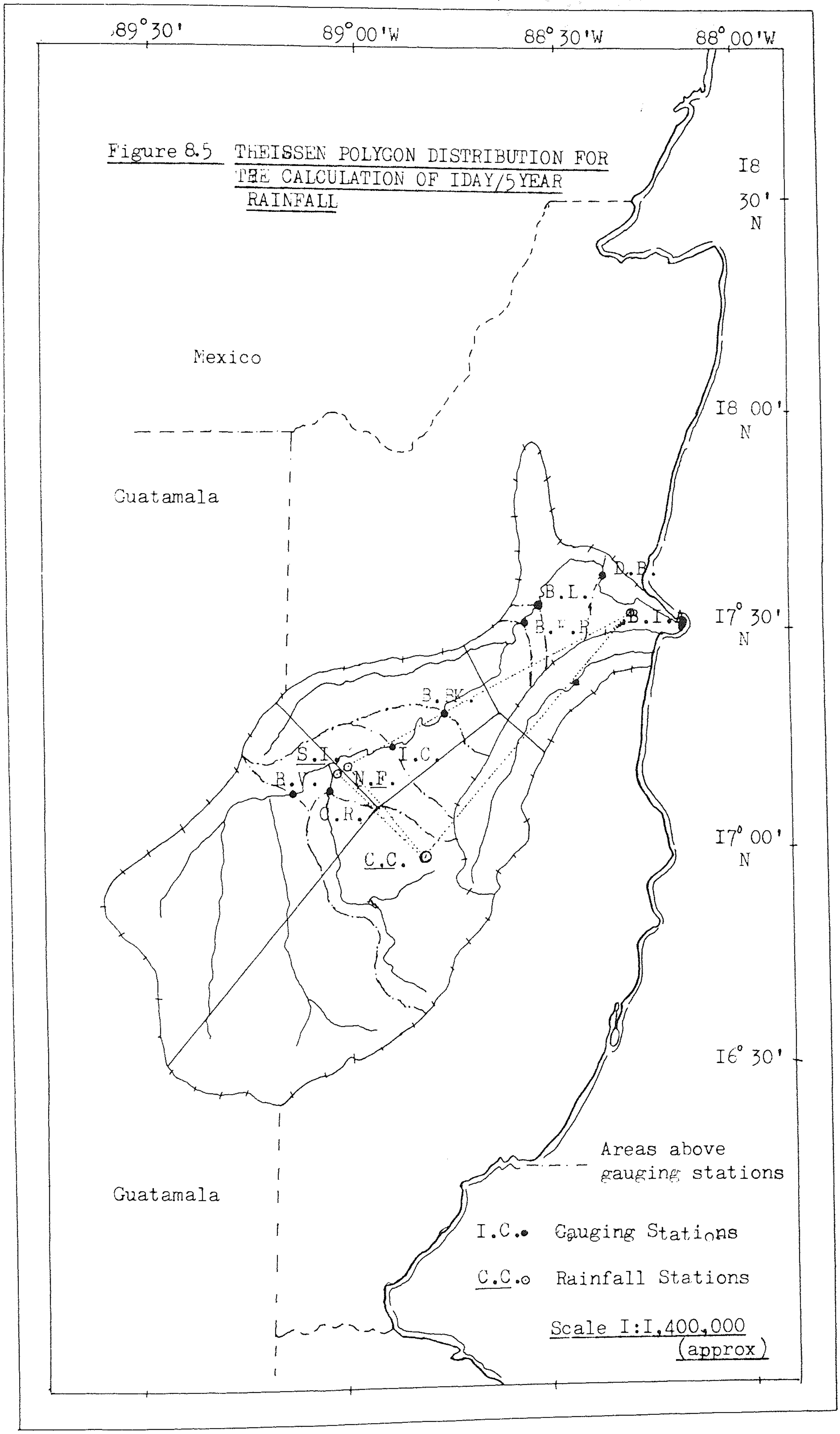


Figure 8.5 THEISSEN POLYGON DISTRIBUTION FOR THE CALCULATION OF IDAY/5YEAR RAINFALL

considered later. Such analysis was clearly impossible with Belize data. Table 8.5 below presents the values of the 1:2 day ratio, the 2 day 5 year rainfall return elicited by the listing of events and the calculated 1 day 5 year rainfall, for the four stations shown above in table 8.4. The data upon which the values given in table 8.5 below are calculated, are given for convenience, at the end of this chapter, in tables 8.12 to 8.14.

Table 8.5 CALCULATED 1 DAY 5 YEAR RAINFALL RETURNS

Rainfall Station	2 day 5 year rainfall (m.m.)	1:2 day ratio	Calculated 1 day 5 year rainfall (mm)
B.I.A.	199.8	0.78	155.8
S.I.	130.4	0.76	99.1
C.C.	195.0	0.72	140.4
N.F.	127.5	0.77	98.2

It is interesting to note that the 1:2 day ratios given above are very consistent and are also very similar to those determined by the F.S.R. for the United Kingdom. Table 8.6 below illustrates this and indicates that regional location does not necessarily alter such relationships and that where levels of average annual rainfall (A.A.R.) are similar, such relationships may be transferable.

Table 8.6 1:2 DAY RATIOS (U.K. AND BELIZE, BY A.A.R. BANDS)

A.A.R. Band (m.m.)	F.S.R. U.K.value	Belize value
1400-2000	0.75	0.76 (San Ignacio)
2000-2800	0.74	0.78 (Belize Airport)
2400-4000	0.73	0.72 (Cooma Cairn)

With the calculation of 1 day 5 year return rainfall values, it was necessary, according to the adopted practises of the F.S.R., to calculate the Areal Reduction Factor (A.R.F.) for point rainfall values, and apply this to the 1 day 5 year return rainfalls.

8.4.iii Calculation of the Areal Reduction Factor (A.R.F.)

The A.R.F. is expressed by the F.S.R. as a simple proportion of point rainfall within a given catchment area, which for return period T will increase with storm duration D. It will decrease for specified time T and D, with increasing area A. Variations of this proportion with changing values of T will be insignificant(104). The manner of calculation was as follows.

For the maximum (annual) areal event, the station rainfalls (R1) were noted. For these stations, the station annual maxima were also noted (R2). Ratios of R1:R2 were calculated to give the A.R.F. while the F.S.R. plots such values on national maps and interpolates values where necessary. This treatment was not suitable for Belize where only 11 stations could be used to cover an area of 9,000 km^2 and where accurate interpolation would be impossible. Table 8.7 below presents the average 1 day R1:R2 A.R.F. ratio for the period 1960-81 where records permit and converted 1 day 5 year rainfall values. A complete tabulation of the calculation of these values is given in Table 8.15 at the end of this chapter.

Table 8.7 1 DAY R1:R2 A.R.F. RATIOS (AVERAGE)

Rainfall Station	1 Day 5 Year rainfall (m.m.)	Average A.R.F. (from 11 stations)	Converted 1 day 5 year rainfall (mm)
B.1.A	155.8	0.62	96.6
S.I.	99.1	0.62	61.4
C.C.	140.4	0.62	87.0
N.F.	98.2	0.62	60.9

The overall weighted average A.R.F. as shown above, and calculated in table 8.15, can be seen to = 0.62 for 1 day events. Weighting for the average was made by simple account of length of record. A similarly derived value for 2 day events was 0.69. These values were somewhat lower than those obtained by the F.S.R. for similar sized U.K. catchments which were given as 0.83 and 0.85 respectively (105). They are, however, in close agreement to values obtained by previous research done in tropical regions(106), (107), where values of 0.65 and 0.70 were calculated. In the light of this satisfactory comparison, the A.R.F. value for the 1 day event was retained and used to give the converted 1 day values shown above.

Two points of consideration, aimed at the Belize data and its possible shortcomings, can be stated at this juncture.

1. That the distribution of rainfall stations is not even. This may possibly lead to a higher than correct value.
2. Where a limited number of stations are used, the annual maximum rainfall values for one station may dominate the selection of maximum areal events.

Despite these factors, it was thought appropriate to use actual Belize data, rather than import possibly spurious values from another world region.

With finally converted 1 day 5 year rainfall event values obtained for the area of the Belize and Sibun catchments, they were applied to catchment areas above gauging stations. Table 8.8. below presents these values according to % areal weightings by the Theissen method. The construction of this weighting is illustrated in map figure 8.5.

Table 8.8 FINAL 1 DAY 5 YEAR RAINFALL VALUES BY CATCHMENT AREAS ABOVE GAUGING STATIONS

Gauging Stations	Rainfall Stations (% weightings) S.I.	N.F.	B.I.A.	C.C.	Weighted 1 day 5 year rainfall (m.m.)
B.V.	54.4	0.0	0.0	45.6	73.1
C.R.	12.5	0.0	0.0	87.5	83.8
I.C.	42.0	4.4	0.0	53.6	75.1
B.BK.	38.8	8.8	0.0	52.4	74.8
B.F.R.	35.5	15.9	3.4	45.2	74.1
B.L.	35.0	15.8	4.6	44.6	74.4
D.B.	32.5	14.5	11.7	41.3	76.0
G.R.	0.0	0.0	27.8	72.7	90.1

With these values established, the final step of the process of the R.S.M.D. variable calculation was to define the soil moisture deficit by the balance between rainfall and evapotranspiration.

8.4.iv Calculation of the Soil Moisture Deficit (S.M.D.)

The focus of this research is upon the flood flows of the Belizé and Sibun rivers. These flood flows occur only during the "wet" season. The seasonal pattern of river discharge of these rivers has been described in the following way. ". . . the annual minimum flow in May is followed by a rapid rise during June and July, a less steep ascent in August and a final rise to the annual maximum in September/October, from which there is a gradual descent to May" (108). Consequently, the calculation of the soil moisture deficit of the catchments is concentrated upon the period September to January inclusive rather than the whole year, since it is soil moisture levels at this time that will influence flood discharge.

It was expected from a consideration of hydrological records and personal experience, that any soil moisture deficit would be small or insignificant and that for all practical purposes it could be ignored. However, this supposition had first to be substantiated.

The manner of calculating evapotranspiration has been widely discussed and the method according to Penman(109), with modifications by Chidley(110) was adopted. Data available for the period 1974-1977 inclusive from Belize International Airport was the only available. The potential evapotranspiration of an area is accepted to be modified by the conditions of vegetation and changes in the soil moisture deficit itself. When evaporation exceeds rainfall, the soil begins to dry out and a soil moisture deficit occurs. As the soil becomes drier, actual evapotranspiration is reduced. It may be assumed that evapotranspiration takes place at the potential rate until 50% of field capacity is reached, after which the rate falls to one tenth of the potential rate. The soil moisture content equal to 50% of field capacity is termed the "root constant" and will vary with vegetational type(111).

Using the potential evapotranspiration values according to Penman calculations, a series of values of root constants, reduction rates and vegetational coverages were applied. In this way several ranges of estimated S.M.D. values were obtained rather than attempting to calculate S.M.D. values that would be fixed by parameters, which in practice are difficult to define. Table 8.9 below lists the ranges of the values of the parameters

Table 8.9 RANGE OF EVEPOTRANSPIRATION PARAMETERS USED IN THE CALCULATION OF SOIL MOISTURE DEFICITS

Root constants (m.m.)			Albedo	Reduction Factor	% Forest	% Mixed	% Grass
Forest	mixed	grass	rate				
200	140	60	0.31, 0.22	0.1	50	35	15
200	140	60	0.31, 0.22	0.2	50	35	15
200	140	60	0.31, 0.22	0.3	50	35	15
250	200	90	1.31, 0.22	0.1	50	35	15
250	200	90	0.31, 0.22	0.2	50	35	15
150	100	40	0.31, 0.22	0.1	50	35	15
150	100	40	0.31, 0.22	0.2	50	35	15

Vegetation maps were used for the calculation of % vegetation type, albedo values 0.31, 0.22 are alternative values representing the extreme reflectance levels(112). Root constants were values of those used commonly in hydrological practice.

Table 8.10 and 8.11 show values obtained for the two ranges including that most likely to give large S.M.D. values (table 8.10) and small S.M.D. values (table 8.11). It will be seen that in both cases, and especially that of table 8.11, soil moisture deficit levels are insignificant for the period September to January.

Consequently, the R.S.M.D. climate variable used in multiple regression analysis was simply the final value of the 1 day 5 year return rainfall, presented for catchment areas above gauging stations, in table 8.8.

TABLE 8.10 MAXIMUM SOIL MOISTURE DEFICITS

Root constants : Forest - 200mm (% weighting 50%)
Mixed - 140mm (% weighting 35%)
Grassland - 60mm (% weighting 15%)
Reduction factor - 0.30

Month	Rainfall (mm)	Evap. 0.31	Evap. 0.22	SMD 0.31	SMD 0.22	SMD 0.22	Weighted SMD
Jul 74				200	200	200	
Aug 74	131	150	171	206	206	212	207
Sep 74	252	126	143	80	97	179	101
Oct 74	443	102	116	0	0	0	0
Nov 74	97	93	107	0	10	10	5
Dec 74	193	80	93	0	0	0	0
Jan 75	239	84	97	0	0	0	0
Feb 75	29	108	124	79	95	71	83
Mar 75	26	81	90	134	143	90	131
Apr 75	1	160	182	228	191	144	202
May 75	0	162	184	277	239	199	252
Jun 75	12	158	178	320	283	249	297
Jul 75	63	166	188	351	314	287	328
Aug 75	123	157	178	361	324	303	340
Sep 75	412	113	128	62	40	19	48
Oct 75	476	116	133	0	0	0	0
Nov 75	157	97	111	0	0	0	0
Dec 75	147	88	101	0	0	0	0
Jan 76	1025	79	91	0	0	0	0
Feb 76	73	95	109	22	36	36	29
Mar 76	7	154	175	169	153	103	153
Apr 76	18	154	175	232	194	150	206
May 76	91	171	193	256	218	181	231
Jun 76	666	111	125	0	0	0	0
Jul 76	12	160	181	148	142	93	138
Aug 76	209	151	171	90	104	55	90
Sep 76	316	127	144	0	0	0	0
Oct 76	106	115	131	9	25	25	17
Nov 76	216	90	103	0	0	0	0
Dec 76	381	43	50	0	0	0	0
Jan 77	43	88	101	45	58	58	52
Feb 77	73	89	102	61	87	68	71
Mar 77	50	146	165	157	153	103	147
Apr 77	58	131	150	209	175	130	185
May 77	100	146	166	223	189	150	200
Jun 77	233	129	145	119	101	124	113
Jul 77	407	152	172	0	0	0	0
Aug 77	118	156	177	38	59	59	49
Sep 77	313	131	148	0	0	0	0
Oct 77	86	115	131	29	45	45	37
Nov 77	51	89	102	67	96	71	78
Dec 77	415	78	90	0	0	0	0
Jan 78	151	85	99	0	0	0	0
Feb 78	9	68	83	59	74	64	65
Mar 78	88	116	133	87	119	78	97
Apr 78	56	150	170	181	162	112	164
May 78	164	156	176	173	160	116	160
Totals	8336	5516					

TABLE 8.11 MINIMUM SOIL MOISTURE DEFICITS

Root constants : Forest - 150mm (% weighting 50%)
Mixed - 100mm (% weighting 35%)
Grassland - 40mm (% weighting 15%)
Reduction factor - 0.10

Month	Rainfall (mm)	Evap. 0.31	Evap. 0.22	SMD 0.31	SMD 0.22	SMD 0.22	Weighted SMD
Jul 74				200	200	200	
Aug 74	131	150	171	202	202	204	202
Sep 74	252	126	143	76	93	193	99
Oct 74	443	102	116	0	0	0	0
Nov 74	97	93	107	0	10	10	5
Dec 74	193	80	93	0	0	0	0
Jan 75	239	84	97	0	0	0	0
Feb 75	29	108	124	79	95	46	80
Mar 75	26	81	90	134	105	52	112
Apr 75	1	160	182	164	121	70	136
May 75	0	162	184	181	137	88	151
Jun 75	12	158	178	195	152	105	166
Jul 75	63	166	188	205	162	118	177
Aug 75	123	157	178	209	165	123	181
Sep 75	412	113	128	0	0	0	0
Oct 75	476	116	133	0	0	0	0
Nov 75	157	97	111	0	0	0	0
Dec 75	147	88	101	0	0	0	0
Jan 76	1025	79	91	0	0	0	0
Feb 76	73	95	109	22	36	36	29
Mar 76	7	154	175	152	108	56	122
Apr 76	18	154	175	166	122	72	136
May 76	91	74	83	149	120	71	127
Jun 76	666	54	60	0	0	0	0
Jul 76	12	80	90	68	78	44	68
Aug 76	209	65	74	0	0	0	0
Sep 76	316	39	44	0	0	0	0
Oct 76	106	69	79	0	0	0	0
Nov 76	216	90	103	0	0	0	0
Dec 76	381	43	50	0	0	0	0
Jan 77	43	88	101	45	58	42	49
Feb 77	73	79	91	51	76	44	59
Mar 77	50	147	167	148	107	55	120
Apr 77	58	130	148	157	115	64	128
May 77	100	119	136	159	116	68	130
Jun 77	233	98	110	24	0	0	12
Ju; 77	407	117	133	0	0	0	0
Aug 77	118	124	140	6	22	22	14
Sep 77	313	93	105	0	0	0	0
Oct 77	86	99	112	13	26	26	20
Nov 77	51	80	92	42	67	43	51
Dec 77	415	51	59	0	0	0	0
Jan 78	151	69	80	0	0	0	0
Feb 76	9	68	83	59	74	43	62
Mar 78	88	116	133	87	100	48	86
Apr 78	56	122	138	150	107	56	121
May 78	164	127	144	113	87	36	92
Totals	8336	4764					

TABLE 8.12 BELIZE INTERNATIONAL AIRPORT 1:2 DAY EVENT RATIOS AND RETURN PERIODS

1 Day:2 Day Rainfall Event Ratios				1 Day and 2 Day Rainfall Event Returns			
Year	1 Day (m.m.)	2 Day (m.m.)	1:2 Day Ratio	1 Day (m.m.)	2 Day (m.m.)	Recurrance (Years)	Rank (m)
1960	89.4	89.4	1.00	56.6	66.5	1.05	22
1961	194.6	194.6	1.00	56.7	77.7	1.05	21
1962	56.7	103.8	0.55	58.9	81.3	1.15	20
1963	102.4	128.8	0.80	61.2	83.8	1.20	19
1964	117.1	154.7	0.76	72.4	92.7	1.25	18
1965	110.7	169.9	0.65	85.6	94.9	1.35	17
1966	99.8	115.3	0.87	89.4	98.6	1.44	16
1967	58.9	66.5	0.89	91.9	103.8	1.53	15
1968	91.9	94.9	0.97	99.1	107.4	1.64	14
1969	99.1	112.6	0.88	99.8	112.6	1.77	13
1970	72.4	98.6	0.73	100.3	115.0	1.92	12
1971	133.6	173.2	0.77	102.4	115.3	2.09	11
1972	56.6	92.7	0.61	104.4	128.8	2.30	10
1973	116.8	157.7	0.74	110.7	154.7	2.56	9
1974	72.6	107.4	0.68	116.8	157.7	2.88	8
1975	169.4	223.2	0.76	122.3	169.9	3.29	7
1976	100.3	115.0	0.87	133.6	173.2	3.83	6
1977	104.4	192.8	0.54	151.9	192.8	4.60	5
1978	202.7	213.6	0.95	169.4	213.6	5.75	4
1979	151.9	239.8	0.63	194.6	223.2	7.67	3
1980	151.9	297.7	0.77	202.7	239.8	11.50	2
1981	61.2	77.7	0.79	228.9	297.7	23.00	1

Average 1 : 2 Day Ratio 0.78

2 Day 5 Year Return Rainfall = 199.8 mm

TABLE 8.13 SAN IGNACIO 1:2 DAY EVENT RATIOS AND RETURN PERIODS

1 Day:2 Day Rainfall Event Ratios				1 Day and 2 Day Rainfall Event Returns			
Year	1 Day (m.m.)	2 Day (m.m.)	1:2 Day Ratio	1 Day (m.m.)	2 Day (m.m.)	Recurrance (Years)	Rank (m)
1930	65.3	69.3	0.94	34.5	43.7	1.02	40
1931	125.7	141.5	0.89	39.1	47.8	1.05	39
1932	114.3	200.7	0.57	42.2	48.5	1.08	38
1933	53.6	80.0	0.67	43.4	49.6	1.11	37
1934	39.1	65.0	0.62	44.5	50.3	1.14	36
1935	134.9	141.6	0.95	44.6	55.1	1.17	35
1936	44.5	55.4	0.80	45.7	55.4	1.20	34
1937	91.1	91.1	1.00	45.8	59.7	1.24	33
1938	33.0	63.5	0.52	46.0	63.4	1.27	32
1939	44.6	49.6	0.90	47.0	63.5	1.31	31
1940	45.7	87.6	0.52	49.8	65.0	1.35	30
1941	45.8	47.8	0.96	50.8	65.8	1.40	29
1942	47.0	72.5	0.65	53.3	69.3	1.45	28
1943	34.5	50.3	0.69	53.6	71.4	1.50	27
1944	42.2	45.2	0.93	57.1	72.3	1.56	26
1945	86.1	110.5	0.78	57.2	72.4	1.62	25
1946	62.7	63.4	0.99	59.0	72.5	1.68	24
1947	85.3	89.4	0.95	59.4	79.8	1.75	23
1948	57.1	86.1	0.66	61.0	80.0	1.83	22
1951	87.4	87.4	1.00	61.1	86.1	1.91	21
1952	96.3	197.8	0.49	62.7	87.1	2.00	20
1953	53.3	55.1	0.96	64.8	87.4	2.10	19
1954	70.6	90.2	0.78	65.3	87.5	2.21	18
1965	65.8	65.8	1.00	70.6	89.4	2.47	17
1966	74.7	115.1	0.65	77.5	90.2	2.63	16
1967	41.9	48.8	0.86	79.0	91.1	2.80	15
1968	79.0	92.5	0.85	80.3	92.5	3.00	14
1969	54.1	54.9	0.99	85.3	95.0	3.23	13
1970	94.7	132.6	0.71	86.1	96.8	3.50	12
1971	104.6	127.5	0.82	87.4	104.6	3.82	11
1972	61.1	71.4	0.86	88.9	110.5	4.20	10
1973	46.0	87.1	0.53	91.1	127.5	4.67	9
1974	64.8	72.4	0.90	94.7	132.6	5.25	8
1975	49.8	79.8	0.62	101.6	141.5	6.00	7
1976	59.4	95.0	0.63	104.6	141.6	7.00	6
1977	101.6	190.5	0.53	114.3	171.2	8.40	5
1978	80.3	96.8	0.83	118.1	174.0	10.50	4
1979	88.9	171.2	0.52	125.7	190.5	14.00	3
1980	118.1	174.0	0.69	134.9	197.8	21.00	2
1981	34.3	68.6	0.50	196.3	200.7	42.00	1

Average 1 : 2 Day Ratio 0.76

2 Day 5 Year Return Rainfall = 130.4 mm.

TABLE 8.14 NORLAND FARM AND COOMA CAIRN 1:2 DAY EVENT RATIOS AND RETURN PERIODS

NORLAND FARM

1 Day:2 Day Rainfall Event Ratios — 1 Day and 2 Day Rainfall Event Returns

Year	1 Day (m.m.)	2 Day (m.m.)	1:2 Day Ratio	1 Day (m.m.)	2 Day (m.m.)	Recurrance (Years)	Rank (m)
1954	76.2	84.6	0.90	36.8	50.8	1.06	17
1954	58.9	102.9	0.57	37.9	58.2	1.13	16
1956	41.9	50.8	0.82	41.9	59.6	1.20	15
1957	125.7	132.6	0.95	50.8	59.7	1.29	14
1958	57.6	77.5	0.74	57.6	69.9	1.38	13
1959	156.0	159.5	0.98	58.2	74.9	1.50	12
1960	95.3	96.3	0.99	58.4	77.5	1.64	11
1961	99.8	154.4	0.65	58.9	84.6	1.80	10
1962	36.8	54.7	0.62	69.9	94.7	2.00	9
1963	44.5	63.5	0.70	73.2	95.8	2.25	8
1964	69.9	94.7	0.74	73.7	96.5	2.57	7
1965	58.4	96.5	0.61	74.9	102.9	3.00	6
1966	58.2	58.2	1.00	76.2	120.7	3.60	5
1967	37.9	69.9	0.54	99.8	125.0	4.50	4
1968	74.9	74.9	1.00	111.0	132.6	6.00	3
1969	73.2	1250.0	0.59	125.7	154.4	9.00	2
1970	73.7	95.8	0.77	156.0	159.5	18.00	1

Average 1 : 2 Day Ratio = 0.77 — 2 Day 5 Year Return Rainfall = 127.5 mm.

COOMA CAIRN

Year	1 Day (m.m.)	2 Day (m.m.)	1:2 Day Ratio	1 Day (m.m.)	2 Day (m.m.)	Recurrance (Years)	Rank (m)
1965	126.4	214.6	0.59	50.8	59.9	1.08	12
1966	68.8	80.7	0.85	56.4	62.2	1.18	11
1967	75.7	117.3	0.65	67.6	80.7	1.30	10
1968	56.4	62.2	0.97	68.8	115.6	1.45	9
1969	135.6	186.2	0.73	74.7	117.3	1.63	8
1970	86.9	129.8	0.67	75.7	123.4	1.86	7
1971	159.3	271.5	0.59	86.4	129.8	2.16	6
1972	86.4	160.5	0.54	86.9	159.8	2.60	5
1976	74.7	115.6	0.65	126.4	160.5	3.25	4
1977	67.6	123.4	0.55	135.6	186.2	4.33	3
1978	54.4	159.8	0.97	154.4	214.6	6.49	2
1981	50.8	59.9	0.85	159.3	271.5	12.99	1

Average 1 : 2 Day Ratio = 0.72 — 2 Day 5 Year Return Rainfall = 195.0 mm.

Table 8.15 DATA FOR THE CALCULATION OF AREAL REDUCTION FACTORS

Year	B.I.A.			C.C.			B.F.R.			AUG			H.H.		
	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio
1960	9.7	78.7	0.12	-	-	-	-	-	-	-	-	-	-	-	-
1961	194.6	237.0	0.82	-	-	-	-	-	-	-	-	-	-	-	-
1962	317.0	317.0	1.00	-	-	-	-	-	-	-	-	-	-	-	-
1963	37.0	102.4	0.36	-	-	-	-	-	-	-	-	-	-	-	-
1964	1.8	165.1	0.11	-	-	-	-	-	-	-	-	-	-	-	-
1965	110.7	110.7	1.00	3.0	126.5	0.24	0.0	76.2	0.0	-	-	-	-	-	-
1966	133.6	133.6	1.00	1.8	68.0	0.26	100.3	100.3	1.00	-	-	-	-	-	-
1967	0.0	89.4	0.0	75.7	75.7	1.00	80.3	80.3	1.00	-	-	-	-	-	-
1968	108.7	108.7	1.00	15.5	56.4	0.28	84.6	84.6	1.00	-	-	-	-	-	-
1969	139.4	148.8	0.94	0.0	135.6	0.0	69.1	87.3	0.79	-	-	-	148.8	148.8	1.0
1970	23.1	153.4	0.15	7.9	86.9	0.09	56.6	102.6	0.55	-	-	-	190.2	190.2	1.0
1971	133.6	152.4	0.88	112.3	159.3	0.70	-	-	-	-	-	-	182.6	182.6	1.0
1972	13.0	99.3	0.13	38.6	113.5	0.34	-	-	-	-	-	-	139.4	139.4	1.0
1973	116.8	116.8	-	-	-	-	-	-	-	-	-	-	102.9	102.9	1.0
1974	47.0	85.0	0.55	-	-	-	-	-	-	78.8	78.8	1.00	82.8	82.8	0.88
1975	169.4	169.4	1.00	-	-	-	-	-	-	25.4	101.6	0.25	-	-	-
1976	195.8	195.8	1.00	34.3	74.4	0.46	-	-	-	26.7	86.1	0.31	-	-	-
1977	96.0	121.2	0.79	63.5	67.6	0.94	-	-	-	79.2	79.2	1.00	-	-	-
1978	10.9	202.7	0.05	154.4	154.4	1.00	-	-	-	264.2	264.2	1.00	-	-	-
1979	151.9	151.9	1.00	-	-	-	-	-	-	-	-	-	81.0	131.8	0.61
1980	38.9	228.9	0.17	-	-	-	-	-	-	-	-	-	184.7	240.0	0.77
1981	58.9	61.2	0.96	-	-	-	-	-	-	-	-	-	68.3	73.4	0.93
No. Years		22			11			6			5			9	
Av. A.R.F.		0.64			0.48			0.72			0.71			0.91	

R1 = Station rainfalls for maximum areal event

R2 = Station annual maxima

Table 8.15 DATA FOR THE CALCULATION OF AREAL REDUCTION FACTORS (continued)

Year	S.I.			N.F.			N.D.			R.R.			C.B.			BEL		
	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio	R1	R2	Ratio
1960	-	-	-	111.0	111.0	1.00	74.0	74.0	1.00	58.6	58.6	1.00	19.1	67.3	0.28	-	-	-
1961	-	-	-	0.0	69.9	0.0	133.4	133.4	1.00	64.6	89.7	0.72	152.4	152.4	1.00	-	-	-
1962	-	-	-	2.2	50.8	0.04	1.3	77.7	0.02	2.0	89.7	0.02	27.4	94.0	0.29	-	-	-
1963	-	-	-	82.0	82.0	1.00	58.6	122.7	0.48	57.9	116.8	0.50	114.3	114.3	1.00	-	-	-
1964	-	-	-	59.2	59.2	1.00	50.0	50.0	1.00	129.5	129.5	1.0	121.1	121.2	1.00	-	-	-
1965	31.5	77.5	0.41	25.4	82.8	0.31	-	-	-	-	-	-	-	-	-	-	-	-
1966	80.5	80.5	1.00	98.6	98.6	1.0	-	-	-	-	-	-	-	-	-	-	-	-
1967	58.7	79.0	0.74	60.1	78.0	0.08	-	-	-	-	-	-	-	-	-	-	-	-
1968	4.5	101.6	0.04	12.7	74.9	0.17	-	-	-	-	-	-	-	-	-	-	-	-
1969	37.8	109.7	0.34	51.8	73.2	0.71	-	-	-	-	-	-	-	-	-	-	-	-
1970	47.2	57.2	0.83	59.7	73.7	0.81	-	-	-	-	-	-	-	-	-	-	-	-
1971	104.6	104.6	1.00	109.2	109.2	1.00	-	-	-	-	-	-	-	-	-	-	-	-
1972	134.6	134.6	1.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1973	0.0	64.3	0.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1974	7.6	64.8	0.12	-	-	-	-	-	-	-	-	-	-	-	-	35.1	89.9	0.39
1975	96.0	96.0	1.00	-	-	-	-	-	-	-	-	-	-	-	-	49.3	125.5	0.39
1976	19.1	59.4	0.32	-	-	-	-	-	-	-	-	-	-	-	-	81.7	154.4	0.53
1977	88.9	101.6	0.88	-	-	-	-	-	-	-	-	-	-	-	-	23.6	109.7	0.22
1978	16.5	80.3	0.21	-	-	-	-	-	-	-	-	-	-	-	-	0.5	108.5	0.00
1979	0.0	99.1	0.0	-	-	-	-	-	-	-	-	-	-	-	-	95.5	103.1	0.93
1980	90.4	94.5	0.96	-	-	-	-	-	-	-	-	-	-	-	-	266.7	266.7	1.00
1981	0.0	55.4	0.0	-	-	-	-	-	-	-	-	-	-	-	-	24.9	62.7	0.40
No. years		17			12			5			5			5			8	
Av. A.R.F.		0.52			0.59			0.70			0.65			0.71			0.48	

OVERALL WEIGHTED MEAN A.R.F. = 0.62

Station abbreviations are given in map figure 8.4

CHAPTER 9 HYDROLOGICAL STUDIES TO DERIVE A DEPENDENT VARIABLE FOR MULTIPLE REGRESSION ANALYSIS

9.1 INTRODUCTION

The hydrological records upon which this chapter is based are obtained from a hydrological study of the Belize and Sibun rivers carried out between 1968 and 1972(113). One other source(114) was available, covering June 1981 to May 1982. Regrettably, the latter source was rejected as unsuitable for this research in that very few stage : discharge readings are given, too few to compile accurate rating curves. This inadequacy is particularly true of high flows.

While the main aim of this chapter is to present the methods and results of deriving a suitable dependent flood flow variable, it also gives, in more general terms, a background description of the flow regime of the Belize and Sibun rivers. Below, in table 9.1, are the recording stations and their periods of record.

Table 9.1 RIVER GAUGING STATIONS

Station	Location on map (scale 1:50,000)	Duration of record (inclusive)
Benque Viejo	Sheet 23, 815953	April 69-Nov 71
Cristo Rey	Sheet 23, 71890	June 68-Dec 71
Iguana Creek	Sheet 24, 953058	April 69-Dec 71
Banana Bank	Sheet 19, 112121	June 68-Dec 71
Big Falls Ranch	Sheet 20, 319351	July 69-Dec 71
Bermudan Landing	Sheet 15, 376416	July 68-Dec 71
Davis Bank	Sheet 16, 518509	Jan 70-Dec 71
Gracie Rock	Sheet 21, 467222	May 70-Dec 71

The accuracy of the discharge readings is reasonable, with the % standard errors at the 95% confidence level between ±5.8 and ±7.8. Greater inaccuracies may be expected where discharges are read from rating curves, the % standard error ranging from ±12.4 to ±26.6(115). The stage readings from the data source are listed as an average of morning and evening readings. Conversion of these stage readings by a short computer program (see Appendix D) was achieved by reference to the parameters of the rating curves. Printouts of listed gauge readings (metres) against discharge (cubic metres per second, or cumecs) were made at intervals of 0.02 metres. This presentation of stage : discharge relationships was found to be more convenient and less open to subjective misinterpretation than taking each value from the rating curve itself.

9.1.i Hydrological background

The Belize river catchment has a total area of 8242 km^2 (1:250,000) scale map interpretation) including the floodplain. It has two major tributaries, the Mopan and Macal. The former drains almost exclusively the Cretaceous limestone of the Vacca Plateau in the west of Belize and the east of Guatamala, only 11.3% of this major subcatchment is comprised of the impermeable lithologies of the Maya Mountains. By contrast, the Macal tributary drains the impermeable area of the Central Maya Mountains (granitic and associated metamorphic lithologies). Compared to the 3,400 km^2 catchment of the Mopan, the Macal has an area of about 1,900 km^2.

Not surprisingly, these two subcatchments have markedly different flow regimes which may be termed 'stable' for the Mopan, 'unstable' in the case of the Macal. The gauging stations Benque Viejo del Carmen and Cristo Rey, located on the tributaries, both lie approximately 15 km from their confluence at San Ignacio. Downstream of this confluence, a further 15 km, is Iguana Creek gauging station which records the highest peak flows within the catchment. Peak flows during flood successively diminish downstream at Banana Bank, Big Falls Ranch, Bermudan Landing and Davis Bank. Gracie Rock on the Sibun river lies in the floodplain, close to the floodplain upstream limit. The map A at 1:250,000 scale shows the location of these gauging stations.

9.1.ii Flow duration

The study of flow duration is a good method for the observation of flow levels over various durations of time, particularly since similar methods of presentation involving the use of consecutive high flows for specified return periods(116) are not suitable for use with the short term records available. Figure 9.1 is compiled from the complete year records of all stations and provides very useful information relating to flow characteristics, particularly of the Belize river. The most important points may be noted as follows, with stations grouped as indicated.

a) Mopan and Macal tributaries (Benque Viejo and Cristo Rey) :

1. The Mopan river contributes a much greater proportion of flow (between 1.6 and 2.0 times) for 97% of flow duration, than does the Macal. This is during low and moderate flows.

2. At periods of very high flow, this proportion drops greatly, such that the discharge of the Macal is equal to 90% of the discharge of the Mopan. Since the Mopan catchment area is 78% greater than that of the Macal, a rationalised runoff ratio of Mopan to Macal would be 1.0 to 1.6. Thus the implications of geology, topography and drainage network differences are substantiated.

3. During 3% of extreme high flows, the graphs of both branches display equally increased gradients, with Mopan flow increases indicating a high direct runoff contribution similar to that of the Macal. This was unsuspected and obviously relates to two factors - the increasing proportion of runoff from the impermeable portion of the catchment, and a rapid contribution to flow by underground river drainage.

4. Peak flow values of both tributaries are very similar.

b) Middle and Lower Belize River (Iguana Creek to Davis Bank Stations).

1. During the lowest (5%) of flows, all stations except Davis Bank exhibit the same level of discharge. It is suspected that the low level of Davis

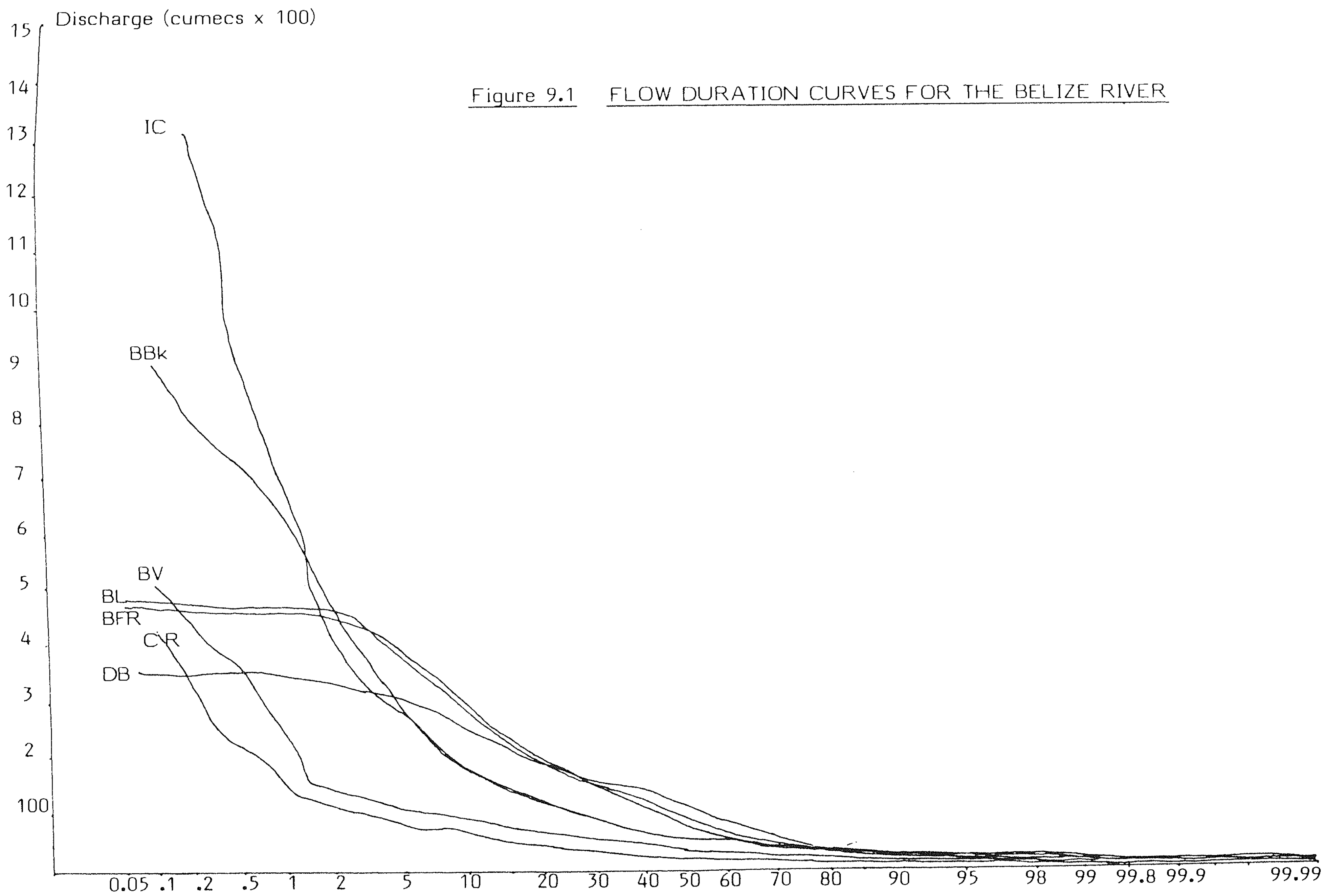


Figure 9.1 FLOW DURATION CURVES FOR THE BELIZE RIVER

Bank discharge is influenced by sea level factors(117), though precise survey information is not available to establish this.

2. It is obvious that the tributaries joining this reach of the river do not provide significant additions to mainstream discharge, at low flows.

3. For low to moderate flows (5% to 95%) the individual graphs diverge such that flow is proportional to the catchment area drained.

4. For the highest 5% of flows the pattern in item 3 above is reversed. The graphs of David Bank, Burmudan Landing and Big Falls Ranch show little or no increase in discharge, and peak flows are inversely related to catchment area.

5. It is significant that for all practical purposes, the volumes of flow at maximum levels at all the stations may be grouped into two types. These are :

   i) Flow that reaches an upper level, after which it does not increase. This is evident at :

Big Falls Ranch	(450 cumecs for max.2.5% duration)
Bermudan Landing	(460 cumecs for max.2.5% duration)
Davis Bank	(360 cumecs for max.2.5% duration)

   ii) Flow that increases to the maximum without reaching a plateau. This is evident at :

   Cristo Rey

   Iguana Creek

   Banana Bank

The processes behind this division are almost certainly those of overflow to the floodplain, from the river channel,combined with the attenuation of the peak by the river channel.

The behavioural patterns described above may be summarised so that they are focussed upon the necessity of use in multiple regression analysis as well as being descriptive hydrological groups.

Three main, important statements can be made, and are listed below.

1. Low stage - Discharge is similar at all stations.

2. Middle stage - Discharge is proportional to catchment area and the flood-plain does not influence peak flow.

3. High Stage - Discharge is inversely proportional to catchment area for all floodplain stations.

These stages relate approximately to 0 to 10%, 10% to 97% and 97% to 100% of the flow duration curve.

It is important to state that the stage changes from low to middle and middle to high take place at clearly defined parts of the graph. These changes can be identified by reference to figure 9.1. The case of the middle to high flow is very specific.

9.2 FLOOD DISCHARGE AS THE DEPENDENT VARIABLE FOR MULTIPLE REGRESSION-PEAK OVER THRESHOLD (P.O.T.) METHOD

Usually, river discharge as a dependent variable takes two forms(118).

1. As a mean annual flood (M.A.F.).

2. As a flood flow, a specified, selected return discharge.

In this research, both will be investigated for suitability as the dependent variable. Importantly, it also investigates the use of the descriptive parameters of a particular distribution, rather than simply alternative levels of flow, so that multiple regression analysis formulae can incorporate factors applicable to any discharge.

The main difficulty in the statistical analysis of discharge in Belize is the shortness of hydrological records. Various methods described in the F.S.R. were inspected and the Peak-Over-Threshold (P.O.T.) method was chosen as the most suitable for the following reasons(119), to extend these records.

1. It is based on a simple exponential series, the validity of which can be easily verified, even for short records.

2. It can be used to determine the mean annual or other return period flows. This is especially useful in the case of the Belize and Sibun river

catchments, where changes in vegetation, cultural and other factors will not vary over many years.

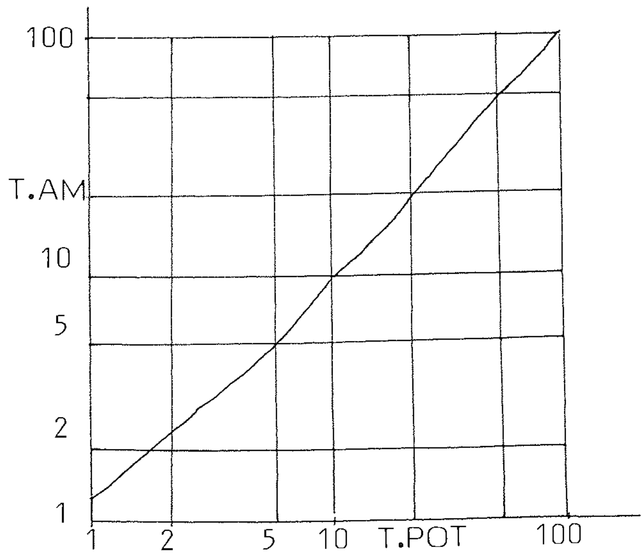
3. It is adaptable to both seasonal and non-seasonal variations of flow.

4. It can make use of homogeneous, short period records such as were available.

It is understood that the P.O.T. method must be used carefully in floodplain areas. The F.S.R. states that in these circumstances, caution must be used "where flood peaks may not follow an exponential (P.O.T.) form and indeed may register a maximum channel flow". This statement may be checked to discover which stations are affected by channel flow limitations and indicate quantities of water diverted to the floodplain. It will be seen that the correct understanding and interpretation of this basic fact may be used to advantage without compromising the validity of the exponential distribution of the P.O.T. series.

9.2.i The Theory of the P.O.T. method of calculating the dependent variable.

Langbein(120) has shown that for return periods of more than five years, the P.O.T. value of discharge and the series return period discharge are close, such that the two may be regarded as the same.



T.POT.	T.AM
0.50	1.16
1.00	1.58
1.45	2.00
2.00	2.54
5.00	5.52
10.00	10.50
50.00	50.50
100.00	100.50

Figure 9.2 RELATIONSHIP BETWEEN P.O.T. AND MAXIMUM SERIES FLOW

The theory of the P.O.T. series distribution of river peak discharge is extensively covered by the F.S.R.(121). It was from this work that the basic tenets of the distribution were obtained. Two alternative methods of data extraction are used in this research, since one lends itself to more convenient use with data from the floodplain stations, the other to use with the non-floodplain stations. They are, however, based upon the same fundamental principles of the P.O.T. theory, which are outlined below.

The method of data extraction termed 'Method 2' by the F.S.R. is used to explain the theory of the P.O.T. distribution, and it is this method that lends itself best to work with non-floodplain data. This method obviates the need of establishing a random (Poisson) distribution of flood peaks throughout the year, for return periods of more than one year. Since peaks in the flow of the Belize and Sibun rivers is seasonal, this is advantageous. F.S.R. also states that, concerning floodplain stations, the exponential assumption may be used at high threshold levels, close to maximum channel flows(122).

The exponential distribution of magnitudes is acknowledged, while their distribution within the year is ignored(123). The T year flood is found by treating the flow Q (peak flow) and the threshold value qo as a variable and deriving the value of Q (any flow) which is exceeded twice in T years, such that :

$$F\ (Q \quad Q(T)/Q(T) \quad qo) \ = \ 1 - \frac{1}{\lambda} T \qquad (9.2.1)$$

and where F ( ) is exponential, $Q(T) = qo + \beta \ \text{In.}\lambda \ + \ \beta \ \text{In. T}$ (9.2.2)

(124)

Where β is the exponential gradient and λ is the number of exceedences of qo, the threshold. Equation 9.2.2. provides the basic formula for the derivation of any peak discharge QT. The process of data extraction and the implementation of the P.O.T. distribution is as follows :

Noteable flood events are listed and a fixed number of exceedences (λ) of threshold (qo) are chosen, with λ = 1, 3 and 5 per year. The equations that link the unknown values of qo and exponential parameter (B) with those obtained from the raw data are(125):

$$qo\ (\text{threshold}) = \frac{M.q_{min}.\bar{q}}{M - 1} \qquad (9.2.3)$$

$$\beta\ (\text{exp. parameter}) = \frac{M(\bar{q} - q_{min}.)}{M - 1} \qquad (9.2.4)$$

where M = $N.\lambda$

N = number of years record

λ = exceedences per year

$\bar{q}$ = mean value of the peaks (whether 1, 3 or 5 per year)

qmin = minimum value of the peaks (whether 1, 3 or 5 per year)

Thus, the estimated T year flood is found from equation 9.2.2. which is most conveniently presented in the form : $Q(T) = qo + \beta(\ln\lambda + \ln T)$ (9.2.5)

Thus the T year discharge may be found by a simple listing of data and the calculation of the P.O.T. distribution parameters. However, before use, it is necessary to establish that the actual data to be used does indeed conform to an exponential distribution, since if it did not, the application of equation 9.2.5. would be inappropriate.

9.2.ii Checking the exponential assumption and the selection of most suitable exceedence (λ) for the T year flood

To verify the exponential assumption, the F.S.R.(126) recommends that the raw data discharge values are plotted on graphs against a 'reduced variate' y, where y is in the form :

$$y = \sum_{j=1} \frac{1}{n+1-j} \qquad (9.2.6)$$

For example, with n = 3 then $y_1 = \frac{1}{3}$, $y_2 = \frac{1}{3} + \frac{1}{2}$, $y_3 = \frac{1}{3} + \frac{1}{2} + \frac{1}{1}$ (127)

The plotting of these graphs represents the first determination of the validity of the exponential assumption, and by inspection, the graphs indicate the probable value of λ that is most suitable for use. Table 9.2 gives the raw discharge data, listed in order of magnitude that was used to obtain the parameters of the P.O.T. distribution, for all gauging stations. These parameter values are listed in table 9.4. Table 9.3 shows the data used for the plotting of the P.O.T. check graphs, giving values of discharge Q and reduced variate Y. These check graphs are shown in figures 9.3 to 9.10 inclusive. So as not to interrupt the text, all tables and figures are presented at the end of this chapter.

Inspection of the graphs 9.3 to 9.10 shows that while they may indicate the best fitting value of λ , this selection is subjective and in some cases a choice is not easy to make. In such circumstances, the F.S.R. recommends the use of the sampling variance and standard error of the distribution to determine the most suitable value of λ . They may be calculated by the following equations(128).

$$\text{Variance QT} = \frac{\beta^2}{N}\left[\frac{(1 - \ln\lambda - \ln T)^2}{N\lambda - 1} + (\ln\lambda + \ln T)^2\right] / \lambda \qquad (9.2.7)$$

whereas N = NO. of years data

$$\text{Standard error (s.e.)} = \sqrt{\text{Variance QT}} \qquad (9.2.8)$$

These statistics were calculated for all the distributions at all the gauging stations and the results are presented in table 9.6, which covers various values of N, λ and T.

The obvious choice of λ is that which presents the lowest sampling variance and standard error. However, as the F.S.R. is careful to emphasise, these values are estimated for the whole range of discharge versus y, while the P.O.T. method is essentially used to extend short records for use in the calculation of discharge at higher return periods. It is important to recognise therefore that if the plotting positions of discharge versus y is good at low returns, but not at high returns, then this value of λ would not be appropriate. The general rule, therefore, is to select λ with the lowest variance and s.e., as long as these values apply to high return periods.

Where distributions do not fit well at high return periods, the probability of the occurrence of these high flows may be determined by a probability test, that can effectively determine the best value of λ. The F.S.R. assumes that the highest magnitude flows are the most variable and that extreme values in this range should not necessarily cause alarm(129). The probability formula of these maximum flows is(130):

$$\text{Probability of } Qmax \leqslant q \quad = \quad \left[1-e^{-(q-qo)/\beta}\right]^N \qquad (9.2.9)$$

In the cases of the non-floodplain stations (Benque Viejo, Cristo Rey, Iguana Creek and Banana Bank), the $\lambda = 5$ distributions were seen to be the most suitable, as judged by both the check graphs and values of variance and standard error. In addition the probability of the maximum discharge values was checked using formula 9.2.9, and as shown in table 9.7, the use of $\lambda = 5$ was reaffirmed.

In contrast to these stations, the floodplain stations exhibited the best fits with the $\lambda = 1$ distributions at higher return periods, but their behaviour was not consistent. The lower portions of the check graphs for these stations showed consistent underestimates compared to the actual discharge values, where $\lambda = 3$ and $\lambda = 5$ were considered, $\lambda = 1$ distributions gave overestimates. In the higher portions of the graphs this pattern was reversed and a distinct "cross-over" point was noticed. While $\lambda = 1$ distributions gave the best fits, especially at higher return periods, even these did not seem satisfactory. The difficulties of applying the P.O.T. assumption in a floodplain region were apparent.

The F.S.R. examines and rejects the use of more flexible distributions and recommends an alternative method of data abstraction ('Method 1') to overcome these problems. In this method, values of the threshold (qo) are selected and in the case of floodplain stations, qo is made high. This depresses the exponential parameter β and makes growth of the distribution slow, thus reflecting more closely the true nature of discharge increase at the floodplain stations. In this method, the linking formulae are(131):

$$\beta = \bar{q} - qo \qquad (9.2.10)$$

and

$$\lambda = M/N \qquad (9.2.11)$$

The formula for the Q(T) discharge is the same as that for method 2, that is, equation 9.2.5. It can be seen clearly that for these stations, qo becomes the dominant factor in the estimation of the Q(T) flood and may approximate, for all intents and purposes, the maximum channel flow. The check graphs for the floodplain stations illustrates the distributions according to both method 1 and method 2. For the purpose of this research, the method 1 distributions were selected to apply to the floodplain stations, since they most closely reflect the distribution of actual discharge values.

9.2.iii Using the P.O.T. distribution for Mean Annual flood (M.A.F.)

The mean annual flood is a commonly used dependent variable(132), (133). The Flood Studies Report states "even when the exponential distribution is an inadequate description of (flood peak) data as a whole it does, in nearly all cases, represent flow values near to the threshold fairly closely and discrepancy when it does exist is due to failure of the distribution to represent the upper end of the data. There is therefore the possibility that P.O.T. model (abstraction method) 2 could be used in all circumstances to estimate floods of low return periods. One such flood is the mean annual flood.

Gumbel(134) has shown empirical evidence that river discharge values have an extreme value (Gumbel or E.V.I.) distribution, with a return period of 2.33 years. The F.S.R. describes the parameters of this distribution as being $U = U^1 + 0.5722\,\beta$. where $U^1 = qo + \beta \ \mathrm{In}.\lambda$

Thus $Q = qo + \beta \mathrm{In}.\lambda + 0.5772\,\beta$ (9.2.12)

Since in the E.V.I. distribution, a proportion of $e^{-e^{-0.5772}}$ of variate values are less than mean, while in the P.O.T. models a proportion of $e^{-\lambda}$ of annual maxiumum values are less than qo, then qo is less than the mean if and only if $e^{-\lambda}$ is less than $e^{-e^{-0.5772}}$, that is if λ is 0.5615. This is unlikely and would depend upon an extremely high value of qo(135). If the P.O.T. model assumption is used,

$$QM.A.F. = qo + 0.5722\beta \quad \text{where} = 1 \quad (9.2.13)$$

$$= qo + 1.2704\beta \quad \text{where} = 2 \quad (9.2.14)$$

$$= qo + 1.6758\beta \quad \text{where} = 3 \quad (9.2.15$$

9.3 THE SELECTION OF P.O.T. DISTRIBUTIONS AND PARAMETERS FOR REGRESION ANALYSIS

The ultimate aim of the use of the P.O.T. methods is to provide flow magnitudes, or parameters that describe flow magnitudes, as dependent variables in multiple regression analysis. Section 9.2 has illustrated the methods by which the P.O.T. distributions may be described and the methods by which the most suitable of these distributions may be selected. It has done this for both the T year flood and the mean annual flood.

Section 9.2 has shown, however, that in Belize (and this is no doubt applicable to other regions) where floodplain and non-floodplain data is used, a significant effect upon the P.O.T. distribution parameters. For non-floodplain stations, $\lambda = 5$ distributions, obtained from method 2 are seen to be most suitable. For floodplain stations method 1, $\lambda = 1$ values can be seen to be most suitable. In the case of M.A.F. values, $\lambda = 3$ distributions were seen to be the most suitable for non-floodplain stations when they and $\lambda = 1$ were plotted against actual discharge values as seen below in figure 9.11. $\lambda = 1$ values were seen to be the most suitable for the floodplain stations.

These facts mitigate for the separate regression of floodplain and non-floodplain station data. This, however, would lead to severe limitation of independent variables available for use in such regression, the maximum number would be three. It would also prevent the regionalisation of the resultant regression formulae.

With these factors in mind, it was determined that the most appropriate manner of presenting the dependent variables for regression was not to regress the P.O.T. derived value of discharge for particular return periods, but to regress the parameters of qo and β themselves against catchment characteristics. In this way all station values of β and qo could be regressed, giving a maximum total of seven independent variables and the appropriate value of could be inserted into equation 9.2.5., when the T year discharge was calculated. Table 9.8 below gives the details of the parameters used in regression. Chapter 10 'Multiple Regression Analysis' gives details of the results.

Table 9.8 DEPENDENT VARIABLES USED IN REGRESSION ANALYSIS

	NON FLOODPLAIN STATIONS				FLOODPLAIN STATIONS			
Case No.	1	2	3	4	5	6	7	8
Station name	B.V.	C.R.	I,C,	B.BK.	B.F.R.	B.L.	D.B.	G.R.
Q(T) Flood								
qo	28.39	-4.67	117.80	123.23	400.0	400.0	280.0	305.0
β	115.30	196.07	407.79	269.38	26.33	20.20	28.00	12.50
λ	5	5	5	5	2	1.5	1	1
M.A.Flood								
qo	58.90	37.93	166.40	170.56	328.65	362.17	267.00	302.50
β	127.39	243.68	545.40	336.64	79.05	35.33	40.00	15.00
λ	3	3	3	3	1	1	1	1

Table 9.2 DATA FOR USE IN P.O.T. MODEL (FLOW PEAKS IN CUMECS LISTED IN ORDER OF MAGNITUDE)

Order No.	No.of Years Data	B.V. 5	C.R. 3	I.C. 3	B.BK 5	B.F.R. 3	B.L. 4	D.B. 2	G.R. 2
1		510.0	600.0	1350.0	1110.0	443.0	426.0	327.0	325.0
2		373.0	505.0	1349.0	950.0	435.0	425.0	310.0	310.0
3		255.0	300.0	900.0	790.0	425.0	422.0	287.0	268.0
4		217.0	280.0	865.0	730.0	425.0	420.0	252.0	228.0
5		182.0	195.0	790.0	562.0	420.0	415.0	249.0	207.0
6		175.0	194.0	447.0	505.0	410.0	413.0	212.0	200.0
7		162.0	158.0	385.0	430.0	382.0	398.0	211.0	158.0
8		143.0	157.0	270.0	420.0.	355.0	375.0	186.0	143.0
9		140.0	120.0	270.0	380.0	353.0	372.0	162.0	128.0
10		138.0	115.0	270.0	330.0	341.0	371.0	123.0	59.0
11		130.0	110.0	230.0	330.0	317.0	357.0		
12		128.0	64.0	227.0	315.0	284.0	356.0		
13		120.0	41.0	194.0	303.0	213.0	353.0		
14		113.0	23.0	192.0	288.0	131.0	330.0		
15		107.0	8.0	145.0	288.0	104.0	290.0		
16		102.0			273.0		285.0		
17		96.0			257.0		285.0		
18		91.0			250.0		198.0		
19		80.0			240.0		193.0		
20		69.0			225.0		186.0		
21		68.0			202.0				
22		67.0			193.0				
23		47.5			165.0				
24		46.0			145.0				
25		33.0			134.0				

KEY FOR TABLE 9.2

Underlining indicates uisage :-

1. all readings used for λ = 5 (5 peaks exceeding qo per year)
2. indicates use when λ = 3 (3 peaks exceeding qo per year)
3. indicates use when λ = 1 (1 peak exceeding qo per year)

Table 9.3 PLOTTING POSITIONS OF REDUCED VARIATE y AND DISCHARGE Q. BELIZE RIVER

$\lambda = 5$

B.V.		C.R.		I.C.		B.BK.		B.F.R.		B.L.		D.B.	
Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q
0.040	33.0	0.067	8.4	0.067	145.0	0.40	134.0	0.067	104.0	0.050	186.0	0.100	123.0
0.082	46.0	0.138	23.0	0.138	192.0	0.082	145.0	0.138	131.0	0.103	193.0	0.211	162.0
0.125	47.5	0.215	41.0	0.215	194.0	0.125	165.0	0.215	213.	0.158	198.0	0.336	186.0
0.171	67.0	0.298	64.0	0.298	227.0	0.171	193.0	0.298	284.0	0.214	235.0	0.479	211.0
0.218	68.0	0.389	110.0	0.389	230.0	0.218	202.0	0.389	317.0	0.276	285.0	0.646	212.0
0.268	69.0	0.489	115.0	0.489	270.0	0.268	225.0	0.489	341.0	0.414	330.0	0.846	249.0
0.321	80.0	0.600	120.0	0.600	270.0	0.321	240.0	0.600	353.0	0.491	353.0	1.036	252.0
0.376	91.0	0.732	157.0	0.723	271.0	0.376	250.0	0.723	355.0	0.575	356.0	1.429	287.0
0.435	96.0												
0.498	102.0	0.868	158.0	0.868	385.0	0.435	257.0	0.868	382.0	0.666	357.0	1.929	310.0
0.564	107.0	1.035	194.0	1.035	447.0	0.498	273.0	1.035	410.0	0.766	371.0	2.929	327.0
0.636	113.0	1.235	195.0	1.235	790.0	0.564	288.0	1.235	420.0	0.932	372.0		
0.713	120.0	1.485	280.0	1.485	865.0	0.636	288.0	1.485	425.0	1.057	375.0		
0.797	128.0	1.818	300.0	1.818	900.0	0.713	303.0	1.818	425.0	1.200	398.0		
0.885	130.0	2.318	505.0	2.318	1349.0	0.797	315.0	2.318	435.0	1.367	413.0		
0.988	138.0	3.318	600.0	3.318	1350.0	0.888	330.0	3.318	443.0	1.567	415.0		
1.099	140.0					0.988	330.0			1.817	420.0		
1.244	143.0					1.099	380.0			2.150	422.0		
1.366	162.0					1.224				2.650	425.0		
1.533	175.0					1.366	430.0			3.650	426.0		
1.733	182.0					1.533	505.0						
1.983	217.0					1.733	562.0						
2.316	255.0					1.983	730.0						
2.816	373.0					2.316	790.0						
						2.316	950.0						
2.816	510					3.816	1110.0						

Table 9.3 PLOTTING POSITIONS OF REDUCED VARIATE y AND DISCHARGE Q. BELIZE RIVER (continued)

$\lambda = 3$

B.V.		C.R.		I.C.		B.BK.		B.F.R.		B.L.		D.B.	
Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q
0.067	68.0	0.111	64.0	0.111	227.0	0.067	193.0	0.111	213.0	0.083	285.0	0.167	212,0
0.138	91.0	0.236	157.0	0.236	270.0	0.138	250.0	0.236	341.0	0.174	290.0	0.367	249.0
0.215	102.0	0.379	158.0	0.379	270.0	0.215	273.0	0.379	353.0	0.274	356.0	0.617	252.0
0.298	120.0	0.547	194.0	0.547	385.0	0.298	288.0	0.549	355.0	0.385	357.0	0.950	287.0
0.389	128.0	0.747	195.0	0.747	790.0	0.389	315.0	0.747	420.0	0.510	371.0	1.450	310.0
0.489	138.0	0.996	280.0	0.996	865.0	0.489	330.0	0.996	425.0	0.653	372.0	2.450	327.0
0.600	140.0	1.329	300.0	1.329	900.0	0.600	330.0	1.329	425.0	0.820	375.0		
0.723	143.0	1.829	505.0	1.829	134.0	0.723	380.0	1.829	425.0	1.020	415.0		
0.868	162.0	2.829	600.0	2.829	1350.0	0.868	420.0	2.829	443.0	1.270	420.0		
1.035	175.0					1.035	430.0			1.603	422.0		
1.235	182.0					1.235	562.0			2.103	425.0		
1.485	217.0					1.485	730.0			3.103	426.0		
1.818	255.0					1.818	790.0						
2.318	373.0					2.318	950.0						
3.318	510.0					3.318	1110.0						

= 3

Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q	Y	Q
0.200	120.0	0.333	280.0	0.333	385.0	0.200	380.0	0.333	355.0	0.250	371.0	0.500	287.0
0.450	175.0	0.833	300.0	0.833	1349.0	0.450	420.0	0.833	425.0	0.583	372.0	1.500	327.0
0.783	255.0	1.833	600.0	1.833	1350.0	0.783	430.0	1.833	443.0	1.083	422.0		
1.283	373.0					1.283	950.0			2.083	426.0		
2.283	510.0						111.0						
							2.283						

Table 9.3 PLOTTING POSITIONS OF REDUCED VARIATE y AND DISCHARGE Q. BELIZE RIVER (continued)

G.R., λ =5		G.R., λ = 5		G.R., λ = 1	
Y	Q	Y	Q	Y	Q
0.100	59.0	0.167	143.0	0.500	310.0
0.211	128.0	0.367	207.0	1.500	325.0
0.336	143.0	0.617	228		
0.479	158.0	0.950	268.0		
0.646	200.0	1.450	310.0		
0.846	207.0	2.450	325.0		
1.036	228.0				
1.429	268.0				
1.929	310.0				
2.929	325.0				

Table 9.4 P.O.T. PARAMETERS FOR ALL GAUGING STATIONS (ABSTRACTION METHOD 2))

Station	N	λ	M	mean q	q min	qo	β
BENQUE VIEJO	5	5	25	143.7 cumecs	3B.0 cumecs	28.39 cumecs	115.30
	5	3	15	186.9	68.0	58.90	127.39
	5	1	5	286.8	120.0	67.90	208.25
CRISTO REY	3	5	15	191.4 cumecs	8.4 cumecs	4.67 cumecs	196.07
	3	3	9	272.6	64.0	37.93	234.68
	3	1	3	361.7	280.0	239.15	122.55
IGUANA CREEK	3	5	15	525.6 cumecs	145.0 cumecs	117.80 cumecs	407.79
	3	3	9	711.8	227.0	166.40	545.40
	3	1	3	1028.0	385.0	63.50	964.50
BANANA BANK	5	5	25	392.6 cumecs	134.0 cumecs	123.23 cumecs	269.38
	5	3	15	507.2	193.0	170.56	336.64
	5	1	5	658.0	380.0	310.50	347.50
BIG FALLS RANCH	3	5	15	335.9 cumecs	104.0 cumecs	87.44 cumecs	248.46
	3	3	9	378.9	213.0	192.26	196.64
	3	1	3	407.7	355.0	328.65	79.05
BERMUDAN LANDING	4	5	20	341.0 cumecs	186.0 cumecs	177.84 cumecs	163.16
	4	3	12	376.2	285.0	276.71	99.49
	4	1	4	397.5	371.0	362.17	35.33
DAVIS BANK	2	5	10	231.9	123.0	110.90	121.0
	2	3	6	272.8	212.0	199.84	72.96
	2	1	2	307.0	287.0	267.0	40.0
GRACIE ROCK	2	5	10	207.6	59.0	42.60	164.4
	2	3	6	246.8	143.0	122.2	124.6
	2	1	2	317.5	310.0	302.5	15.0

Table 9.5 P.O.T. PARAMETERS FOR FLOODPLAIN STATIONS (ABSTRACTION METHOD 1)

Gauging Station	N	λ	M	Q O	β
B.F.R.	3	2	6	400	26.33
B.L.	4	1.5	6	400	20.20
D.B.	2	1	2	280	28.00
G.R.	2	1	2	305	12.50

Table 9.6 VARIANCE AND STANDARD ERRORS OF P.O.T. DISTRIBUTIONS (METHOD 2)

T =	5 years		10 years		25 years		50 years		100 years	
	V	S.e.	V.	S.e.	V.	S.e.	V.	S.e.	V.	S.e.
B.V.										
$\lambda = 1$	23271	152.5	49665	222.9	100545	317.1	151129	388.8	212131	406.6
$\lambda = 3$	8160	90.3	12960	113.8	21016	145.0	28406	168.5	36906	192.1
$\lambda = 5$	5618	75.0	8325	91.2	12722	112.8	16665	129.1	21140	145.4
C.R.										
$\lambda = 1$	13899	117.9	30793	175.5	64194	253.4	97840	312.8	138706	327.4
$\lambda = 3$	47107	217.0	75195	274.2	122486	350.0	165940	407.4	216003	464.8
$\lambda = 5$	27461	165.7	40776	201.9	62432	249.9	81872	286.1	103964	322.4
I.C.										
$\lambda = 1$	859909	927.3	1905367	1380.4	3972121	1193.0	6054054	2460.0	8582668	2929.6
$\lambda = 3$	254055	504.0	405538	636.8	660584	812.8	894936	946.0	1164932	1079.0
$\lambda = 5$	118789	344.7	176381	420.0	270059	519.7	354148	595.1	449711	676.6
B.BK.										
$\lambda = 1$	64798	254.5	138290	371.9	279961	529.1	420811	648.1	590667	768.5
$\lambda = 3$	56981	238.7	90503	300.8	146758	383.1	198367	445.0	257727	507.7
$\lambda = 5$	30666	175.1	45441	213.5	69445	263.5	90968	201.6	115934	339.7
B.F.R.										
$\lambda = 1$	57820	76.0	12182	113.2	26760	163.4	40710	102.8	57713	240.2
$\lambda = 3$	29795	172.6	47561	218.1	77472	278.3	106117	325.8	136621	369.6
$\lambda = 5$	44097	210.0	65477	255.9	100253	316.6	13169	362.6	166945	408.6
B.L.										
$\lambda = 1$	847.0	29.1	1831	42.8	3745	61.2	5658	75.2	7970	89.3
$\lambda = 3$	6268	79.2	9975	99.9	16201	127.3	21841	147.8	28495	168.8
$\lambda = 5$	14136	118.9	20964	144.8	32059	179.0	42015	205.0	53309	230.9
D.B.										
$\lambda = 1$	2370	48.7	5599	74.8	12227	110.6	19027	137.9	27364	165.4
$\lambda = 3$	7024	83.8	11285	106.2	18490	136.0	25128	158.5	32302	179.7
$\lambda = 5$	15973	126.4	23784	154.2	36515	191.1	47764	219.0	60965	246.0
G.R.										
$\lambda = 1$	333	18.3	787.4	28.1	1719	41.5	2676	51.7	3848	62.0
$\lambda = 3$	20485	143.1	32913	181.4	53927	232.2	73827	270.7	95627	309.2
$\lambda = 5$	29487	171.1	43906	209.5	67406	259.6	88542	297.6	112542	335.5

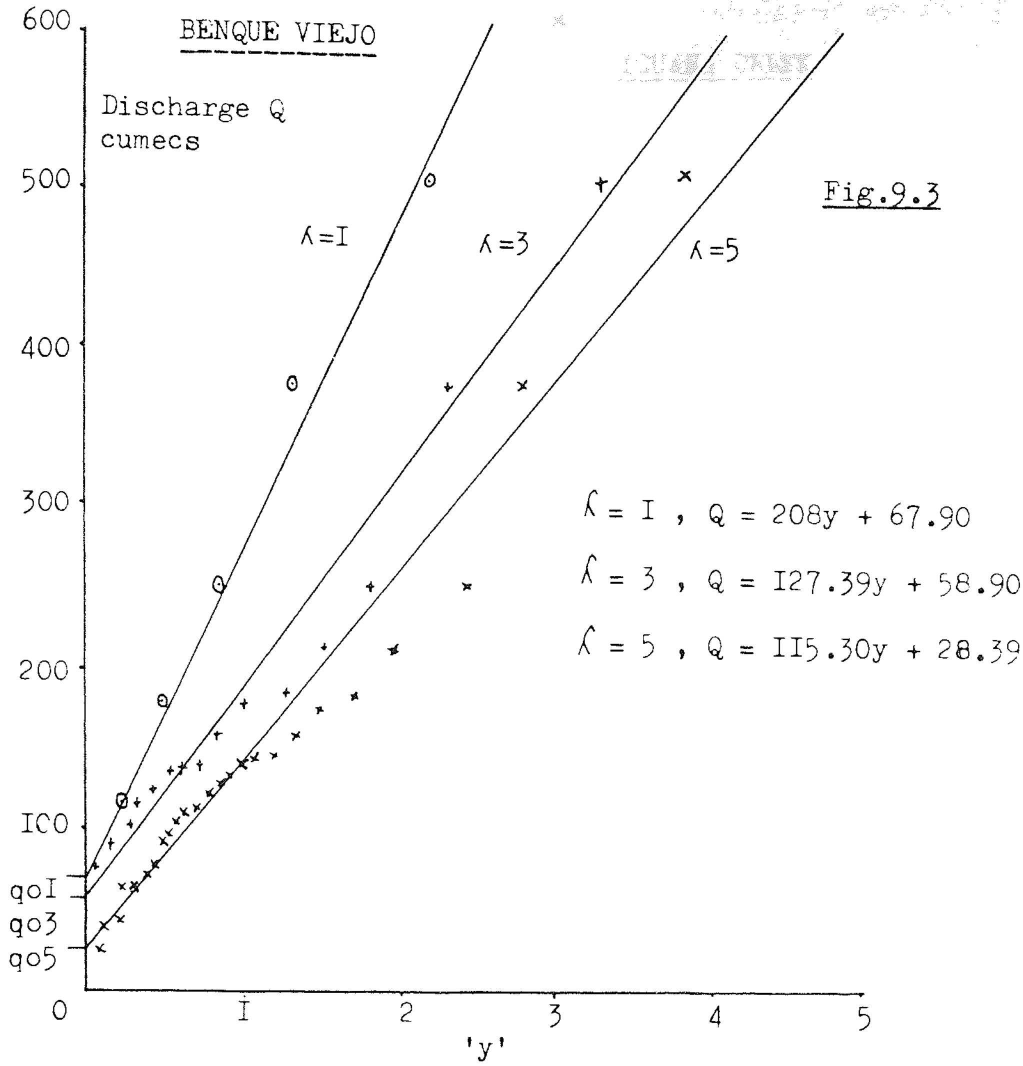
Table 9.6 VARIANCE AND STANDARD ERRORS OF P.O.T. DISTRIBUTIONS (METHOD 2) (continued)

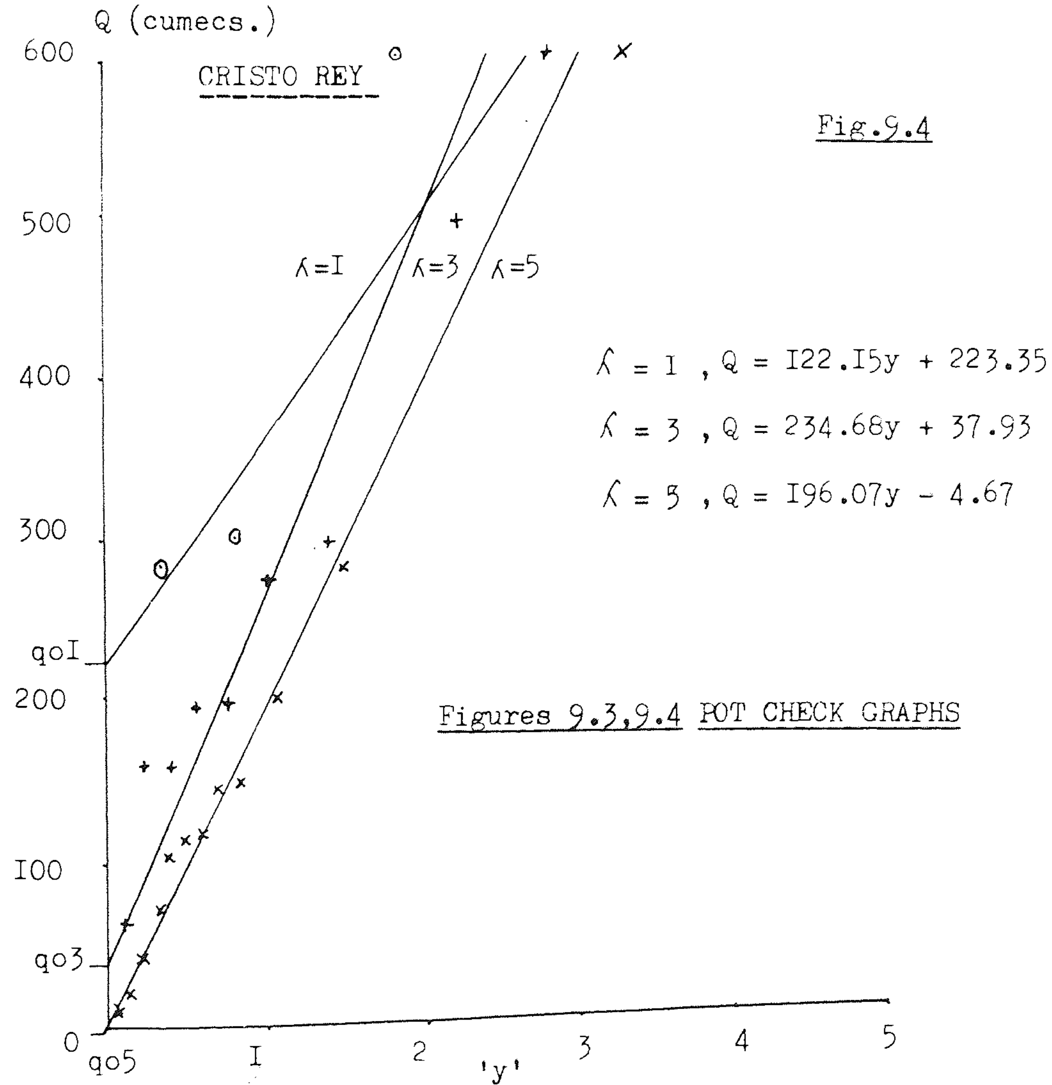
Method 1 (Floodplain Stations only)

T =	5 years		10 years		25 years		50 years		100 years	
B.F.R.	V	S.e.	V.	S.e.	V.	S.e.	V.	S.e.	V.	S.e.
$\lambda = 2$	652	25.5	1129	33.6	1964	44.3	2750	52.4	3701	60.6
(N = 3)										
B.L.										
$\lambda = 1.5$	349	18.7	404	20.1	740	27.2	1021	32.0	1926	43.9
(N = 4)										
D.B.										
$\lambda = 1$	1161	34.0	2744	52.4	5991	77.4	9323	96.6	13408	115.8
(N = 2)										
G.R.										
$\lambda = 1$	231	15.2	547	23.3	1194	35.6	1858	43.1	1474	38.4
(N = 2)										

Table 9.7 PROBABILITY CHECK FOR MOST SUITABLE VALUE OF λ FOR LARGE RETURN PERIODS

Non-Floodplain Stations	No.years Data N	λ	Max.Recorded Event q	Threshold qo	Exponential Gradient β	No.Events (M)	PR (Q Max.)
B.V.	5	5	510.0	28.39	115.30	25	0.9250
B.V.	5	3	510.0	58.90	127.39	15	0.8632
B.V.	5	1	510.0	67.90	208.25	5	0.5287
I.C.	3	5	1350.0	117.80	407.79	15	0.8608
I.C.	3	3	1350.0	166.40	545.40	9	0.6951
I.C.	3	1	1350.0	63.50	964.50	3	0.3996
B.BK.	5	5	1110.0	123.22	269.38	25	0.8766
B.BK.	5	3	1110.0	270.56	336.64	15	0.7281
B.BK.	5	1	1110.0	310.50	347.50	5	0.5905
C.R.	3	5	600.0	-4.67	196.07	15	0.8688
C.R.	3	3	600.0	37.92	234.68	9	0.9094
C.R.	3	1	600.0	223.35	122.55	3	0.8673

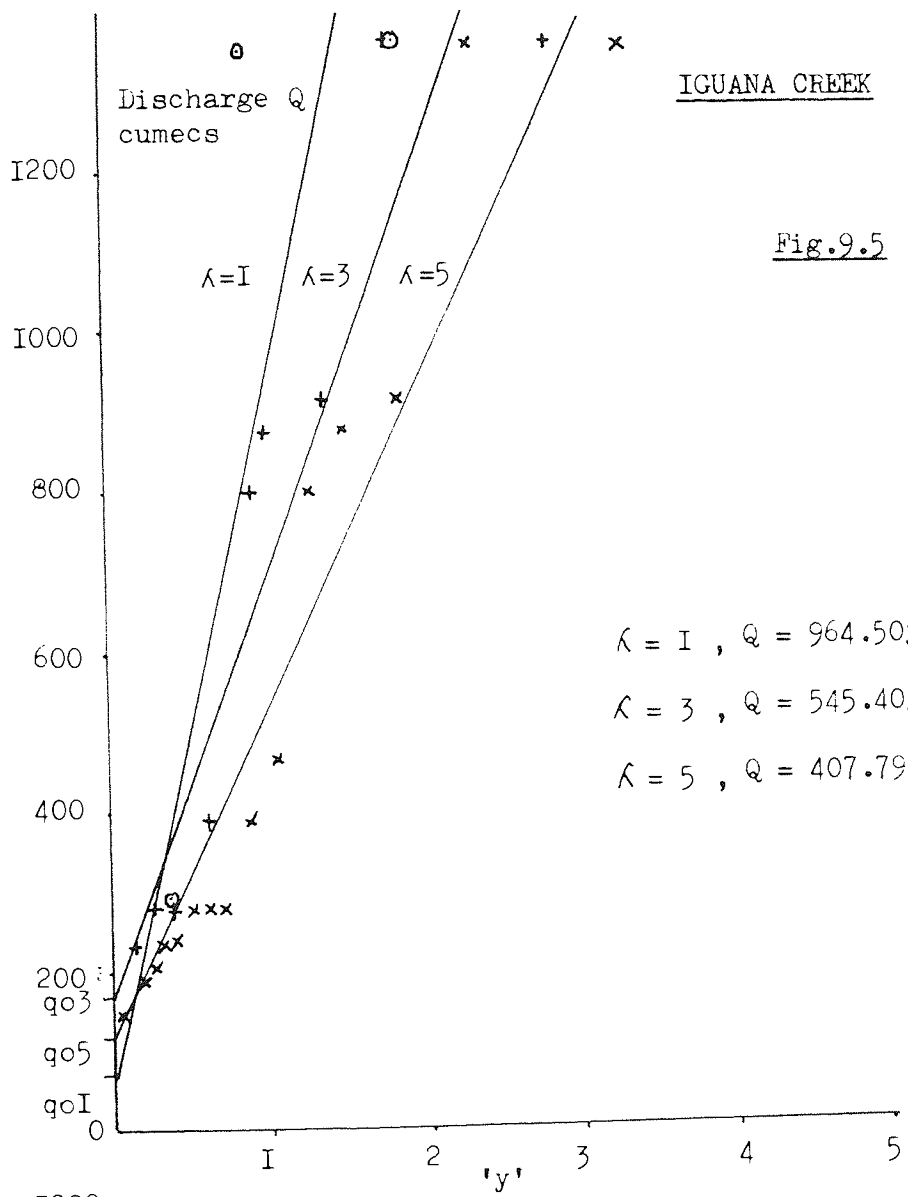




Figures 9.3,9.4 POT CHECK GRAPHS

IGUANA CREEK

Fig.9.5



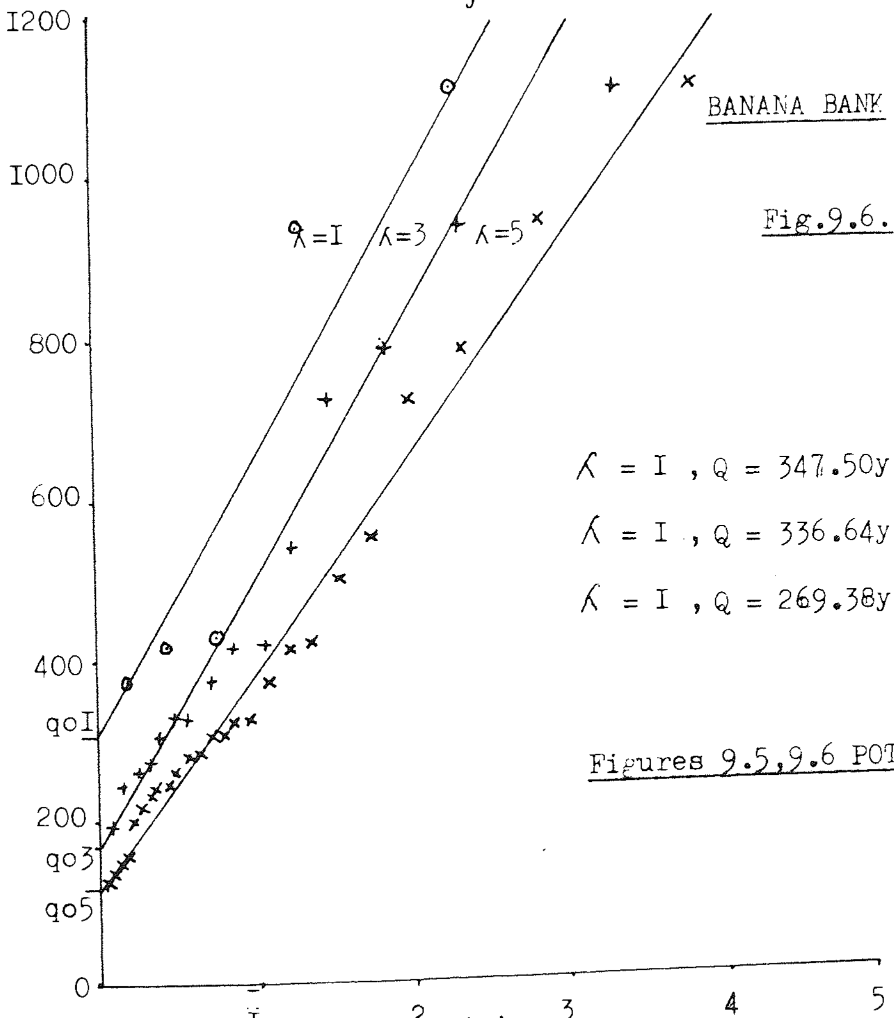
ʎ = I , Q = 964.50y + 63.50

ʎ = 3 , Q = 545.40y + I66.40

ʎ = 5 , Q = 407.79y + II7.80

BANANA BANK

Fig.9.6.

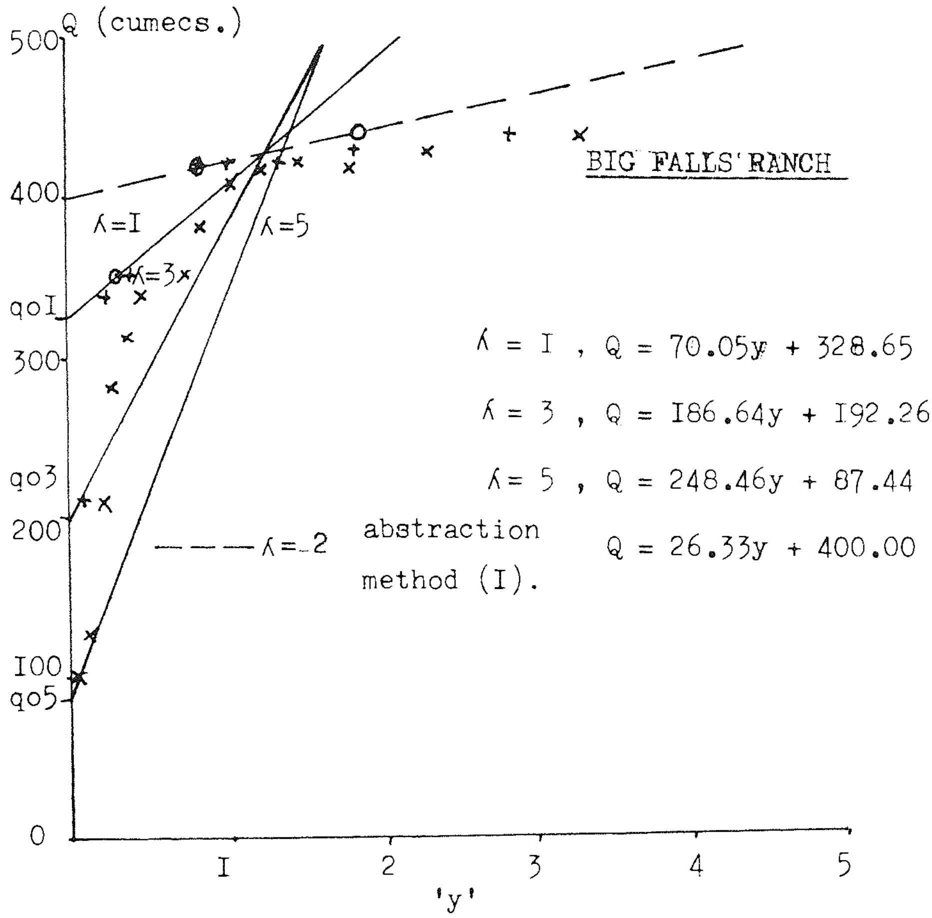


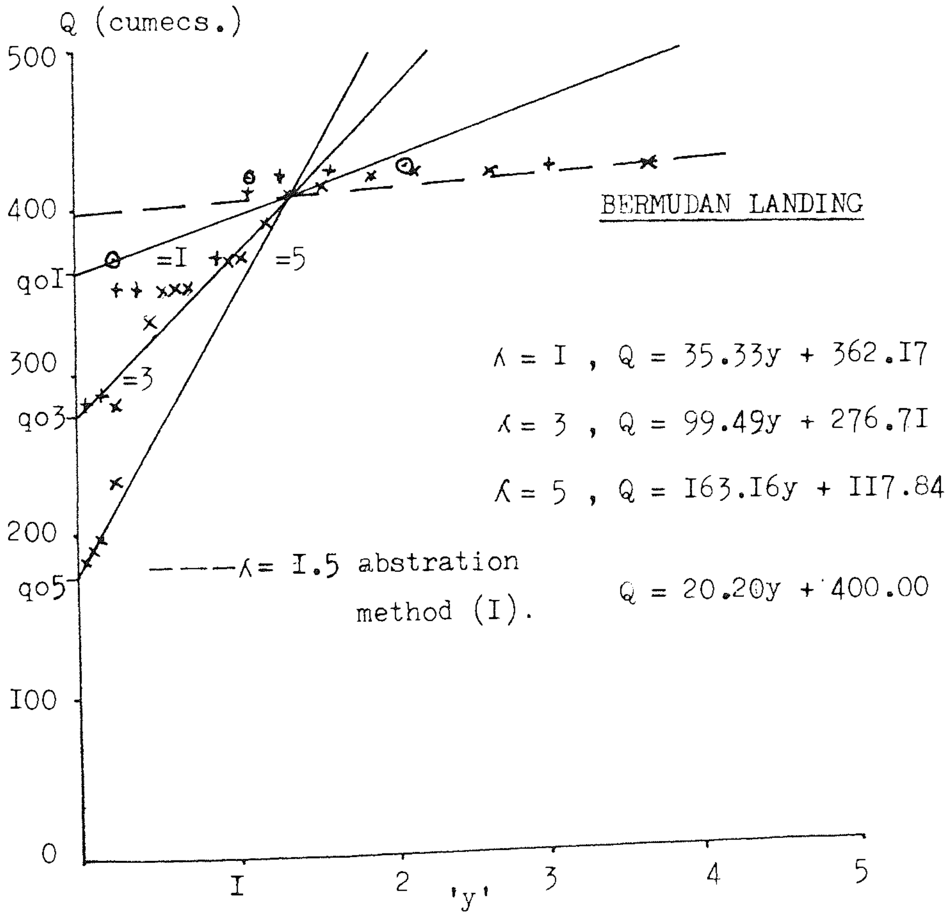
ʎ = I , Q = 347.50y + 3I0.50

ʎ = I , Q = 336.64y + I70.56

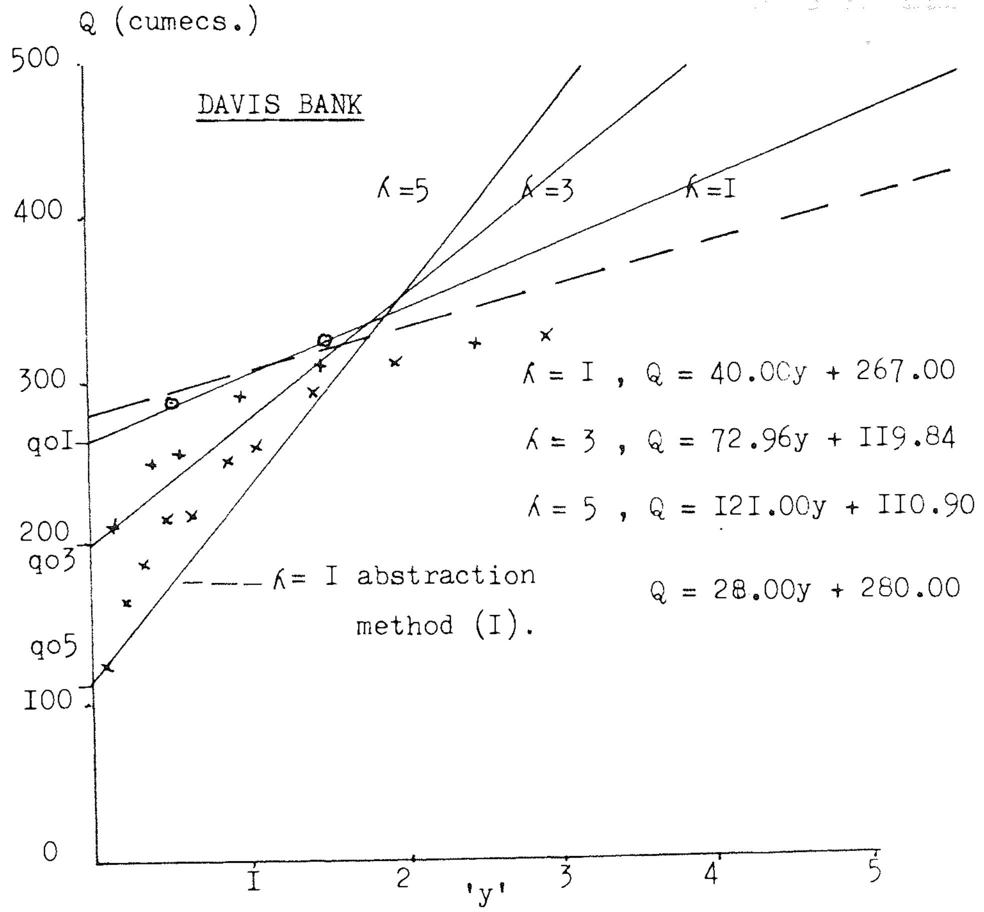
ʎ = I , Q = 269.38y + I23.22

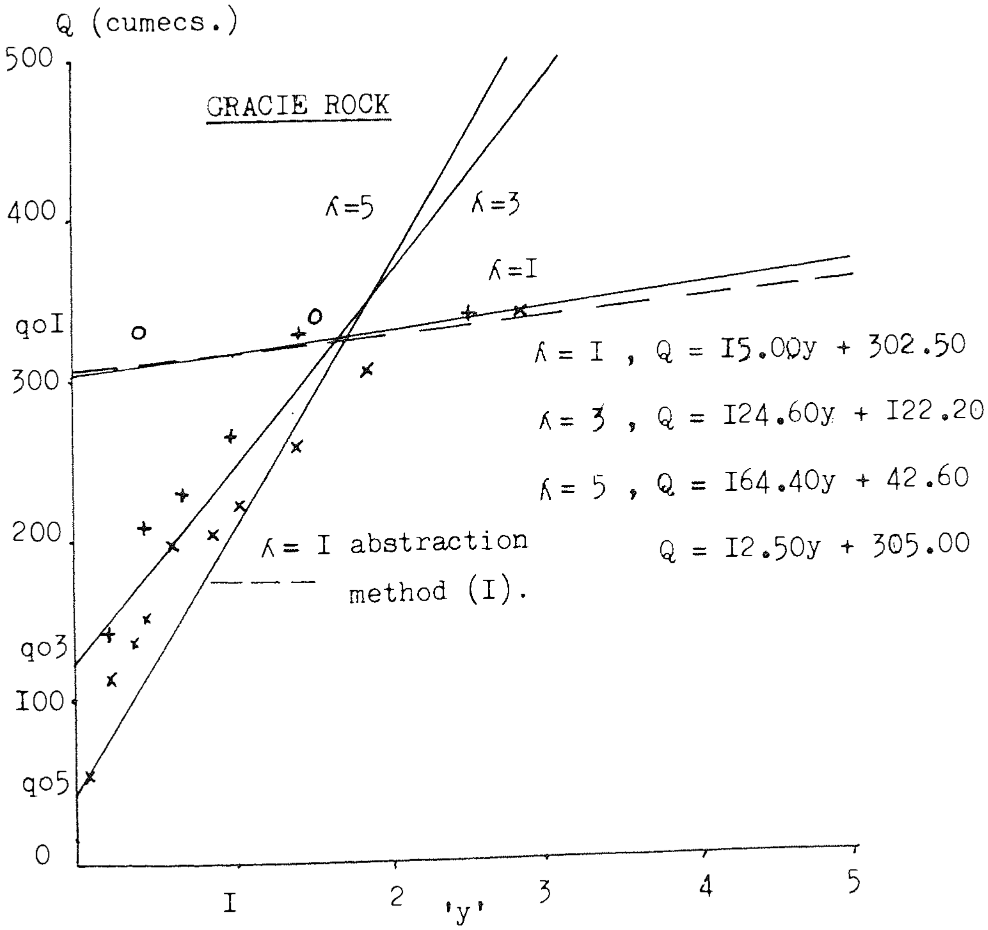
Figures 9.5,9.6 POT CHECK GRAPHS





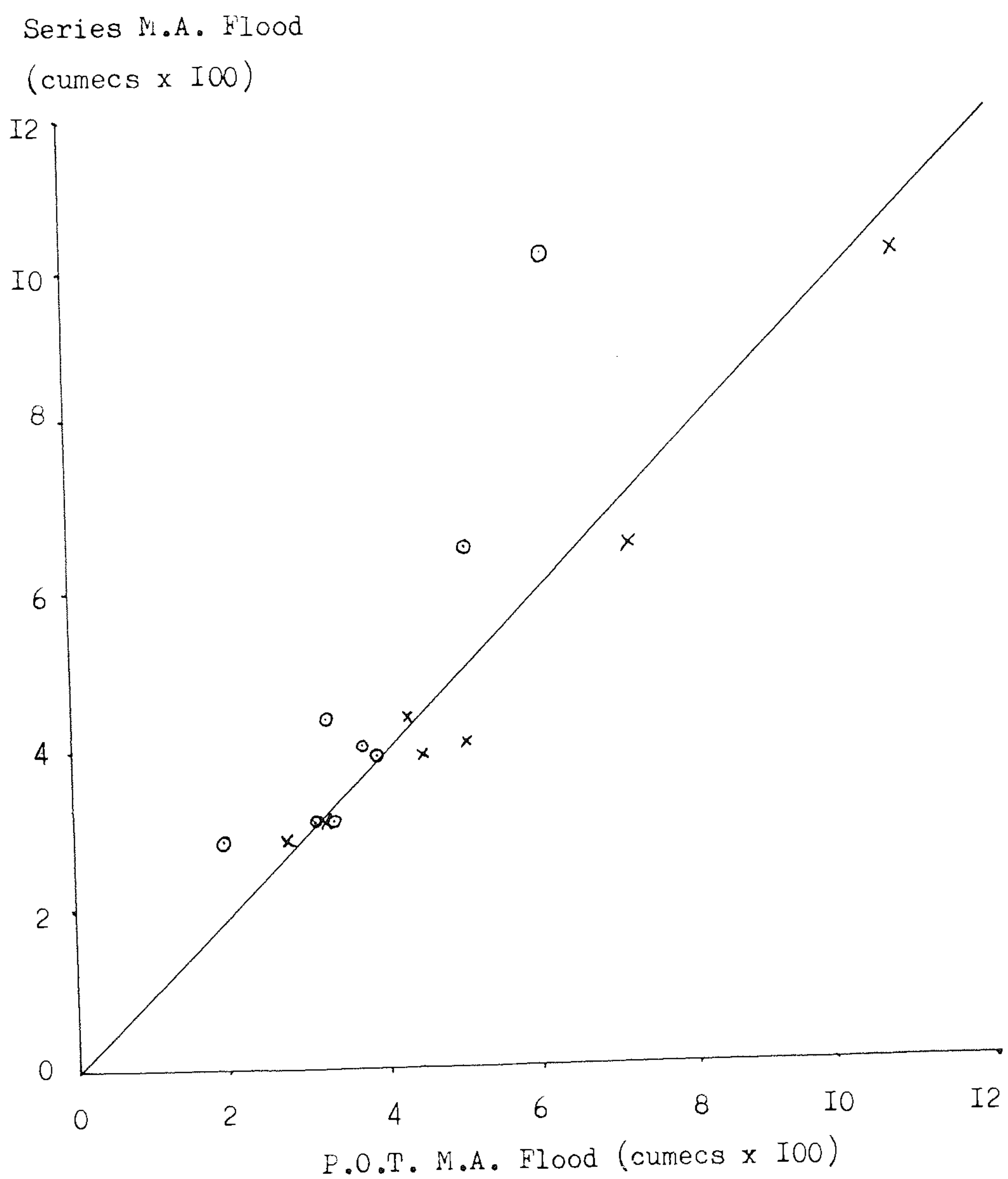
Figures 97,8 POT CHECK GRAPHS (discharge Q : reduced variate 'y')





Figures 9.9,IO POT CHECK GRAPHS (discharge Q : reduced variate 'y')

Figure 9.II. MEAN ANNUAL FLOOD (SERIES) VERSUS P.O.T. MEAN ANNUAL FLOOD FOR λ = I AND 3 (ABSTRACTION METHOD 2)



Discharge plotting positions

Station	A.M.F	P.O.T ⊙	P.O.T. ×
B.V.	286.6	I88.I	272.4
C.R.	440.0	324.2	43I.2
I.C.	I028.3	620.2	I080.4
B.BK.	658.0	5II.2	734.7
B.F.R.	407.6	374.3	505.0
B.L.	397.5	382.6	443.4
D.B.	307.0	336.3	322.I
G.R.	3I7.5	3II.2	33I.0

⊙ where λ = I
× where λ = 3

CHAPTER 10 MULTIPLE REGRESSION ANALYSIS

10.1 INTRODUCTION

Multiple regression analysis is the extension of simple regression used to fit linear equations to experimental data, the coefficients of the terms of which are chosen to minimise the sums of the squares of differences between the observed and calculated points. The variable for which predictions are made is the 'dependent' variable, the variables that predict its value are 'independent' variables. The use of multiple regression analysis is widespread in hydrology and many alternative regression equations have been derived for different regions(136). The transformation of values to logarithms to the base 10 is similar for all observations. Given that this is so(137) the arithmetic form : dependent variable $y = bo + b_1x_1 + b_2x_2 + \varepsilon$ becomes

$$y = 10^{bo} \; x_1^{b1} \; x_2^{b2} \; 10^{\varepsilon}$$

where 10^{bo} and 10^{ε} are the antilogarithms of bo and ε , respectively the constant (or intercept) and the residual. The antilog of the standard error of estimate(s.e.e. or s.e.) is the 'factorial standard error' and may be regarded as an 'average' of these factors(138).

While the selection of the independent variables is made on hydrological grounds, the results must not be assumed as implying a cause and effect relationship between the dependent and independent variables. In this research, the dependent variables regressed against the catchment characteristics were Qo (the threshold values) and β (the exponential parameter) of the P.O.T. flood peak flow formulae. For gauging stations outside the floodplain, exceedence (λ) values of 5 were assumed, within the floodplain values of $\lambda = 1$ were assumed. Although optimum values of λ between 1 and 2 were appropriate for floodplain stations, the use of the generalised form of $\lambda = 1$ generated a maximum discrepancy of only 3.7% at the 25 year return level.

Such an inaccuracy was considered insignificant compared to inaccuracies generated by the P.O.T. series itself and those likely to be inherent within the regression formulae.

Regression analysis for both 1:250,000 scale map values and 1:250,000 scale LANDSAT print values of catchment characteristics was carried out. The primary set of independent variables for both information sources are presented below in table 10.1.

Table 10.1 PRIMARY SET OF CATCHMENT CHARACTERISTICS AS INDEPENDENT VARIABLES

	Map		LANDSAT Prints
1.	Area	1.	Area
2.	RSMD/AAR (Climate variables)	2.	RSMD/AAR
3.	STRFQ (Stream frequency)	3.	STRFQ
4.	GFPN (Gross floodplain area)	4.	GFPN
5.	SPFPN (Specific floodplain area)	5.	SPFPN
6.	AMSSL (Average mainstream slope)	6.	CIRC
7.	SOS (Soil/Slope index)	7.	L:W
8.	BSL (Basin slope)	8.	MSLE
9.	CIRC (Circularity index)		
10.	L:W (length:width ratio)		
11.	MSLE (Mainstream length)		

10.2 CORRELATION AND MULTIPLE REGRESSION

10.2.i Correlation

Correlation study is an important prerequisite to regression analysis, since it is preferable not to include, within the regression set, variables that are highly correlated to one another, especially as these variables may be used to substitute for one another. The F.S.R. (Volume 2, 4.2.6. page 312) discusses the details of correlation to some length.

The correlation of variables from both information sources was undertaken in two ways :

1. Variables within each group were correlated to indicate significant relationships within the group, to allow for most suitable selection.

Table 10.2 CORRELATION MATRIX OF MAP INDEPENDENT VARIABLES

Independent Variables	Independent variables									
	Area	RSMD	STFRQ	GRFPN	SPFPN	AMSSL	SOS	BSL	CIRC	LW
AREA	1.000									
RSMD	- 912	1.000								
STRFQ	- 580	627	1.000							
GRFPN	203	083	-311	1.000						
SPFPN	129	158	-297	995	1.000					
AMSSL	-933	852	748	-415	-355	1.000				
SOS	-489	607	961	-105	-094	606	1.000			
BSL	-752	742	962	-412	-358	895	875	1.000		
CIRC	-161	061	343	-636	-650	424	140	424	1.000	
LW	748	-448	-246	648	596	-759	-025	-479	-450	1.000
MSLE	905	-712	-654	580	524	-959	-483	-825	-441	885

Table 10.3 CORRELATION MATRIX OF LANDSAT PRINT INDEPENDENT VARIABLES

Independent Variables	Independent variables							
	Area	RSMD	STFRQ	GRFPN	SPFPN	CIRC	LW	MSLE
Area	1.000							
RSMD	-881	1.000						
STRFQ	-635	651	1.000					
GRFPN	256	152	-234	1.000				
SPFPN	643	-315	-338	837	1.000			
CIRC	-129	-196	-004	-767	-756	1.000		
LW	-142	440	319	796	504	-618	1.000	
MSLE	965	-786	-529	419	798	-333	053	1.000

2. Variables from both groups were correlated to identify the level at which significant relationships between the same variable in each group existed, as an indicator of substitution between LANDSAT and map data. Tables 10.2, 10.3 and 10.4 give these correlation matrices.

Tables 10.2 and 10.3 show that some of the variables are quite highly correlated and suggest mutual exclusion from regression analysis. This is not necessarily disadvantageous, for instance in the cases of variables 'SPFPN' and 'GFPN', and 'BSL' and 'SOS' it is possible to discard completely, one variable from each pair. A significant correlation in both variable sets is the highly negative relationship reflecting an inverse occurence between rainfall and catchment area. This is due to the fact that the smaller catchment areas above gauging stations are located in the upland regions of Belize, and consequently receive a greater average rainfall amount, due to orthographic rainfall processes, than the large catchment areas that occupy a greater proportion of the drier, lowland areas. Such an effect indicates certain problems in "regionalising" the data where a limited number of observation stations are available. Since both rainfall amount and area of catchment are obviously closely linked to the volume of river flow, this relationship was troublesome.

Generally, the correlations between LANDSAT and map data can be seen to be extremely high, indicating a high degree of interchangability. Table 10.4 gives a clear indication of the possibility of substituting data from the different sources.

Table 10.4 CORRELATION MATRIX OF LANDSAT VERSUS MAP VARIABLE VALUES

LANDSAT variables	Map variables							
	Area	RSMD	STFRQ	GFPN	SPFPN	CIRC	L:W	MSLE
AREA	0.991							
RSMD		1.000						
STRFQ			0.992					
GFPN				0.996				
SPFPN					0.810			
CIRC						0.932		
L:W							0.460	
MSLE								0.975

10.2.ii Regression analysis

In the light of the correlation information, a series of regressions were made involving the dependent variables Qo and β. No more than four independent variables were used at any time, so that the degrees of freedom of the regression, which become progressively smaller as the number of variables increases, were left as large as practicable in the circumstances of only 8 observation stations. Regression was by full regression, with a manual permutation of variables. Table 10.5, overleaf, gives values of dependent variables.

1. Regression on Qo and β using RSMB

This first series of regression analyses were relatively unsuccessful. The coefficients of the variables, notably RSMD, were extremely large and very sensitive to inaccurate measurement. Conversely, the multiplier was extremely small or zero. The standard errors of the equation were very large and the coefficient of multiple correlation (R^2) was very low. No significant differences were seen between the regressions of LANDSAT and map data. Table 10.6 below gives examples of these regression formulae for dependent variable Qo.

Table 10.6 PARAMETERS OF REGRESSION EQUATIONS USING RSMD

Dependent Variable	Independent variables	Coefficient	s.e.b.	R^2	s.e.e.	Multiplier	Source
Qo	AREA	3.6983	1.0247	0.893	0.383	0	MAP
	RSMD	46.0293	11.7839				
	STFQ	-7.4413	1.7765				
				(-83% to +483% at 95% confidence levels)			
Qo	AREA	3.2669	1.0947	0.835	0.475	2.69×10^{-84}	LANDSAT
	RSMD	37.6857	12.2295				
	STFQ	-3.6940	1.4241				
				(-89% to +790% at 95% confidence levels)			

s.e.b. = Standard error of the variable

s.e.e. = Standard error of the equation

Table 10.5 DEPENDENT VARIABLES FOR USE IN MULTIPLE REGRESSION ANALYSIS

Case No.	1	2	3	4	5	6	7	8
Gauging Station	B.V.	C.R.	I.C.	B.BK.	B.F.R.	B.L.	D.B.	G.R.
M.A.F.Flood								
qo	58.90	37.93	166.40	170.56	328.65	362.17	267.00	302.5
B	127.39	234.68	545.40	336.64	79.05	35.33	40.0	15.0
	3	3	3	3	1	1	1	1
Q(T) Flood								
qo	28.39	-4.67	117.80	123.23	400.00	400.00	280.00	305.00
B	115.30	196.07	407.79	269.38	26.33	20.20	28.00	12.50
	5	5	5	5	2	1.5	1	1

2. Regression on Qo and B using A.A.R.

The F.S.R. found average annual rainfall a successful variable in regression, performing almost as well as R.S.M.D.(139). Its simple method of calculation and universal availability make it attractive as a climate variable. It was tested in regression, but little improvement in the resultant formulae was found. Table.10.7 below gives examples of the regression parameters for dependent variable Qo.

Table 10.7 PARAMETERS OF REGRESSION EQUATIONS USING A.A.R

Dependent Variable	Independent variable	Coefficient	s.e.b.	R^2	s.e.e.	Multiplier	Source
Qo	AREA	2.7523	0.6605	0.928	0.314	0	Map
	A.A.R.	30.0499	6.0612				
	STFQ	-10.9411	1.7861	(-76% to +325% at 95% confidence levels)			
Qo	AREA	2.9041	0.5961	0.934	0.300	0	LANDSAT
	A.A.R	31.2609	5.7206				
	STFQ	-6.4991	1.1263	(-75% to +298% at 95% confidence levels)			

An improvement in these results was attempted by the combination of the highly correlated climate and area variables. A.A.R. was chosen due to its ease of availability by rationalising the variables in the form A.A.R. - catchment area.

3. Regression on Qo and B using A.A.R. - Catchment Area

Tables 10.8 to 10.11 present a group of combinations from both LANDSAT and map variable sets. The tables show the parameters of the equations with the smallest standard errors and highest multiple correlation coefficients. Predictions at the 95% confidence level lie between -50% and +100%, approximately. It can be seen that standard errors do not automatically reduce with increasing numbers of variables, though with less than three, s.e.e. values are high. The relatively crude nature of the estimates obtained from the regression equations, show that distortion and measurement errors in the

Table 10.8 REGRESSION PARAMETERS FOR DEPENDENT VARIABLE Qo (MAP)

Var	Name	Coeff	s.e.b.	t	R^2	s.e.e.	Const.	68% Confidence
1	ARR/AREA	-1.0271	0.8134	-1263	0.210	0.850	1.646	-80 to +608%
1	AAR/AREA	-0.1003	0.9221	-0.189	0.481	0.755	-3.6643	-82 to +469%
	STFQ	-5.6290	3.4829	-1.616				
1	AAR/AREA	-0.614	0.7680	0.080	0.712	0.628	-2.8293	-76 to +325%
2	STFQ	-4.3865	2.9812	-1.471				
3	GFPN	0.314	0.1751	1.793				
1	AAR/AREA	-0.7371	0.6835	-1.079	0.557	0.698	1.2412	-80 to +399%
3	GFPN	0.3739	0.1892					
1	AAR/AREA	-0.8660	3.2132	-0.270	0.557	0.780	1.733	-83 to +502%
3	GFPN	0.3826	0.2989	1.280				
4	MSSL	0.2205	5.3420	0.041				
1	AAR/AREA	-0.1196	0.6620	-0.181	0.756	0.579	-5.0789	-74 to +279%
3	GFPN	0.3765	0.1569	2.399				
5	SOS	-15.1749	8.3977	-1.807				
1	AAR/AREA	0.6150	3.3046	0.186	0.689	0.743	-3.1747	-82 to +455%
3	GFPN	0.4796	0.2961	1.620				
4	AMSSL	-2.5341	5.5915	-0.453				
9	CIRC	6.7299	5.6674	1.187				
1	AAR/AREA	2.4218	1.037	2.350	0.835	0.476	-12.9387	-77 to +199%
10	L:W	7.9770	2.4736	3.225				
5	SOS	-33.2985	8.9442	-3.723				

Table 10.9 REGRESSION PARAMETERS FOR DEPENDENT VARIABLE B (MAP)

Var	Name	Coeff	s.e.b.	t	R^2	s.e.e.	Const.	68% Confidence
1	AAR/AREA	-0.1482	0.5978	-0.248	0.010	0.625	1.7864	-76 to +322%
1	AAR/AREA	0.6273	0.7619	-0.823	0.178	0.623	4.5291	-76 to +320%
2	STFQ	2.907	2.8778	1.011				
1	AAR/AREA	0.6741	0.1990	-3.387	0.955	0.163	3.5241	-31 to +46%
2	STFQ	1.4142	0.7726	1.830			(95%	-53 to 112%)
3	GFPN	-0.3779	0.0454	-8.326				
1	AAR/AREA	-0.6266	0.1912	-3.278	0.953	0.167	3.9546	-32 to +47%
5	SOS	4.1846	2.4249	1.726			(95%	-54 to +116%)
3	GPPN							
1	AAR/AREA	-1.8708	0.5450	-3.433	0.470	0.132	8.0538	-26 to +36%
3	GFPN	-0.3015	0.0507	-5.949			(95%	-46 to +84%)
4	AMSSL	2.4212	0.9060	2.672				
1	AAR/AREA	-0.9767	0.814	-1.200	0.462	0.564	2.9071	-73 to +266%
9	CIRC	3.0951	3.3970					
10	LW	-2.6461	2.4939					
1	AAR/AREA	-0.7149	1.6780	-0.426	0.918	0.220	3.5298	-40 to +66%
3	GFPN	-0.3625	0.2315	-1.565			(95%	-66 to +175%)
11	MSLE	-0.6479	4.1682	-0.155				
1	AAR/AREA	-3.2474	0.7649	-4.245	0.895	0.287	16.6931	-49 to +93%
2	STFQ	1.2139	1.3887	0.874				
11	MSLE	-6.5697	1.7224	-3.814				
9	CIRC	0.078	1.9216	0.037				

Table 10.10 REGRESSION PARAMETERS FOR DEPENDENT VARIABLE Qo (LANDSAT)

Var	Name	Coeff	s.e.b.	t	R^2	s.e.e.	Const.	68% Confidence
1	AAR/AREA	-1.1693	0.7827	-1.494	0.271	0.815	1.5890	-85 to +553%
1	AAR/AREA	-0.3811	1.0177	-0.374	0.427	0.791	-0.553	-84 to +518%
2	STFQ	-2.7662	2.3738	-1.165				
1	AAR/AREA	-0.2494	0.8297	-0.301	0.697	0.643	-0.1351	-73 to +399%
2	STFQ	-2.3113	1.9435	-1.189				
3	GFPN	-0.3570	0.1888	1.891				
1.	AAR/AREA	-0.7634	0.4503	-1.695	0.848	0.455	2.620	-65 to +185%
3	GFPN	0.7985	0.2067	3.864				
4	CIRC	9.0738	3.4766	2.610				
1	AAR/AREA	-0.8788	0.9483	-0.927	0.590	0.748	1.2195	-82 to +460%
3	GFPN	0.3907	0.4541	0.860				
7	LW	-0.0570	3.8247	-0.015				
1	AAR/AREA	-9.2340	1.0143	-9.104	0.983	0.174	29.8007	-33 to +49%
3	GFPN	0.3870	0.1054	3.671			(95%	-55 to +123%)
7	LW	5.2545	1.0884	4.828				
8	MSLE	-14.8654	1.7616	-8.439				
1	AAR/AREA	-5.9233	1.9165	-3.091	0.855	0.445	20.8369	-64 to +179%
3	GFAN	0.7525	0.1882	3.999				
8	MSLE	-9.9475	3.6855	-2.699				

Table 10.11 REGRESSION PARAMETERS FOR DEPENDENT VARIABLE β (LANDSAT)

Var	Name	Coeff	s.e.b.	t	R^2	s.e.e.	Const.	68% Confidence
1	AAR/AREA	-0.0929	0.6020	-0.154	0.004	0.6020	1.8031	-68 to +299%
1	AAR/AREA	-0.5282	0.8326	-0.634	0.114	0.648	2.7113	-889 to +345%
2	STFQ	1.5278	1.9420	0.787				
1	AAR/AREA	-0.6803	0.2279	-2.985	0.947	0.177	2.8035	-33 to +50%
2	STFQ	1.0024	0.5337	1.878			(95%	-56 to +126%)
3	GFPN	-0.4123	0.5180	-7.952				
1	AAR/AREA	-0.4328	0.1954	-2.216	0.934	0.197	1.8846	-36 to +57%
3	GFPN	-0.5222	0.897	-5.824			(95%	-60 to +148%)
6	CIRC	-2.1454	1.5082	-1.422				
1	AAR/AREA	-0.5955	0.2666	-2.233	0.925	0.210	2.0467	-39 to +62%
3	GFPN	-0.5523	0.1277	-4.326			(95%	-62 to +163%)
7	LW	1.2288	1.075	1.143				
1	AAR/AREA	0.1734	1.3962	-0.124	0.928	0.239	0.6028	-42% to +73%
3	GFPN	-0.5521	0.1451	-3.804			(95%	-67 to +200%)
7	LW	0.9605	1.4983	0.641				
8	MSLE	0.7510	2.4249	0.310				
1	AAR/AREA	0.4318	0.9500	0.455	0.918	0.221	-1.0357	-40 to +66%
3	GFPN	-0.4853	0.0933	-5.204			(95%	-64 to +177%)
8	MSLE	1.6499	1.8269	0.903				

data are insignificant and that substitution of LANDSAT data for map data is feasible. Within the parameters of tables 10.8 to 10.11, interestingly, only LANDSAT data provides a reasonable equation for Qo, and little or no advantage is gained by the inclusion of any slope variable.

10.3 WORKED EXAMPLES OF THE REGRESSION EQUATIONS

Examples of the best equations (judged by s.e. and R^2) were selected for both maps and LANDSAT data. They were used to obtain values of Qo and B which were then applied to the calculation of the 25 year flood and compared to P.O.T. estimates of the same flood. These examples were undertaken for Benque Viejo, Iguana Creek, Bermudan Landing and Gracie Rock gauging stations, since each represents a particular flow regime of the Belize and Sibun rivers. Table 10.12 below presents these examples for both map and LANDSAT data.

Table 10.12 WORKED EXAMPLES OF THE REGRESSION EQUATIONS FOR Qo and β, 25 YEAR FLOOD

1. MAP SOURCE

Station	Qo (cumecs)	POT Qo	β	POT β	Regression Q25 (cumecs)	POT Q25 (cumecs)	% Difference
B.V.	129	28	121.2	115.3	715	585	+22
I.C.	45	118	407.9	407.8	1358	2087	+35
B.L.	372	400	24.1	20.2	450	473	-5
G.R.	126	305	13.7	12.5	170	345	-51

2. LANDSAT SOURCE

Station	Qo (cumecs)	POT Qo	β	POT β	Regression Q25 (cumecs)	POT Q25 (cumecs)	% Difference
B.V.	22	28	128.3	115.3	437	585	-25
I.C.	172	118	274.8	407.8	1449	2087	-28
B.L.	283	400	27.9	20.2	373	473	-21
G.R.	289	305	11.6	12.5	326	345	-5

As these examples are taken from the stations providing information for regression, it is obvious that they will provide answers defined by the parameters of the regression equations. Therefore, examples were taken from two gauging stations outside the Belize and Sibun catchments. Values of catchment characteristics for the two stations are given below.

Table 10.13 DETAILS OF KENDAL AND BIGFALLS (SOUTH) GAUGING STATIONS

Station	Location	Variables	Map Value	LANDSAT Value
Kendal	16°48'52" N	AREA	383 km^2	345 km^2
	88°22'43" W.	GFPN	0 km^2	0 km^2
		SOS	0.3895	NA
		AMSSL	0.006	NA
		STRFQ	NA	0.300
		L:W	-	1.89
		MSLE	-	47 km
Big Falls	16°15'23" N	AREA	535 km^2	NA
(South]	88°53'10" W	GFPN	0 km^2	NA
		SOS	0.3709	NA
		AMSSL	0.058	NA

Using the formulae for regression below, calculations of estimated Q25 were made:

1. MAP

$$Qo = \left(\frac{AAR}{AREA}\right)^{-0.6803} \quad GFPN^{0.3765} \quad SOS^{-15.1749} \quad 8.34 \times 1^{-6} \text{ (s.e.e. = 0.579)}$$

$$\beta = \left(\frac{AAR}{AREA}\right)^{-1.8708} \quad GFPN^{-0.3015} \quad AMSSL^{2.4212} \quad 1.13 \times 10^{8} \text{ (s.e.e. = 0.132)}$$

2. LANDSAT

$$Qo = \left(\frac{AAR}{AREA}\right)^{-9.2340} \quad GFPN^{0.3870} \quad L{:}W^{5.2545} \quad MSLE^{-14.8654} \times 6.32 \times 10^{29} \text{ (s.e.e. = 0.174)}$$

$$\beta = \left(\frac{AAR}{AREA}\right)^{0.6803} \quad STFQ^{1.0024} \quad GFPN^{-0.4123} \quad 0.636.10^{3} \text{ (s.e.e. = 0.177)}$$

Values of Qo and B were calculated and combined and applied to the P.O.T.formula,

$$Q25 = Qo + \beta\,(\ln X + \ln 25)$$

Table 10.14 WORKED EXAMPLES FOR KENDAL AND BIG FALLS (SOUTH)

Station	Qo cumecs	P.O.T. Qo	β	P.O.T. β	Regression Q25 cumecs	P.O.T. Q25 cumecs	% Diff.
Map Source							
Kendal	26	66	7.1	6.0	60	85	-29%
Big Falls	57	70	9.4	51.8	102	246	-58%
LANDSAT Source							
Kendal	0	66	50.1	6.0	242	85	+185%
Big Falls	Data not available						

It must be stressed that the P.O.T. series upon which comparisons are made with the regression values of the Q25 flood flow was only 1 year and that in the light of such a fact, probable accuracies can be seen to be good. The lack of other station data prevents further comparisons from being made.

The following conclusions may be drawn in terms of the results of regression analysis.

1. All predicted flows display a large order of inaccuracy, but may be regarded as indicating an order of magnitude of flow.
2. LANDSAT evaluations of catchment characteristics are equally applicable to the methods used to exploit such relationships as exist within regression analysis.
3. No advantage is seen in the addition of slope variables, available only from maps.
4. LANDSAT information may be substituted for map information.
5. Since the value of Qo dominates the predictions of flood flows in floodplain areas, caution should be exercised in the application of Qo regression equations, and the determination of the accuracies of equations defining these threshold values.
6. Values of mean annual flow were found to be described adequately, within the overall accuracies of the regression formulae, by the parameters of the Q(T) flood formulae, where values of $\lambda = 3$ and $\lambda = 1$ were attributed to non-floodplain and floodplain stations respectively.

CHAPTER 11 REMOTE SENSING INVESTIGATIONS OF THE 1979 BELIZE RIVER FLOOD

11.1 INTRODUCTION

The previous chapters of this thesis have been concerned with the use of remotely sensed information in providing evaluations of catchment characteristics that can be linked to flood flows by regression analysis. Chapters 11 to 14 are concerned with the investigation of an actual flood event using remotely sensed data, specifically LANDSAT image 020/48 acquired 26th December 1979.

While the use of remotely sensed images to study the extent of flood events and delineate floodplain boundaries has been investigated in the past, these investigations have usually involved verification by ground survey(140) or have involved the interpretation of multitemporal coverage(141), often with the use of aerial photography(142). Such materials and facilities were beyond the scope of this research, and on the whole they represent favoured circumstances.

The flood scene 020/48 26th December 1979 (details given in Chapter 3) was acquired an unknown period after a large flood. No hydrological records contemporary with the flood were available, though daily rainfall was available for several locations in or around the catchment area. This limitation of data supplementary to the imagery represents typical conditions that prevail in developing countries where remotely sensed information may be expected to be especially important. While there is no obvious sense in deliberately restricting research by ignoring available data, the value and limitations of remotely sensed imagery can be most clearly understood, where supportive sources of information are limited.

Considerable success in the study of floodplain areas has been achieved by the use of LANDSAT imagery, but difficulties have been encountered in areas of dense vegetation, where the interpolation of boundaries has led to misinterpretation(143). With this in mind, the aims of this research have been listed overleaf in table 11.1.

Table 11.1 AIMS OF THE 1979 FLOOD STUDY

1, To locate specific points of overspill of the Belize and Sibun rivers.

2. To estimate the areal extent of the flood on the date of scene acquisition.

3. If possible, to estimate the maximum areal extent of the flood.

4. To estimate the volume of flood water derived from the rivers.

5. To identify the routes of flood water movement.

6. To relate flood volumes via unit hydrographs and rainfall information and identify the 1979 flood return period, targeting this work on the flow volumes of the floodplain gauging stations.

These are a wide variety of aims but are clearly inter-related. The research was carried out using 1:250,000 scale images of prints and c.c.t. slides, as well as 1:250,000 scale c.c.t. slide material. No ground information relating to the flood, was available.

11.1.i General description of the floodplain area from topographic maps

The floodplain at its upstream limits around Banana Bank gauging station was seen to be relatively narrow and confined to the margins of the Belize river. No significant tributaries join the river downstream of Labouring Creek and marsh/swamp areas are not evident. The river follows a winding course through flat or undulating terrain and does not exhibit features commonly associated with floodplain areas, such as marginal lakes, backswamps or isolated water bodies. The river is bordered in the east by cohune palm forest, with riparian vegetation of broadleaved evergreen and semi-evergreen types(144). The vegetation cover is generally dense.

The middle floodplain section, approximately the region between Big Falls Ranch and Davis Bank is different. The tortuosity of the river meanders increases and the adjacent terrain is flatter and of lower elevation. Areas of swamp and standing water are evident, their extent greatest by far in the N.W., where they extend almost to the New River drainage system and include several large lagoons. Topographic maps indicate that this area of lagoon and swamp lies as close as 1 km to the Belize river. Mussel Creek, a significant tributary, joins the Belize river just upstream of Davis Bank, draining an area of swamp located close to the Sibun. Elevations of 15 metres are maximum in this area, some 20 km from the coast and the implication that in part, the Belize and Sibun rivers may share a hydrological connection at time of flood, is not limited solely to the lower floodplain area. Vegetation on this middle section is similar to that of the upper floodplain, but less dense pine forest and orchard savannah occur more frequently.

The floodplain to the east and south of the Belize river and north of the Sibun is very flat, elevations vary from 0 to 7 metres generally, with a few isolated higher areas. There are no tributary rivers in this area with the exception of the small Hector Creek which flows eastwards to the Sibun and joins it not far from the coast. Extensive swamps are indicated and two large lagoons (Almond Hill and Straight lagoons) are located centrally, close to the Western Highway. The area is covered with pine forest and orchard savannah to the exclusion of almost all other vegetation types, though dense mangrove forest is found peripheral to the lagoons and coastal edge, and dense forest covers the river banks.

11.2 INVESTIGATIONS USING 1:250,000 SCALE LANDSAT IMAGERY

11.2.i Introduction

The description of the floodplain area given above, indicates that it may be subdivided into three areas of differing character and that the flooding in each may be of a different type; widespread in the lower floodplain, intimately connected with the lagoonal and swamp areas in the middle floodplain and probably of restricted extent in the upper floodplain.

Research was carried out initially using 1:250,000 scale prints and c.c.t. slides so that the use of this scale and these alternative formats could be assessed. The opportunities of observation of flood details in both cases largely determined by natural vegetation cover and three main categories may be identified.

1. Areas clearly definable as flooded, without dense vegetation cover.
2. Emergent areas, previously flooded and without dense vegetation cover.
3. Areas as in 1 or 2, but with observation not possible due to vegetation.

This list indicates a dichotemy of vegetational type, with areas of pine forest and orchard savannah generally being the predominant areas open to observation, in addition to areas of lagoon and short marsh vegetation. The area that was under study, the details of which are given in this chapter, was that above Davis Bank - the upper and middle floodplain areas. Hydrological information below these areas was not available. Appendix E gives details of the visual characteristics of land cover types associated with the images of both prints and c.c.t. slides.

11.2.ii 1:250.000 scale band 7 photographic prints

The first observation of the 1979 flood event to be made, was an inventory of observable water body areas. These are given below with a same scale map inventory for comparison.

Table 11.2 INVENTORY OF WATER BODIES

LANDSAT Band 7 Prints			1:250,000 Scale Maps	
	Waterbody No.	Area (km^2)	Waterbody No.	Area (km^2)
	1	49.8	1	23.4
	2	12.4	2	9.6
	3	2.9	3	1.0
	4	40.6	4	Not present
	5	4.2	5	Not present
	6	1.1	6	Not present
TOTAL	6	111.0	3	34.0

The identification of the water bodies, open to observation, was not difficult and size was an insignificant factor. The detection of ponds as little as 0.0625 km^2 in area, was possible from the LANDSAT imagery.

Map D at 1:250,000 scale shows the location of flood features obtained from the LANDSAT print image. The assessment of the listed aims of table 11.1 was made.

1. Location of overspill points:

These locations are identified on folded Map D. The overspills were difficult to observe when they did not occur on a relatively broad front or covered an area less tha 1 km^2. The most significant in terms of size, is that located between Davis Bank and Bermudan Landing, where often denser vegetation inhibits conclusive observation. The flooding from these locations appears to be closely related with water movement to the N.W. lagoonal area.

2. Estimates of flood extent at time of scene acquisition

The identification of such a flood extent is more easily accomplished than the estimation of the previous maximum flood level which subsequent recession has diminished. It must however involve the interpolation of water levels below the vegetation canopy except in the most fortunate circumstances(145).

Spot height values were transposed from 1:50,000 scale maps to map D. Two main difficulties were encountered. First was the lack of features assisting their accurate location when associated with roads and cultural features, since band 7 imagery does not present such features clearly. Second and less importantly were the distortional inaccuracies of the scene.

However, the transposition of the spot heights was made as accurately as possible and maximum elevations of the flood were seen to be at or about 6 metres above sea level. Altitudes of 8 metres were seen clearly to be situated outside the flooded areas. Elevations at 2 metres were seen to be the minimum land elevations in the flooded region. The total area of flooding, using the 6m level was 254.9 km^2. The total flood volume using the mean of the difference between the highest and lowest flood levels was = 2m x 254.9 km^2 = $5.1 \times 10^8 m^3$.

3. Probable maximum extent of the flood:

Previous work has indicated that flood events may be observed up to one week after peak, by the identification of tide marks and soil moisture content. This has been achieved in areas without dense vegetation. The use of single band photographic material precludes the use of identification by brightness histograms and can lead to complications of land cover identification where vegetational density, rather than type, is significant and where soil moisture may lead to confusion(146). It was therefore not surprising that in circumstances of post-flood imagery and dense vegetation cover, that the maximum extent of the 1979 flood could not be conclusively identified.

4. Estimates of the Belize river floodwater contribution:

An estimate of the Belize river contribution depends upon the identification of two factors: the total amount of water on the floodplain and the proportion of this derived from the local floodplain catchment. To avoid needless repetition, it is convenient to postpone the presentation of this aspect of the flood study research. Chapter 13 presents a detailed study of the Belize river contribution using 1:50,000 scale c.c.t. slide material based upon an analysis of hydrological data presented in Chapter 12.

5. The identification of water movement:

The identification of water movement in the floodplain above Davis Bank gauging station is closely linked with the points of observable overspill and flood water distribution. In many respects the routes of floodwater passage is summarised by Map D which shows the river courses, the overspill points and the ultimate location of floodwater at the time of scene acquisition. The events encompassed by these details may be assumed to follow the sequence given below:

i. Floodwater (from the local catchment area and later from the Belize river) would move to the low-lying lagoonal area in the N.W. of the floodplain.

ii. The expansion of the lagoonal area would occur.

iii. Floodwater within this area would be contained, regardless of Belize river levels, due to the restriction of few, small outlet channels.

iv. With the continued rise of the Belize river, contributions would continue to increase the area of inundation.

v. Drainage would occur, slowly as Belize river levels fell, supplemented by possible new drainage channels, if lagoonal levels were sufficiently high to break the landform features of the area. Text map figure 11.1 shows the details of probable floodwater movement, indicated by LANDSAT band 7 print imagery.

11.2.iii 1:250,000 scale c.c.t. false colour composite slides

Maps of the floodplain area were traced from slides at a nominal scale of 1:250,000. The image quality in all bands was found to be good and the rectification of dropped lines and striping was not necessary. Operator specified contrast stretches were used to visually enhance the images and are given below in table 11.3.

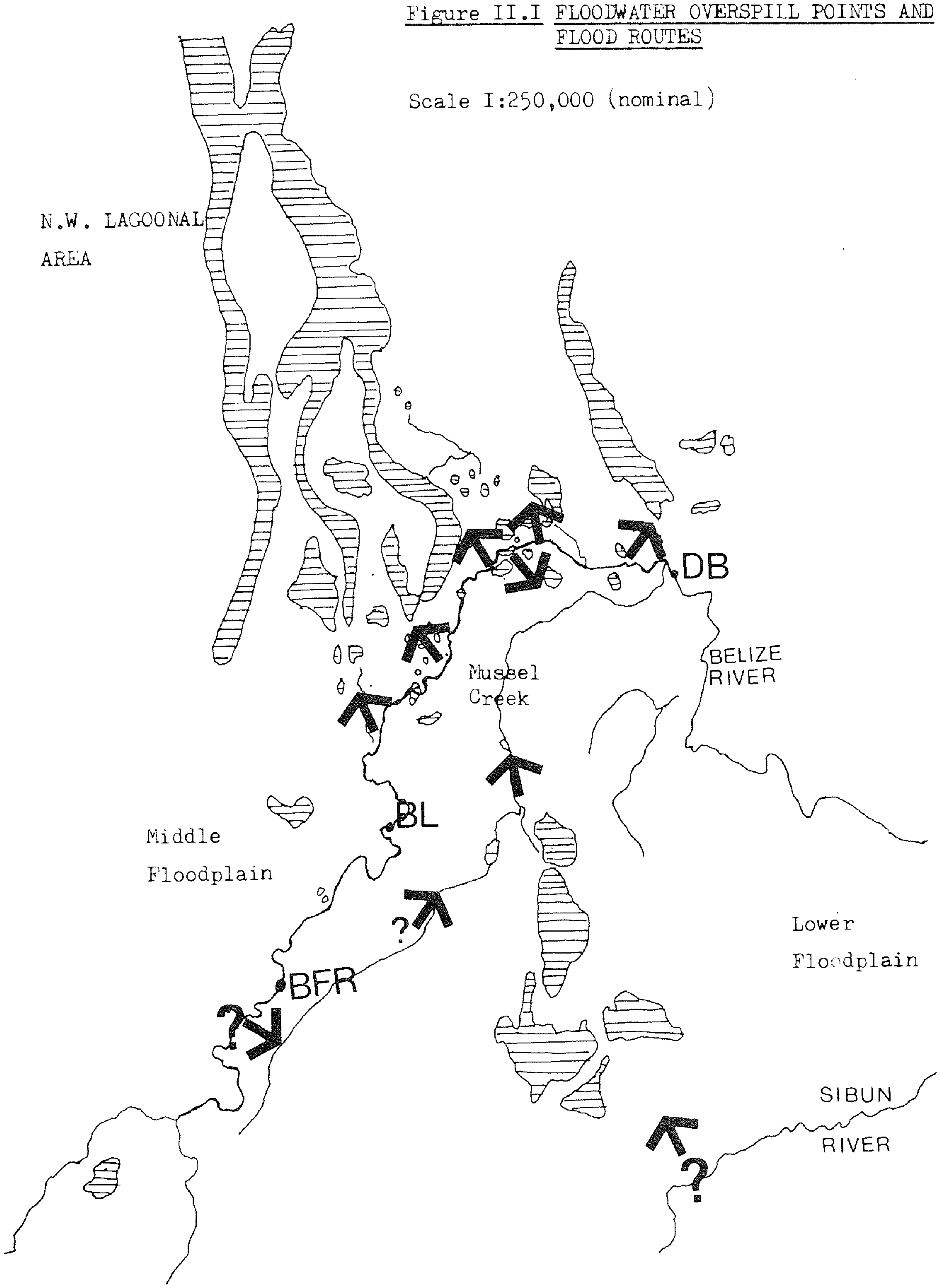
Table 11.3 OPERATOR SPECIFIED CONTRAST STRETCH VALUES

Band	Cut off brightness value	Saturation brightness value
7	5	55
5	0	30
4	0	35

An initial inspection of all bands was made to ascertain quality and usefulness. Bands 4 and 5 proved least useful in terms of the identification of water distribution, but cultural features - field boundaries and roads, were well

Figure II.I FLOODWATER OVERSPILL POINTS AND FLOOD ROUTES

Scale I:250,000 (nominal)



Route of flood water / Overspill point

Suspected route of flood water / overspill point (not observable) presented. Band 7 images proved of good quality and provided water distribution details. False colour composites (f.c.cs.) were identified as the most useful images, with a conventional combination of bands 4, 5 and 7 to be used. In addition, a band ratio of 7 ÷ 5 brightness values was attempted to enhance the information available from the scene. Band 5 vegetation b.vs. are low, those of band 7 high so that such a ratio provides clear distinction from water bodies where b.v. values are low for both bands. On the whole, however, this ratioing was not successful. Chapter 14 describes in detail the image processing techniques applied to the floodplain area.

For the purpose of this study, a series of f.c.c., undecimated images were used, the composite map that was obtained being map E, presented at 1:250,000 scale. It can be seen by the comparison of maps D and E, that far greater detail was presented by the use of computer compatible imagery. It was obvious that should projection at 1:50,000 scale be possible, that such detail could be best expoited at this scale.

To summarise the most important overall conclusions of the preliminary observation of the flood scene, using both information formats, it may be stated that :

1. LANDSAT band 7 prints provided significant information relating to the extent and distribution of the floodwater. It gave details regarding water movement and spillage locations and an inventory of the main water bodies.
2. LANDSAT c.c.t. slides provided still more information and that their use at a scale of 1:50,000 was indicated to fully explore this information.
3. To understand the contribution to flooding, of the Belize river, hydrological analysis of the flood flow volumes of the river was necessary.

It was with regard to this latter point that the study of the Belize river flood flows, in the next chapter, were undertaken.

CHAPTER 12 THE HYDROLOGY OF THE 1979 FLOOD

12.1 INTRODUCTION

The floodscene 020/48, 26th December 1979, records the details of post peak flood conditions that are otherwise undocumented. No hydrological records of the event are available. In this chapter unit hydrograph (u.h.) methods are used to define the parameters of the flood. An attempt is made to relate postulated flows with those indicated by the flood scene and with specified return period flows determined by the peaks over threshold (P.O.T.) series method.

The method of u.h. derivation, the limitations of its use and theoretical qualifications are widely documented in research literature and hydrological textbooks(147), (148), (149). The Flood Studies Report (F.S.R.) devotes considerable space to these details and a resume of these details and conditions is given below:

1. The concept proposes a linearity of runoff, which has been shown not necessarily to be correct. 5% to 25% taller and thinner flood peaks have been suggested(150).
2. The assumption of uniform spacial distribution of rainfall over the catchment is a limiting factor. The F.S.R. recommends a catchment size limit of 500 km^2, but opinions differ and areas as large as 8,000 km^2 (151) have been suggested where reduced accuracy is acceptable.
3. Some assessment of antecedent catchment conditions should be made, primarily catchment wetness.
4. Storm movement up or down the catchment should be considered since this can alter u.h. shape.
5. Storm events of more or less uniform intensity are desirable.
6. Unit hydrographs from a number of storms should be taken and averaged.

In some respects, the data from Belize and the nature of the catchment do not meet these conditions. The catchment sizes involve a range 5,000 km^2 to 8,000 km^2. Rainfall values are daily totals, as are discharge values. The period of significant rainfall in each case is approximately 4 days and rainfall intensities cannot be considered uniform, though the large catchment sizes to some extent lessens this problem. Antecedent conditions cannot be determined accurately, but since both the 1979 flood and the events used to determine the unit hydrographs occur during the 'wet' season, evapotranspiration and soil moisture conditions can be assumed to be similar. The passage of the rainfall events will also be the same.

Thus, while the limitations of hydrological and meteorological data will inevitably reduce the accuracy of the results, general conditions do not prohibit the use of the method to obtain estimates of peak flow, volume and duration. It is the application of such methods in difficult practical circumstances that ultimately prove their worth.

12.2 CONSTRUCTION OF UNIT HYDROGRAPHS FOR THE 1969 AND 1971 FLOOD

12.2.i Background

Only two flood events, occurring in 1969 and 1971 were suitable for the construction of unit hydrographs. The methods of unit hydrograph construction described by the F.S.R. (152), modified for the data, are used. Since comparisons are made for the same catchments the spacial uniformity of rainfall was not a critical factor(153). Variations in antecedent conditions were assumed to be similar in each case.

The rainfall periods giving rise to the 1969 and 1971 flood events are listed below in table 12.2. For convenience they were considered as covering a 4 day period, rising to peak on the second day, declining thereafter. Weighting of rainfall values was done by the Theissen polygon method, though rainfall station distribution inevitably led to rounding of some weighting values.

Because of the general lack of continuous rainfall data in Belize, necessary changes of stations were made for the 1979 event, to provide the maximum amount of rainfall information. Map figure 8.4 shows the location of rainfall stations and abbreviations.

Table 12.1 PERCENTAGE WEIGHTING FOR RAINFALL STATIONS, 1969 AND 1971

Gauging Station	Rainfall Station % Weighting					
1969	BIA	H.H.	C.C.	S.I.	N.F.	B.F.R.
I.C.	NA	10	50	30	10	NA
B.BK.	NA	10	45	25	20	NA
B.L.	NA	7	40	13	25	15
B.F.R.	NA	7	40	13	25	15
D.B.	NA	6.5	35	10	27	19.5
1971						
I.C.	NA	15	50	NA	35	NA
B.BK.	NA	17.5	45	NA	37.5	NA
B.L.	NA	17.5	50	NA	32.5	10
B.F.R.	NA	16	52.5	NA	31.5	13
D.B.	NA	13	67	NA	20	20

Table 12.2 WEIGHTED RAINFALL VALUES FOR GAUGING STATIONS (m.m.)

Date	Catchment Areas/Gauging Stations				
Sept.1969	I.C.	B.BK.	B.F.R.	B.L.	D.B.
2nd	64.25	62.00	60.03	60.03	60.40
3rd	94.05	93.91	86.16	86.16	82.29
4th	23.62	21.33	21.13	21.13	25.77
5th	13.72	17.42	18.70	18.70	19.12
4 day TOTAL	196.64	194.56	186.02	186.02	187.58
Nov.1971					
19th	15.60	16.50	16.35	20.75	20.44
20th	120.15	121.72	124.33	123.46	113.13
21st	84.03	76.61	72.34	71.63	70.11
22nd	12.95	11.66	10.36	10.10	9.58
4 day TOTAL	232.73	226.49	223.38	225.94	213.26

Unit hydrograph construction was achieved by the following steps.

1. The 4 day storm duration was selected, relating to the rainfall giving the 1969 and 1971 peaks.
2. The response runoff was calculated by the subdivision of the hydrographs, according to methods recommended by the F.S.R. relating to lag time and hydrograph separation(154), (155).
3. The rainfall profile was reduced such that net volume equalled response runoff.
4. The 1969 and 1971 unit hydrographs were averaged to provide a mean u.h. In the case of Davis Bank, data for the 1971 flood only was available.
5. The mean u.h. was applied to the net rainfall profile of the 1979 flood.
6. Non-response runoff was determined by estimation from the 1969 and 1971 flow hydrographs and added to the constructed 1979 unit hydrograph.

12.2.ii Alternative methods of hydrograph separation

In this way the unit hydrograph for 1979 was determined from all rainfall records The separation of the flow hydrographs of the 1969 and 1971 events can be considered in detail at this stage and two alternative methods discussed. It will be seen that the use of one method or the other can have a considerable effect upon the nature of the results obtained.

The two methods, the first (Method 1) recommended by the F.S.R., the latter (Method 2) widely used by hydrologists are considered below(156), (157). The essence of the F.S.R. method is explained by the diagram below, figure 12.1

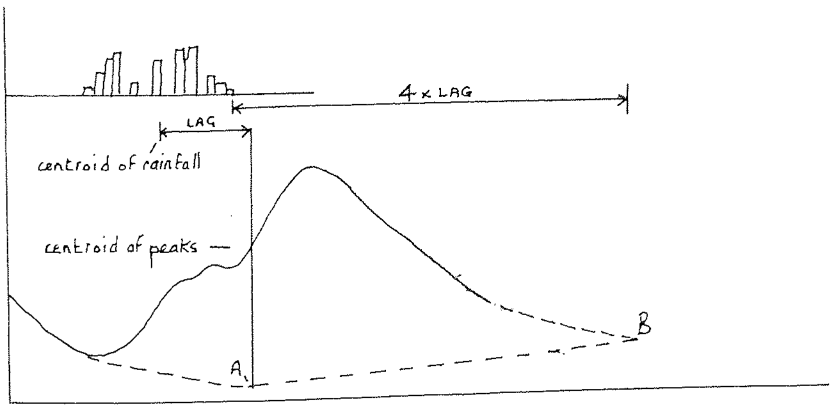


Figure 12.1 UNIT HYDROGRAPH SEPARATION AND LAG TIME EVALUATION

The second method separates the flow components of the flow hydrograph by drawing a line from the point of base flow recession of the peak prior to the study peak, to the point of base flow of the study peak. The points of base flow recession are determined exactly by plotting synthesised recession curves on semi-logarithmic scales to reduce the curve to the components of surface, base and interflow.

Both methods present the idea that response runoff declines until it is insignificant and base flow predominates, but each method provides different proportions of response runoff. The differences for Belize data were noted as follows:

1. In all cases the F.S.R. method gave a greater proportion of flow to response runoff.

2. This difference of response runoff was consistently small in the cases of tall, short duration peaks (12.8% at Iguana Creek, 16.3% at Banana Bank). The difference was large for stations with short, long duration peaks (57.1% at Big Falls Ranch, 30.8% at Bermudan Landing, 192.6% at Davis Bank).

3. The total flow attributable to particular events was increased by the use of the F.S.R. method.

The significance of the difference of these methods is great. It is surprising therefore that the F.S.R. states "compared to other assumptions in hydrological analysis, the method of recession extension (upon which the separation of flow components is based) is not very important (158). Importantly, the F.S.R. reports that a pilot study determined that the lag time model was the most "realistic" and that manual hydrograph analysis produces results very similar to those produced by computer models examined by the Report. In the light of this, unit hydrographs were produced by use of the F.S.R. method. Table 12.3 below shows flow volumes for response, non-response and total flow obtained by the use of both methods, for comparison.

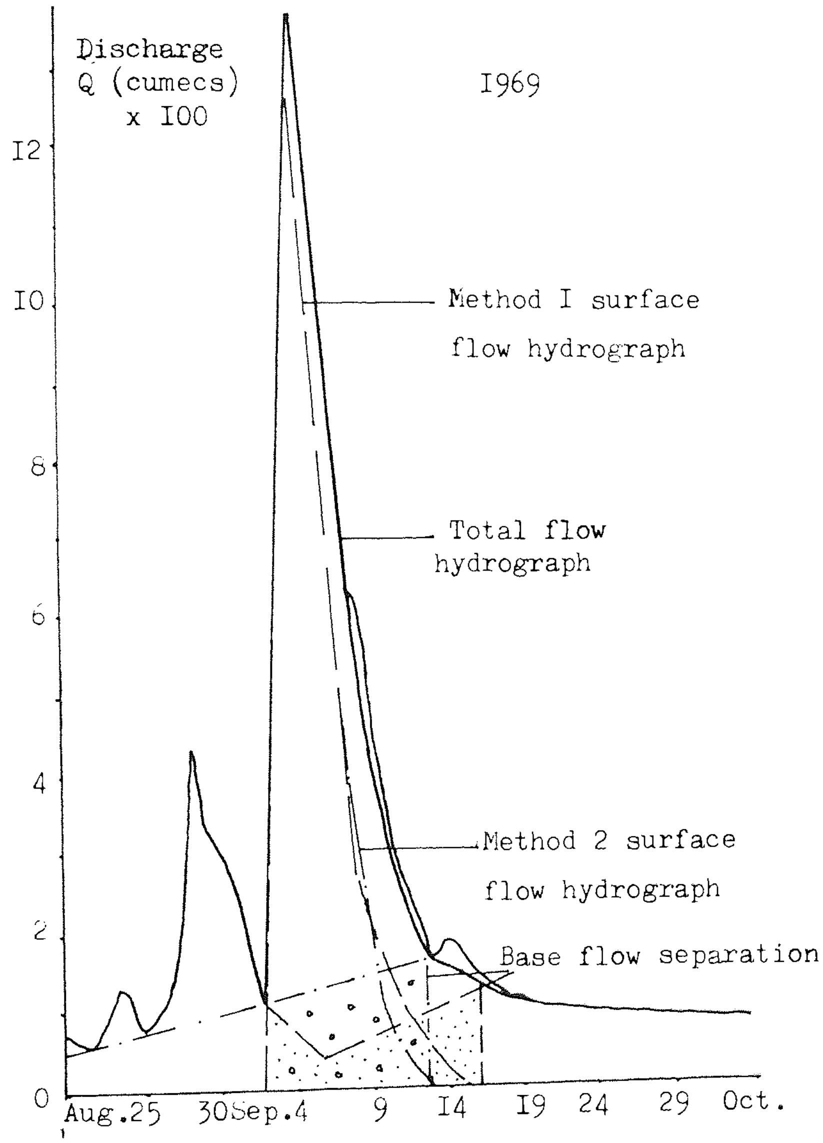


Figure I2.2 IGUANA CREEK RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I969

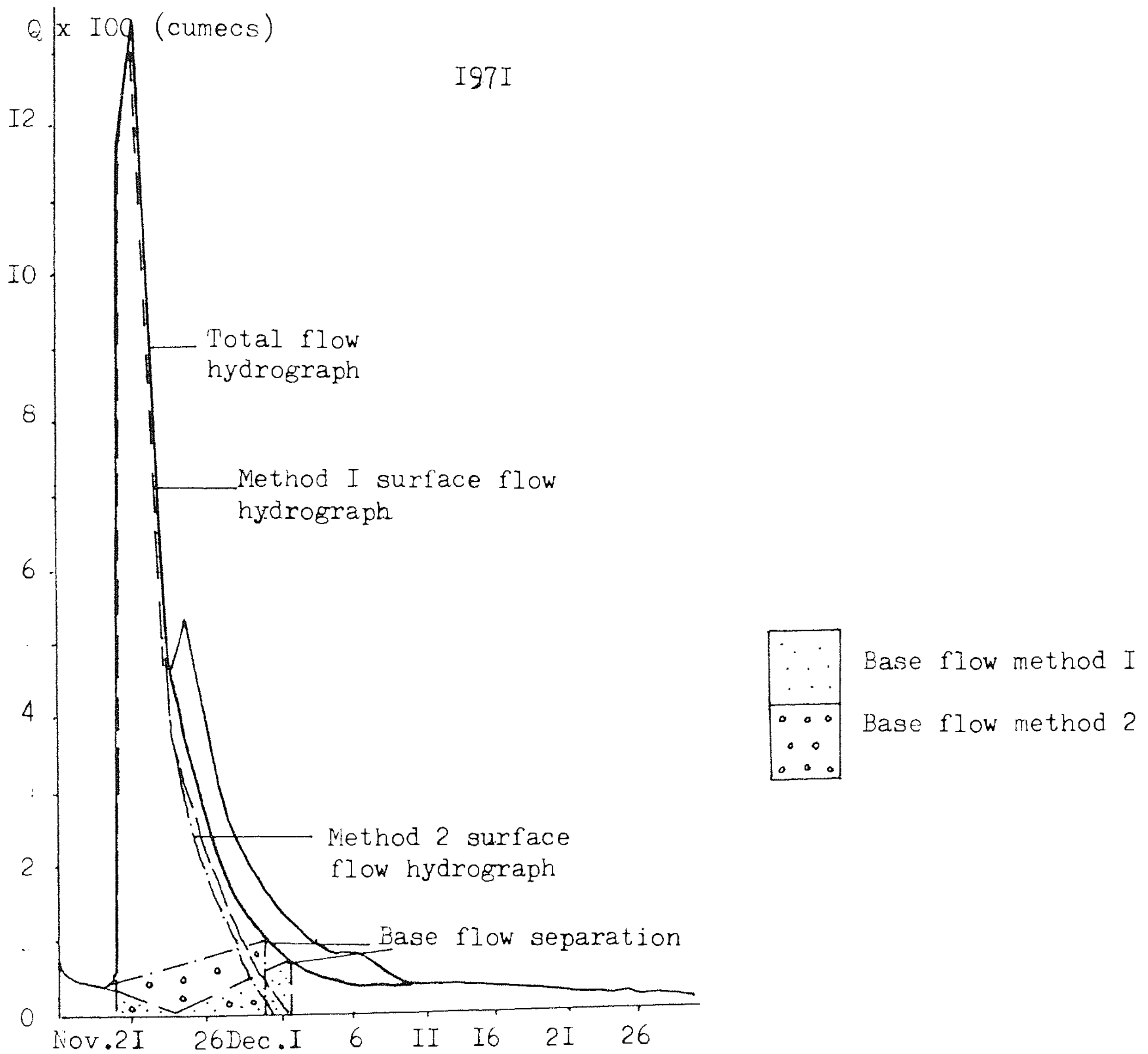


Figure I2.3 IGUANA CREEK RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I97I

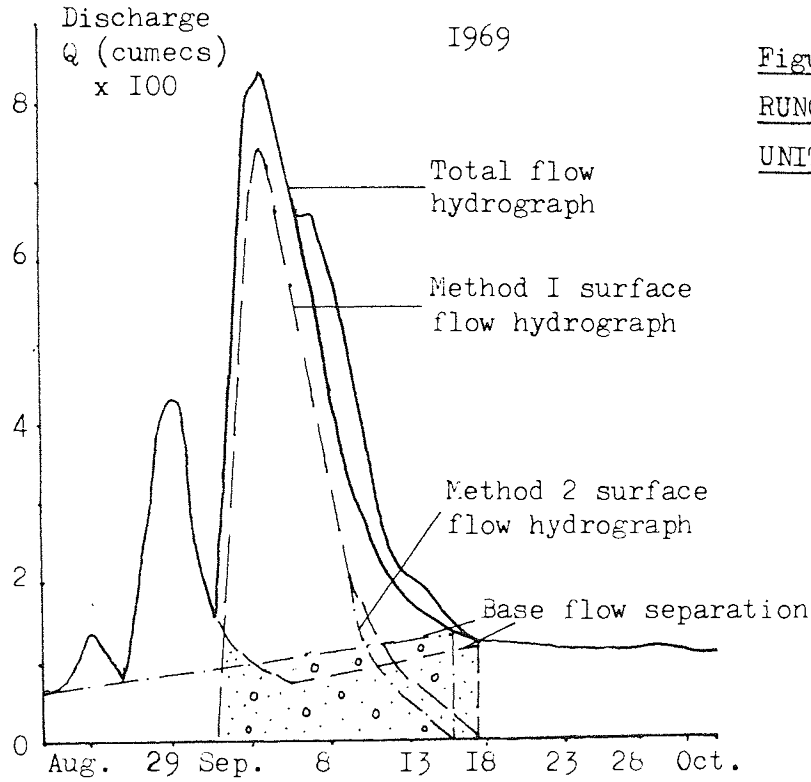


Figure I2.4 BANANA BANK RUNOFF HYDROGAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I969

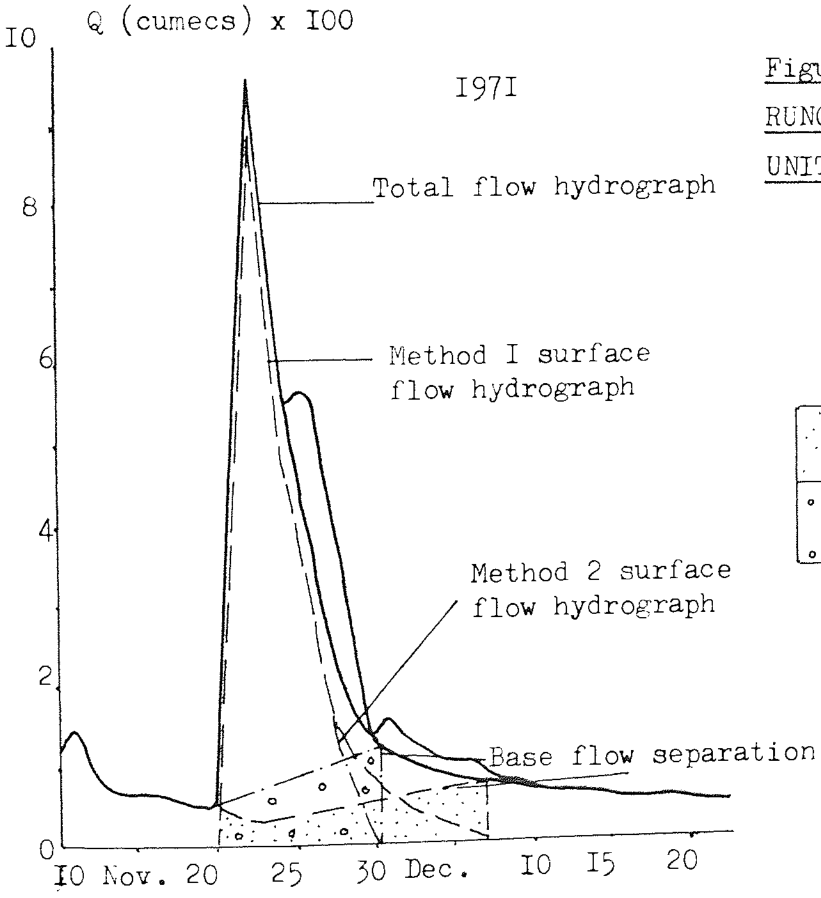
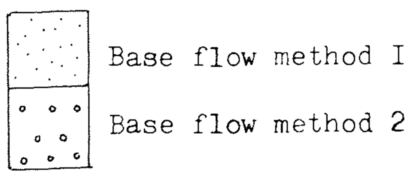


Figure I2.5 BANANA BANK RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I97I



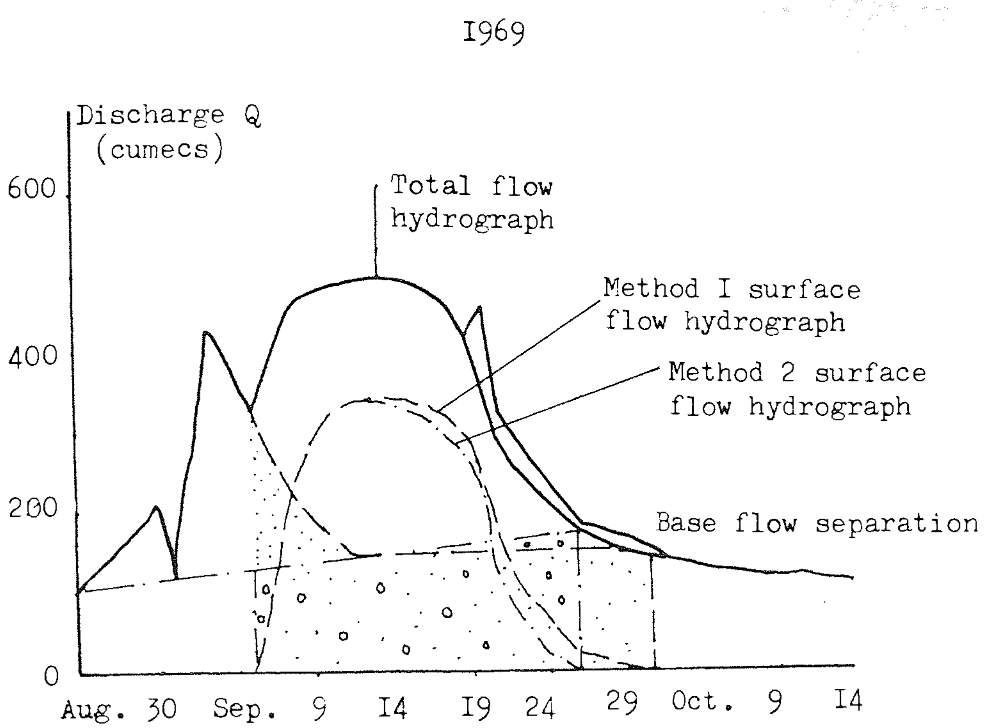
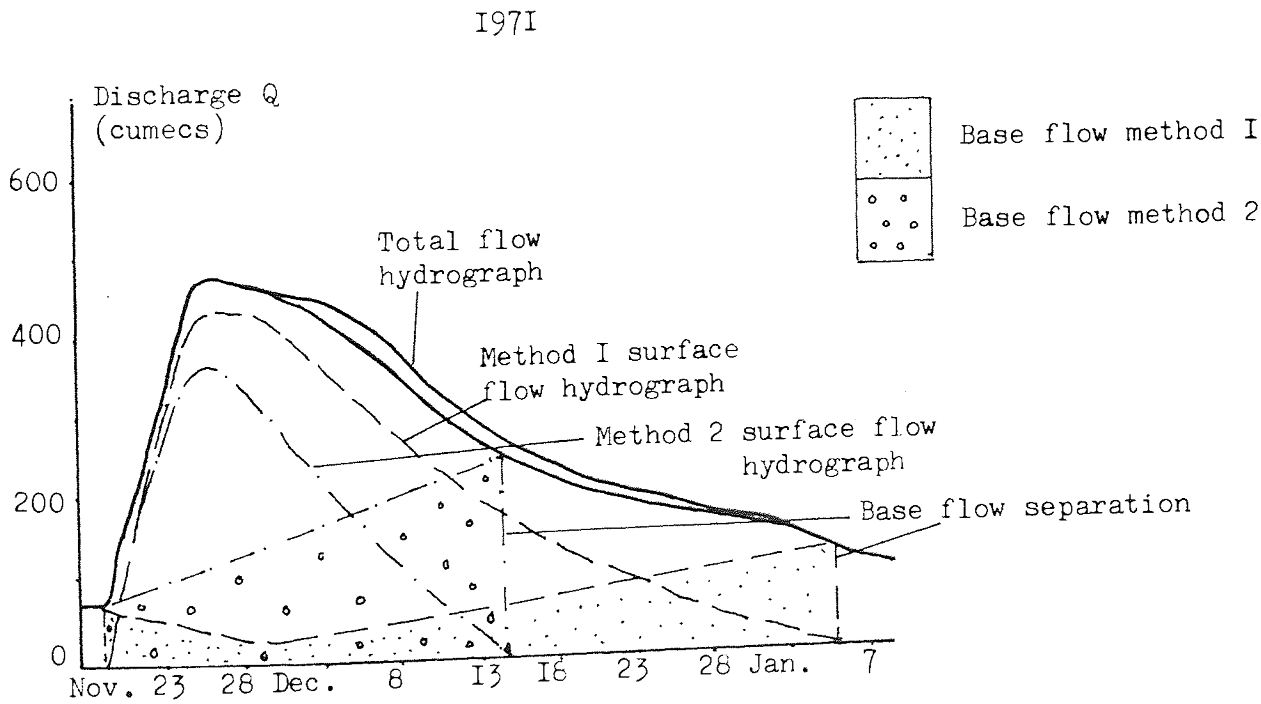


Figure I2.6 BIG FALLS RANCH
RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I969

Figure I2.7 BIG FALLS RANCH
RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I97I



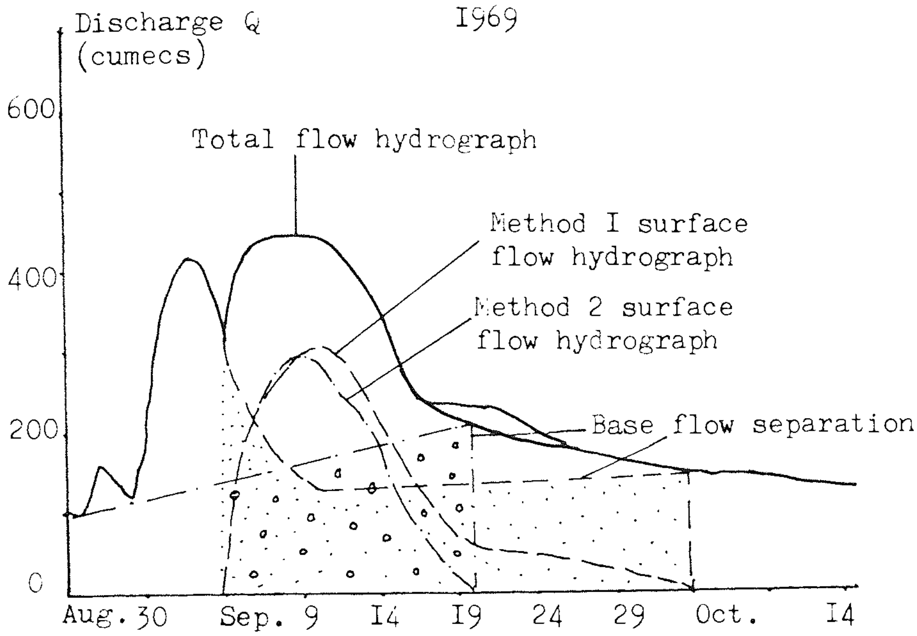
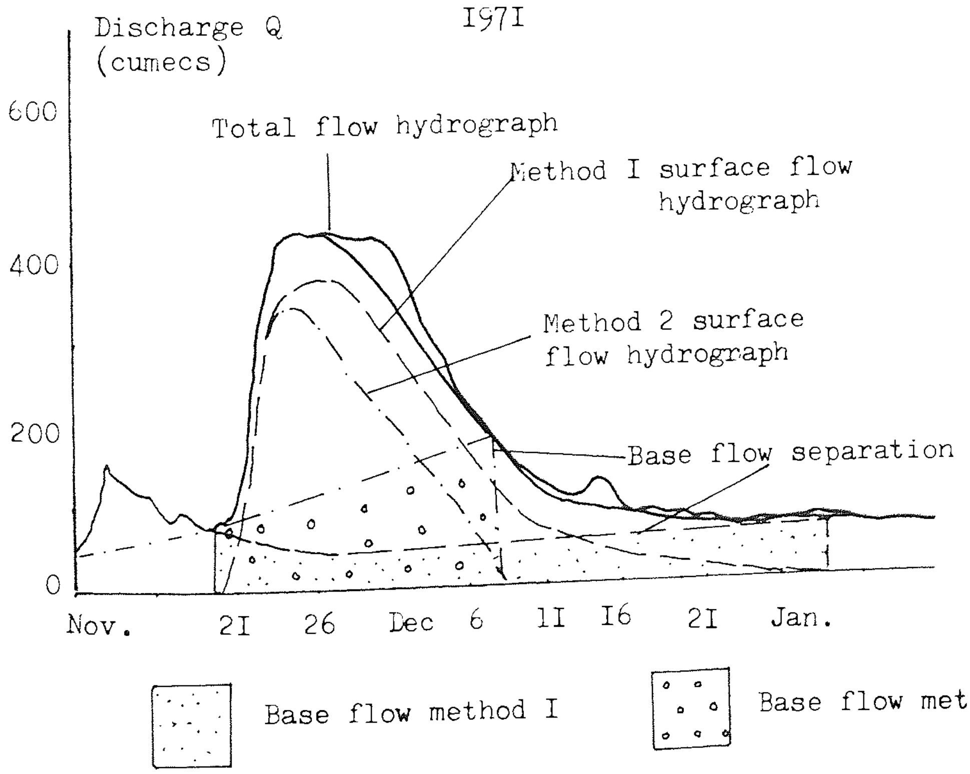


Figure I2.8 BERMUDAN LANDING
RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I969

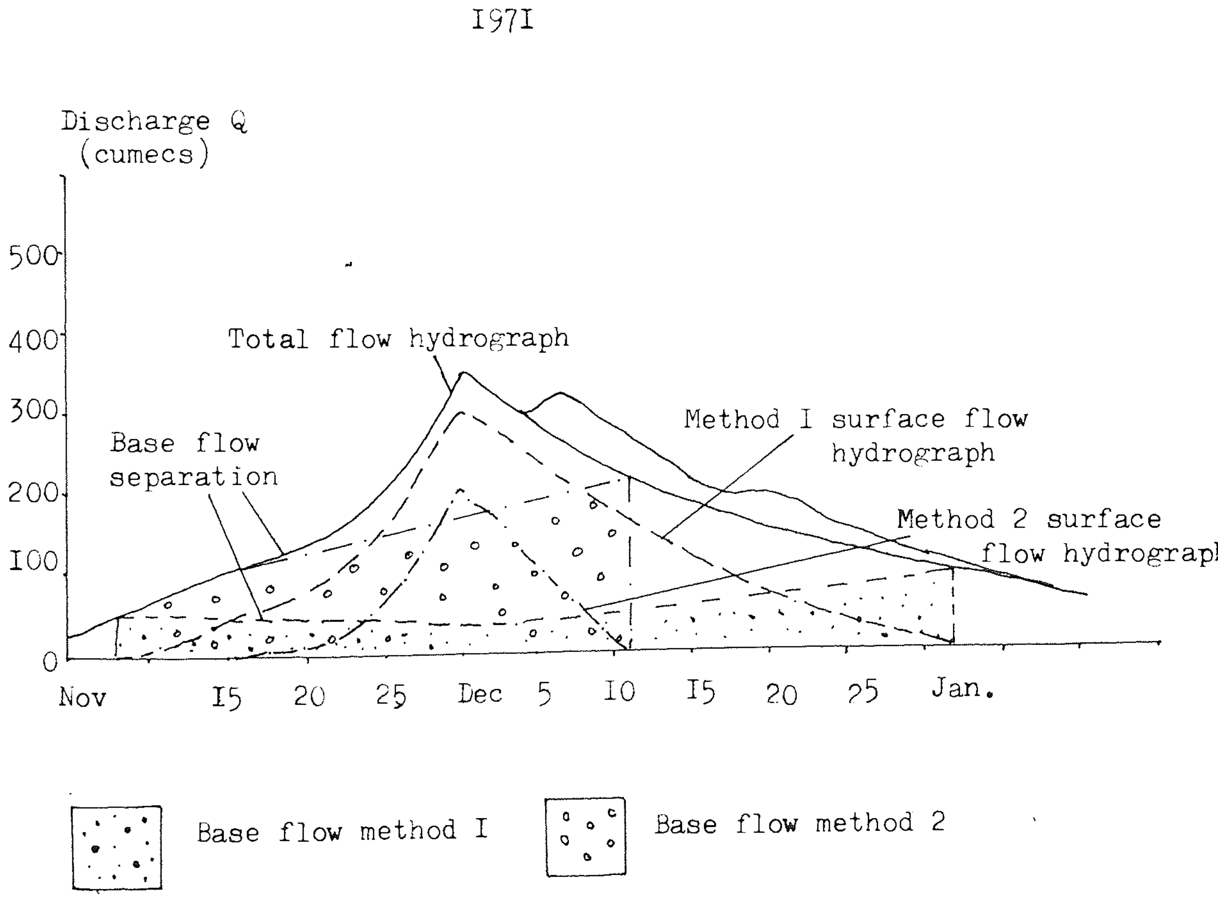
Figure I2.9 BERMUDAN LANDING
RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I97I



Rainfall centroid lag times

I.C.	I969 2.5 days,	I97I 2.5 days
B.BK.	3.0 "	2.5 "
B.F.R.	5.0 "	9.0 "
B.L.	6.0 "	7.5 "
D.B.		I3.0 "

Figure I2.I0 DAVIS BANK RUNOFF HYDROGRAPH USED FOR UNIT HYDROGRAPH SYNTHESIS I97I

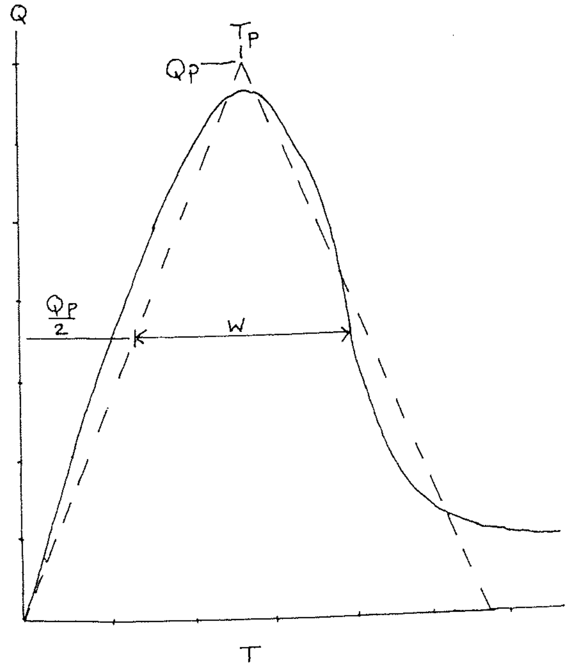


12.2.iii Construction of 4 day unit hydrographs (10 m.m.) and conversion to 1 day

4-day unit hydrographs equivalent to 10 m.m. of rainfall were constructed for 1969 and 1971 for all stations except Davis Bank where only 1971 data was available. The response flow hydrographs as shown in figures 12.2 to 12.10 were reduced in proportion according to rainfall values given in Table 12.4

For example : Iguana Creek 1969; Response runoff discharge values were divided by a factor of 93.8(m.m.) ÷ 10 (m.m.) = 9.38. The reduction of all response runoff discharge values by this factor results in the 10 m.m. 4-day unit hydrograph. This represents the application of a straightforward proportion of the rainfall leading to the 1969 and 1971 flood events, no account was taken of antecedent and changing catchment conditions.

Figures 12.12 to 12.16 show the 4-day unit hydrographs for all stations for 1969 and 1971, and the mean of these hydrographs. These figures also show the parameters necessary to convert them from a 4-day to a 1 day time base. The application of 1 day unit hydrographs is very much more convenient than that of 4 day unit hydrographs. The method of this conversion is discussed below and explained by example, using Iguana Creek data(159).



The unit hydrograph for 1 day is calculated by assuming the product of Qp. Tp and the proportion W/Tp remain the same. Thus for Iguana Creek where : Tp = 2 days, Qp = 159 cumecs and W = 3 days.

The recalculated values are :

$Tp_1 = Tp - \frac{1}{2}(3) = 0.5$ days

$Qp_1 = 318/0.5 = 636$ cumecs

$W_1 = {}^3/_2 \times 0.5 = 0.75$ days

Figure 12.11 CONVERSION OF UNIT HYDROGRAPHS FROM 4 DAY to 1 DAY

Figure 12.12 OBTAINING Tp, Qp AND w FROM 4-DAY UNIT HYDROGRAPH FOR THE CONSTRUCTION OF THE 1-DAY UNIT HYDROGRAPH

IGUANA CREEK

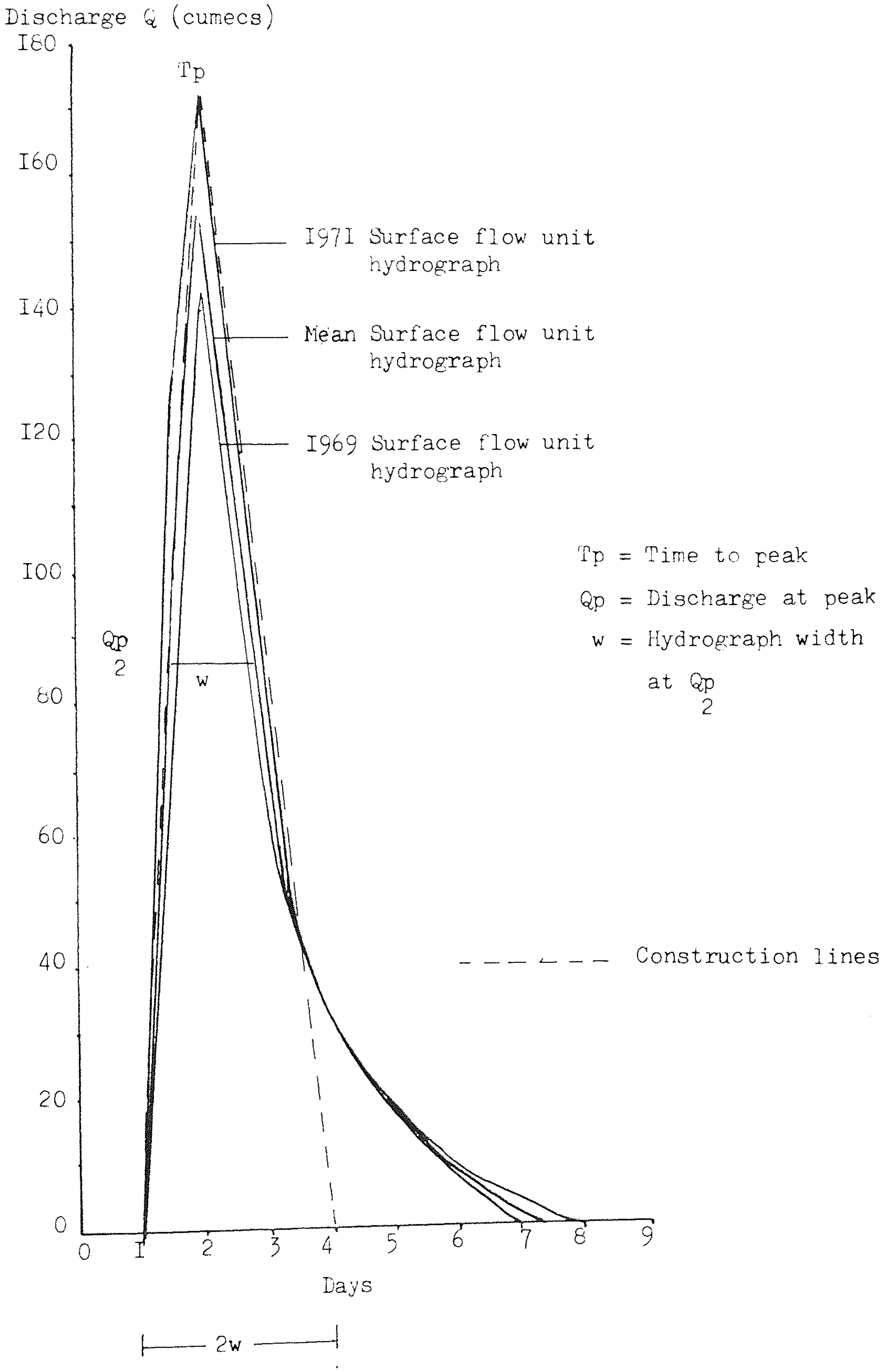


Figure 12.13 OBTAINING Tp, Qp AND w FROM 4-DAY UNIT HYDROGRAPH FOR THE CONSTRUCTON OF THE I-DAY UNIT HYDROGRAPH

BANANA BANK

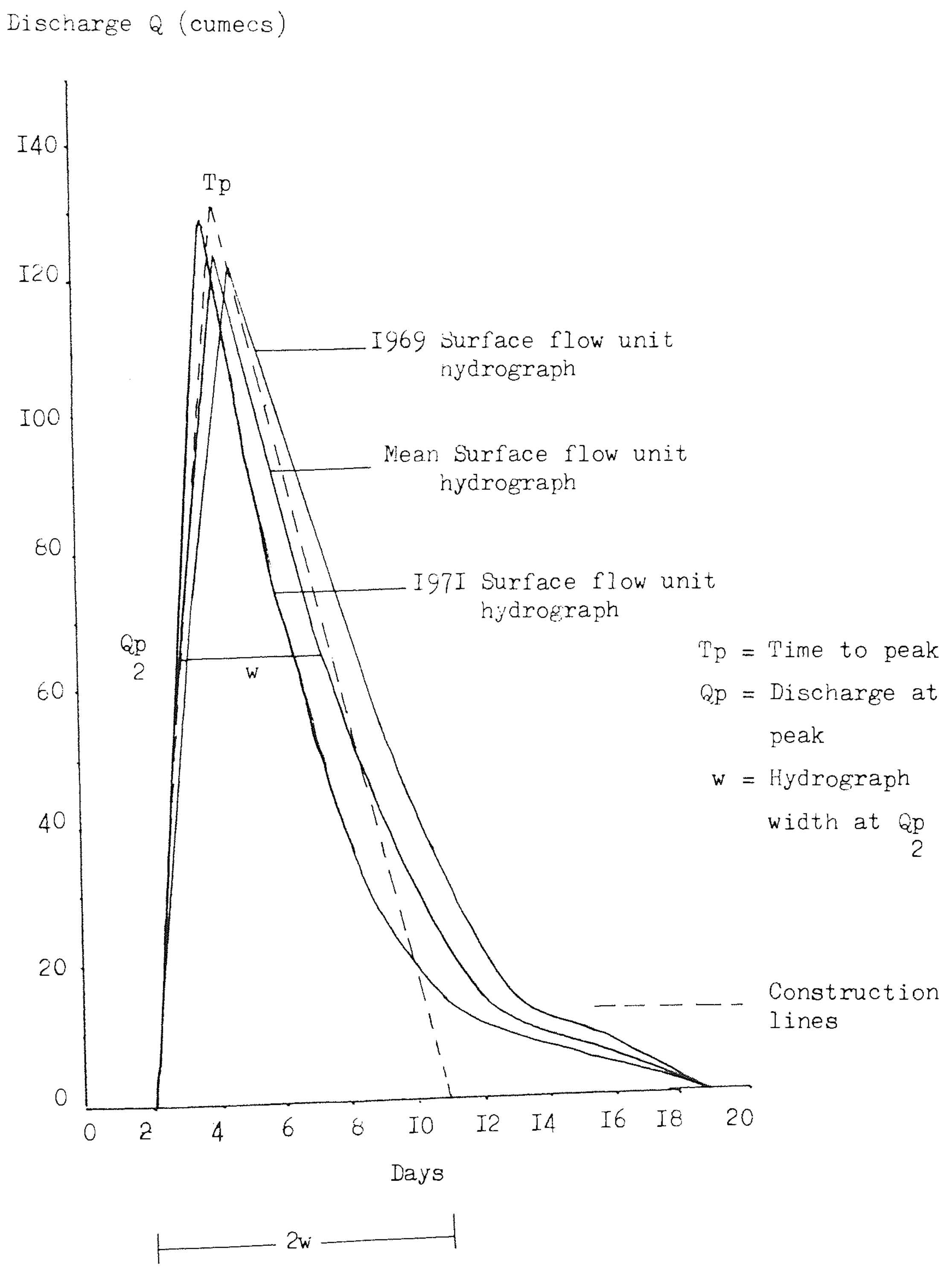


Figure 12.14 OBTAINING Tp, Qp and W FROM THE 4-DAY UNIT HYDROGRAPH FOR THE CONSTRUCTION OF THE 1-DAY UNIT HYDROGRAPH

BIG FALLS RANCH

Tp = Time to peak

Qp = Discharge at peak

W = Hydrograph width at $\frac{Qp}{2}$

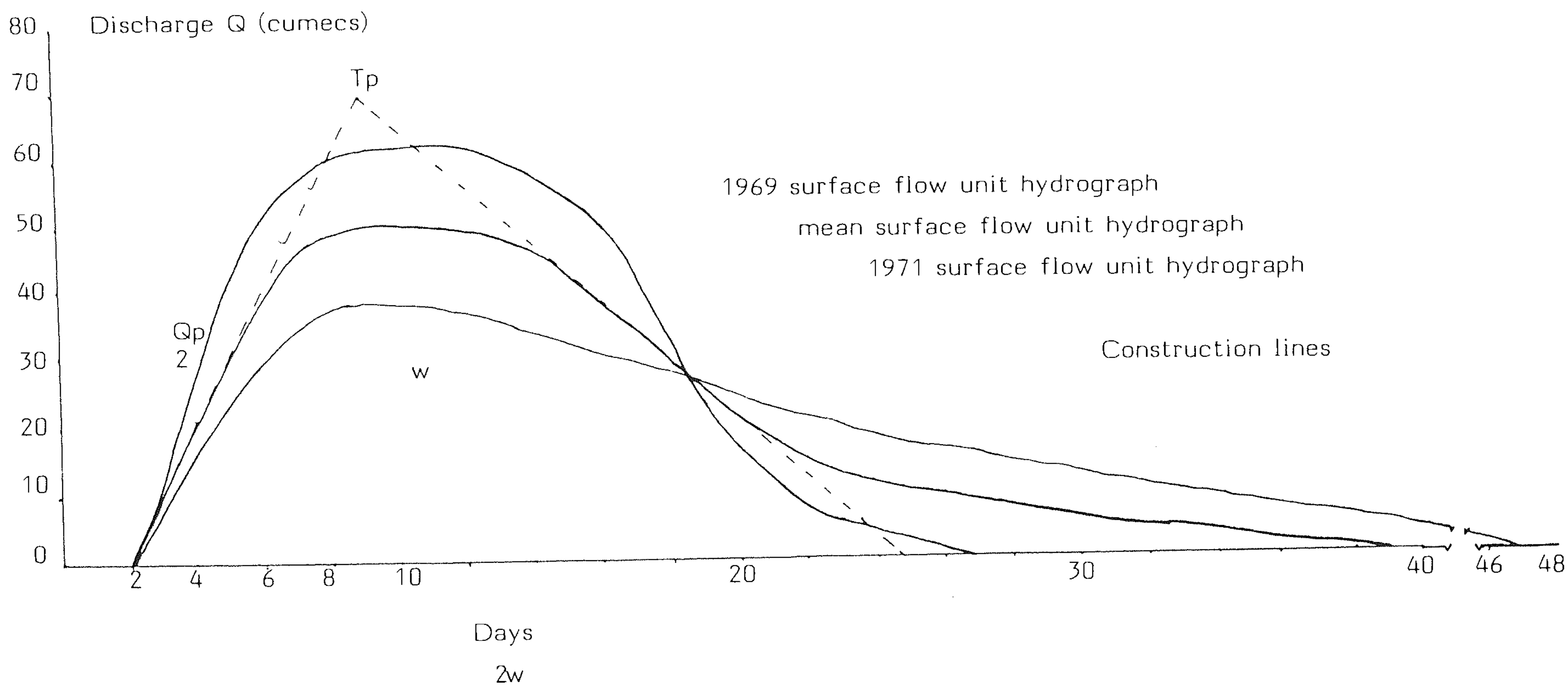
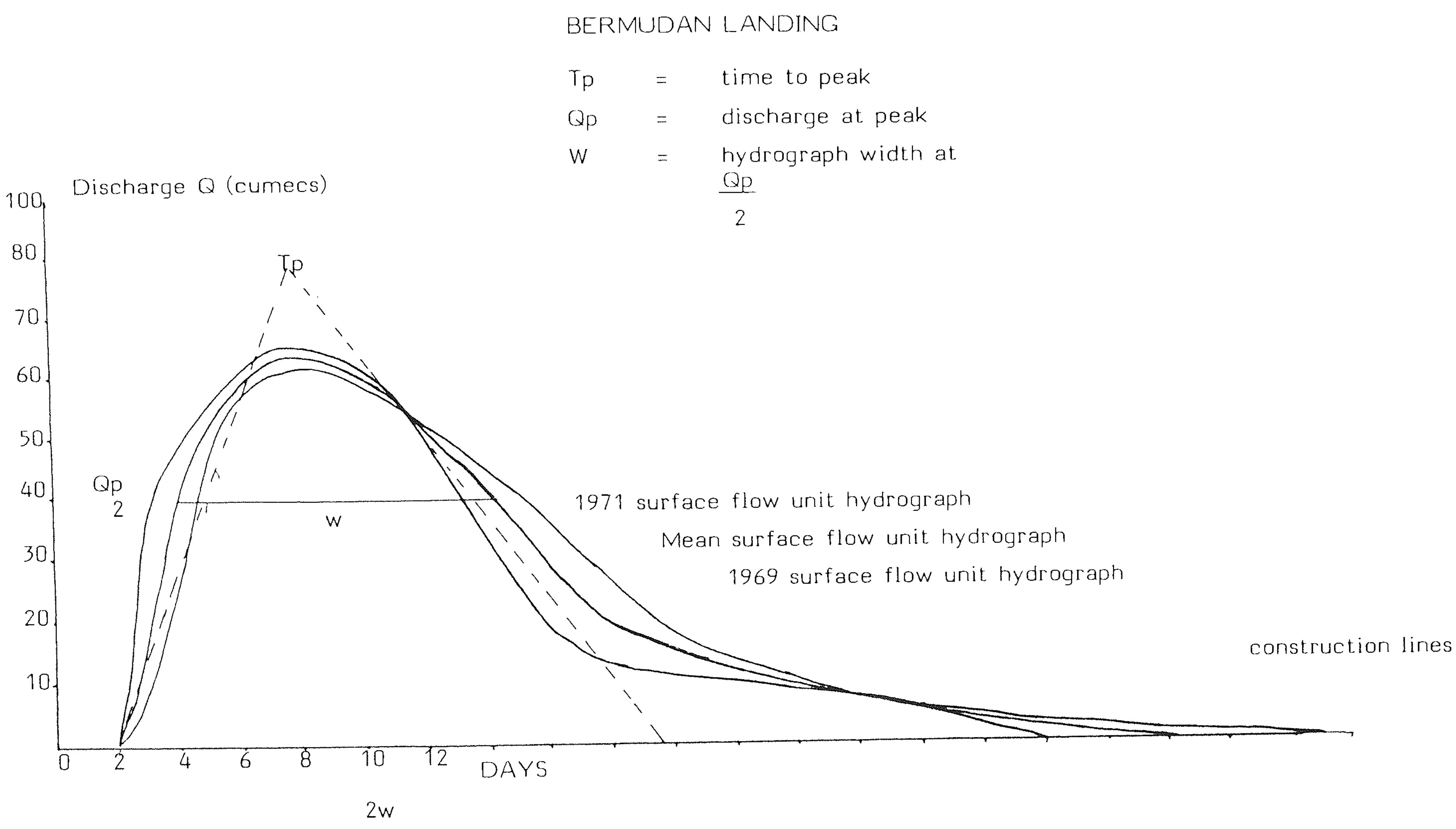


Figure 12.15 OBTAINING Tp, Qp AND W FROM 4-DAY UNIT HYDROGRAPH FOR THE CONSTRUCTION OF 1-DAY UNIT HYDROGRAPH



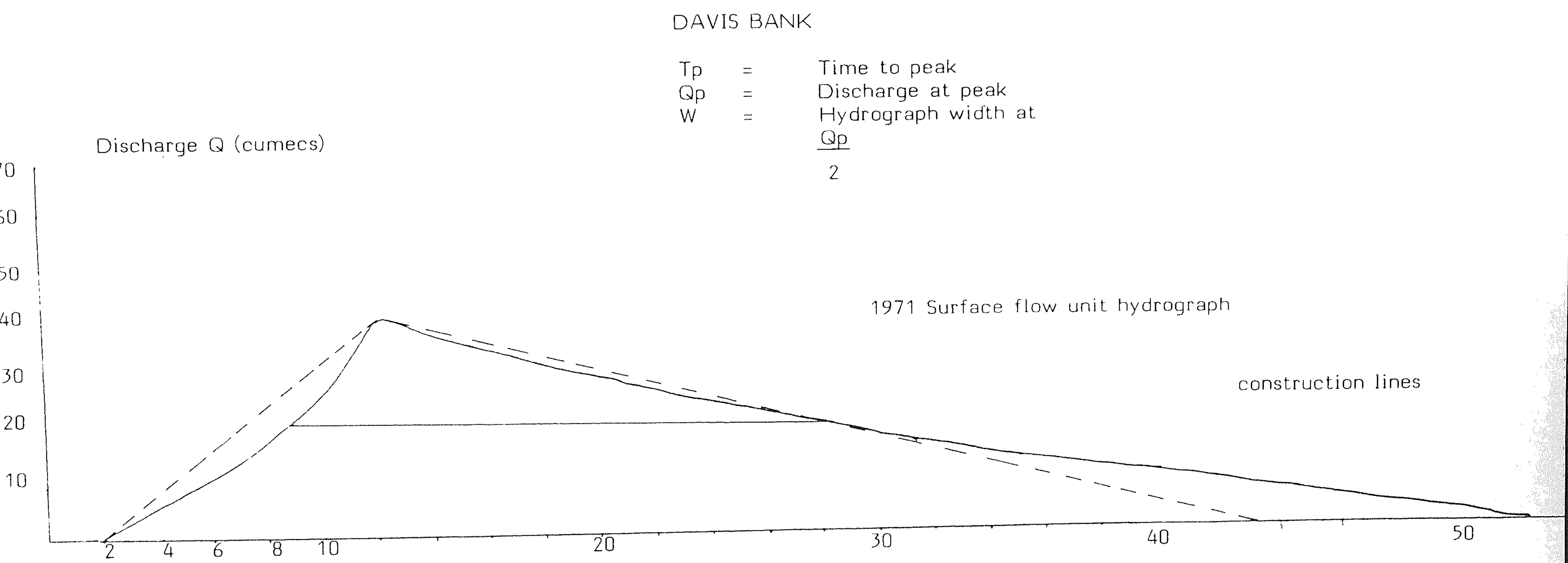
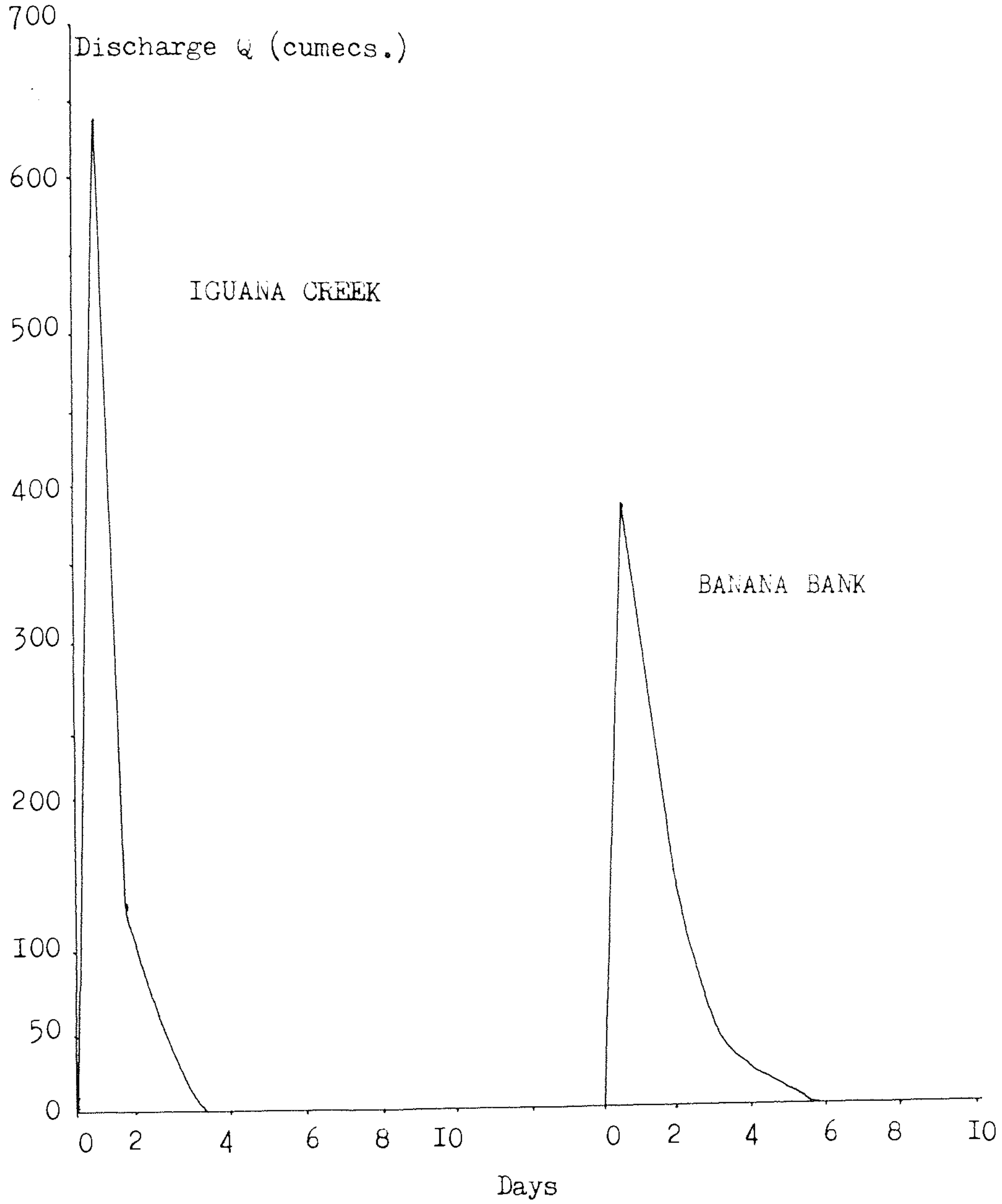


Figure 12.16 OBTAINING Tp, Qp, AND W FROM 4-DAY UNIT UNIT HYDROGRAPH FOR THE CONSTRUCTION OF THE 1-DAY UNIT HYDROGRAPH



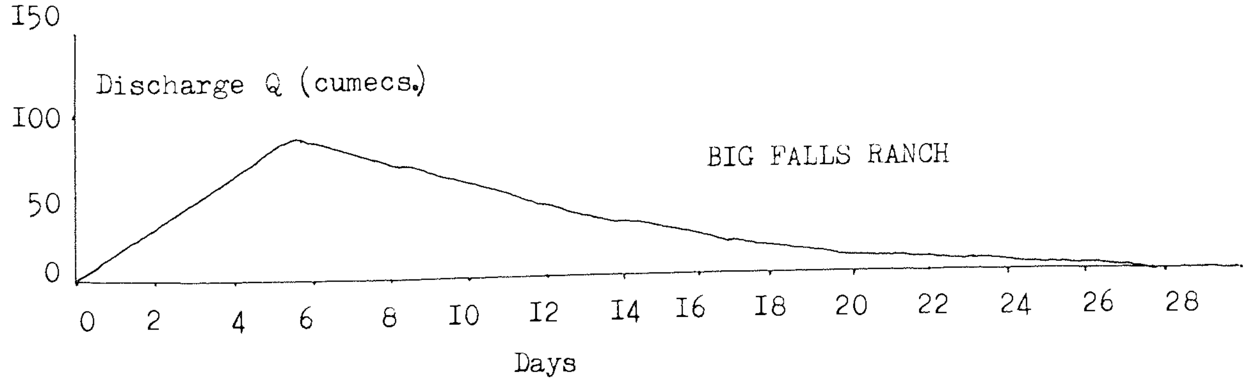


Figure I2.I7 RECONSTRUCTED I-DAY SURFACE FLOW UNIT HYDROGRAPHS

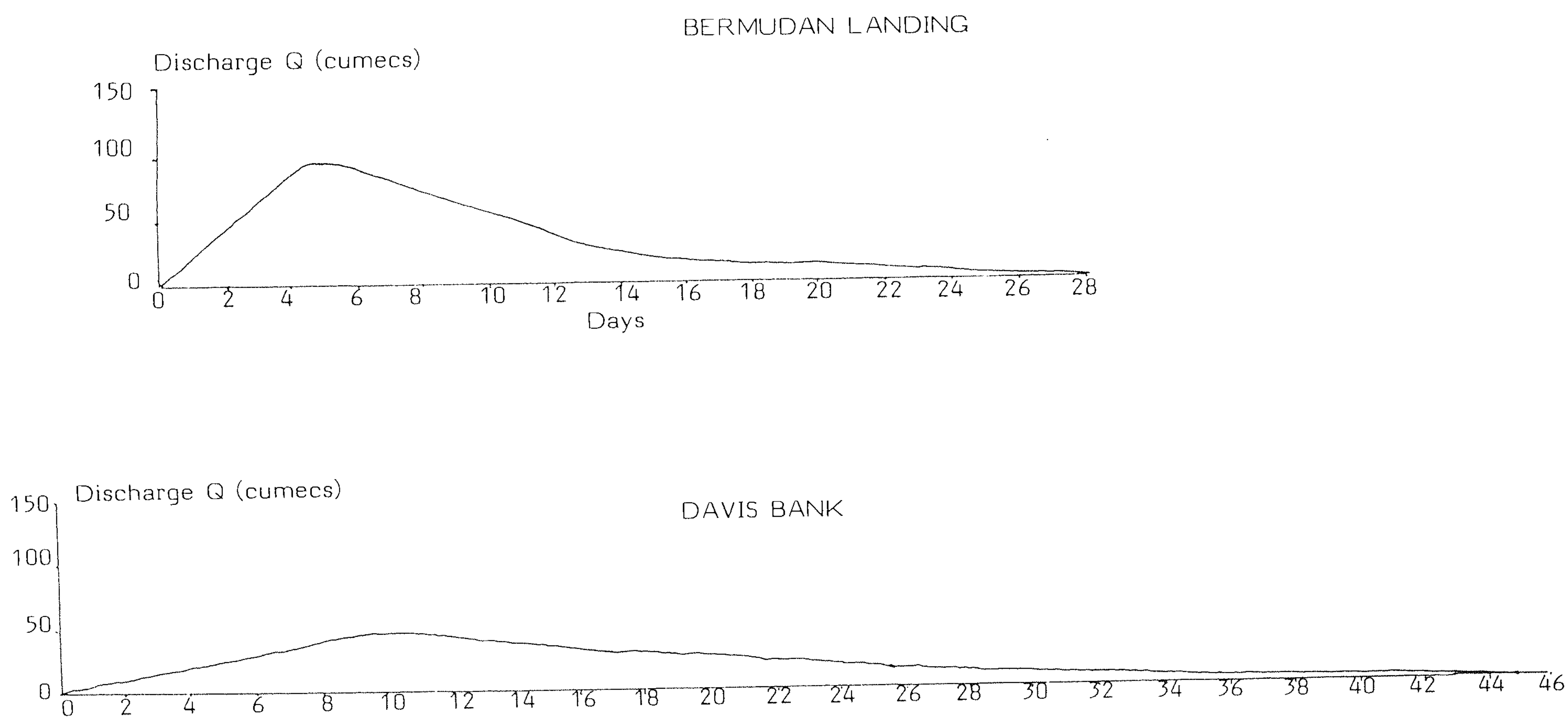


Figure 2.18 RECONSTRUCTED 1 DAY SURFACE FLOW UNIT HYDROGRAPH

Table 12.3 FLOW VOLUMES FOR GAUGING STATIONS, 1969 and 1971 (cumecs x 10^8)

Station	F.S.R. Method (1)			Logarithmic Method (2)		
1969	Response	Non-Response	Total	Response	Non-Response	Total
I.C.	4.89	0.99	5.88	4.32	1.11	5.43
B.BK.	4.21	1.38	5.59	3.63	0.83	4.46
B.F.R.	3.93	2.89	6.82	3.81	2.67	6.48
B.L.	3.20	3.21	6.41	2.50	2.09	4.59
D.B.	NA	NA	NA	NA	NA	NA
1971						
I.C.	4.08	0.73	4.81	3.63	0.83	4.46
B.BK.	3.64	0.47	4.11	3.12	0.72	3.84
B.F.R.	8.43	2.59	11.02	4.06	3.28	7.34
B.L.	4.40	1.76	6.16	3.31	1.52	4.83
D.B.	5.56	2.25	7.81	1.90	2.89	4.79

The response runoff values obtained shown in table 12 3 for the F.S.R. method were converted into equivalent rainfall over the catchment as shown below in table 12.4.

Table 12.4 METHOD 2 RESPONSE RUNOFF AS M.M. RAINFALL OVER CATCHMENTS

Station	Response runoff (cumecs)	Catchment area (km^2)	m.m. rainfall	% Total Rainfall
1969				
I.C.	4.89	5213	93.8	47.9
B.BK.	4.21	6040	69.7	28.5
B.F.R.	3.93	7080	55.5	29.8
B.L.	3.20	7123	44.9	24.1
D.B.	NA	7942	NA	NA
1971				
I.C.	4.08	5213	78.3	33.6
B.BK.	3.64	6040	60.3	26.6
B.F.R.	8.43	7080	119.1	53.3
B.L.	4.40	7123	61.8	27.4
D.B.	5.56	7942	70.0	32.8

Table 12.5 below presents original and converted parameters for all stations, using the mean 4-day unit hydrographs.

Table 12.5 VALUES OF TP, QP, AND W, FOR ALL STATIONS

Station	Original Values			Converted Values		
	Tp	Qp	W	Tp	Qp	W
I.C.	2.0	159.0	3.0	0.5	636.0	0.75
B.BK.	2.25	130.0	4.5	0.75	390.0	1.50
B.F.R.	7.0	70.0	11.5	5.50	89.1	9.0
B.L.	6.0	80.0	9.0	4.50	106.7	6.75
D.B.	10.0	40.0	21.0	8.50	47.1	17.85

The converted 1 day unit hydro graphs are shown in figures 12.17 and 12.18.

12.2.iv Application of 1 day (10 m.m.) unit hydrographs for the 1979 flood

The application of the 1 day unit hydrographs was made considering the 7 day period of rainfall in 1979 that caused flooding. Tables 12.6, 12.7 and 12.8 show the rainfall for the period, weighting percentages obtained by the Theissen method and weighted rainfall.

Table 12.6 DAILY RAINFALL AMOUNTS, 1979 FLOOD (M.M.)

Date		B.I.A.	H.H.	BEL.	C.F.
Nov	28	52.3	4.6	17.8	29.5
	29	53.3	70.1	76.2	86.6
	30	13.0	76.9	31.4	33.5
Dec	1	119.4	49.0	83.8	46.0
	2	120.4	81.0	99.1	76.5
	3	0.0	74.2	20.3	NA
	4	6.4	20.3	20.3	NA

Table 12.7 WEIGHTING PERCENTAGES OF RAINFALL STATIONS, 1979

Date	B.I.A.	H.H.	BEL.	C.F.
I.C.	NA	44%	NA	56%
B.BK.	NA	42%	6%	53%
B.F.R.	NA	38%	12%	50%
B.L.	5%	35%	16%	44%
D.B.	12%	30%	18%	40%

Table 12.8 WEIGHTED RAINFALL FOR GAUGING STATIONS, 1979 (M.M.)

Date		I.C.	B.BK.	B.F.R.	B.L.	D.B.
Nov	28	18.54	18.64	18.63	20.05	22.66
	29	79.34	79.21	78.08	77.50	75.78
	30	52.60	51.65	50.70	48.61	45.12
Dec	1	47.32	49.50	51.68	56.77	62.51
	2	78.48	73.81	88.92	83.89	87.14
	3	74.20	56.69	54.26	43.08	38.51
	4	20.30	20.30	20.30	17.56	16.78
TOTALS		310.78	349.71	354.57	347.55	348.50

Using the 1 day unit hydrographs for 10 m.m. of rainfall, daily discharge values for response runoff were calculated and plotted for each day of the 7 day rainfall period of 1979. This provided a set of basic hydrographs to which base flow of the appropriate levels needed to be added. Because of the lack of data, these base flow levelscould not be added by the procedures of antecedent catchment conditions suggested by the F.S.R.(160). However, a simple comparison of rainfall occurring before the 1969, '71 and '79 floods, indicated that the base flow of the latter would be similar to that of 1969. As the climatic conditions during the 'wet' season of Belize are very similar from year to year and throughout the season, antecedent rainfall will be the predominant factor in determining the level of base fow. The antecedent rainfall for the 5 days before the 1969 flood was averaged at 86.4 m.m., for 1979 it was 125.6.m.m.

Thus the base flow of each station for 1969 was multiplied by a factor of 1.454 to find that for 1979. Base flows for 1969 were deduced by plotting recession curves and Davis Bank 1969 values were necessarily obtained by ratioing 1971:1969 values for the other stations. These values were very consistent (0.29, 0.23, 0.23, 0.26 respectively), averaged to 0.25.

The base flows were added to the 1979 runoff hydrographs of all stations to give the full flow hydrographs for 1979. These are illustrated in figures 12.19 to 12.23. The relative components of flow are given below in table 12.9.

Table 12.9 FLOW COMPONENT VOLUMES, 1979 FLOOD (CUMECS)

Stations	Response Runoff	Non-Response	Total	Peak flow and days before 26 Dec. '79	
I.C.	7.78	1.04	8.82	1980	21
B.BK.	5.66	1.21	6.87	1260	21
B.F.R.	11.80 (6.35)	4.80 (4.37)	16.60 (10.72)	1180	18
B.L.	7.0	4.00	11.00	830	17
D.B.	9.42	7.17	16.59	600	13

The flow volumes of the reconstructed hydrographs display a consistency that emphasises the disproportionately large value of B.F.R. station. It has been stated(161) that while Labouring Creek (with a catchment area of 577km^2) joins the river above Big Falls Ranch and may contribute substantially in the wet season, it is unlikely to be responsible for the massive gain in channel flow seen. It is known that high flow gauge readings are occasionally incorrect (estimates) because of gauge reader negligence. A relationship of B.F.R. : B.L. discharge values of 0.983 has been established(162) and this was used to redraw the B.F.R. flow hydrograph. This was done bearing in mind that :

1. The form of the hydrographs of both stations is very similar
2. No alteration of base time would be necessary
3. The two stations are located only 16 km from each other, in the same area of the floodplain.

The redrawn values are given in brackets in table 12.9. With the 1979 flow hydrographs constructed in their final form, a comparison of flow volumes and rainfall was made to determine the return period of the 1979 flood event.

12.3 RETURN PERIOD COMPARISONS OF THE 1979 FLOOD

12.3.i 7 day rainfall events

A listing of 7 day rainfall events was made, to indicate the return period of the rainfall responsible for the 1979 flood. They are shown below in table 12.10.

Table 12.10 LISTING OF 7 DAY RAINFALLS (BELIZE INT. AIRPORT) IN M.M.

'M'	Rainfall	% probability $\frac{m}{n+1}$	Return period $\frac{n+1}{m}$	'M'	Rainfall	% probability $\frac{m}{n+1}$	Return period $\frac{n+1}{m}$
1	415.6	5	20.00	11	222.2	55	1.80
2	365.6	10	10.00	12	216.2	60	1.67
3	307.4	15	6.67	13	212.6	65	1.50
4	284.6	20	5.00	14	182.6	70	1.40
5	274.0	25	4.00	15	177.8	75	1.30
6	274.3	30	3.33	16	153.7	80	1.25
7	268.9	35	2.86	17	129.7	85	1.18
8	265.4	40	2.50	18	127.1	90	1.11
9	252.6	45	2.20	19	116.2	95	1.05
10	225.8	50	2.00				

The totals of 7 day rainfall for catchments above gauging stations were also listed with return periods obtained from table 12.10.

Table 12.11 RETURN PERIODS OF 1979 RAINFALL FOR GAUGING STATIONS

Station	Rainfall (m.m.)	Return period (years)
I.C.	370.78	11.0
B.BK	349.71	9.0
B.F.R.	354.57	9.0
B.L.	347.55	9.0
D.B.	348.50	9.0

The values in table 12.11 indicate a return period of 9 years with great consistency. However, P.O.T. series estimations of the return period of peak discharge for the 1979 flood event only agreed with this 9 year estimate in the cases of the non-floodplain stations. For floodplain stations, the return periods were very high. This is shown in table 12.12 below and indicates that while the 9 year return is probably correct, the discharge peaks from hydrograph synthesis do not take into account losses to the floodplain and are unrealistically high.

Table 12.12 P.O.T. ESTIMATED RETURN PERIODS OF 1979 DISCHARGE PEAKS

Station	hydrograph peak/Return period		9 year (P.O.T.) discharge
	cumecs	years	cumecs
I.C.	1980	9.3	1964
B.BK.	1260	8.5	1280
B.F.R.	840	9.1×10^{6}	476
B.L.	830	9.6×10^{8}	453
D.B.	600	9.2×10^{4}	342

These correlations form the basis of estimating the probable contribution to the floodplain, from the Belize river. The rainfall leading to the 1979 flood was a 9 year event. By applying a maximum channel discharge equal to the P.O.T. series 9 year return peak, the surplus can be regarded as that lost to the floodplain. This method of estimation can really only be expected to indicate orders of magnitudes of losses to the floodplain. They will probably be underestimates due to the fact that the original hydrographs were obtained for floodplain stations. An increase of 25% has been suggested to overcome this(163). In addition, the imposition of the P.O.T. 9 year maximum will be a constant and will not account for rise and fall of hydrograph. However, these estimates will provide losses in terms of order of magnitude as previously stated and although obtained through a series of extrapolative processes, provide the only estimates since hydrological records contemporary to the 1979 flood are not available.

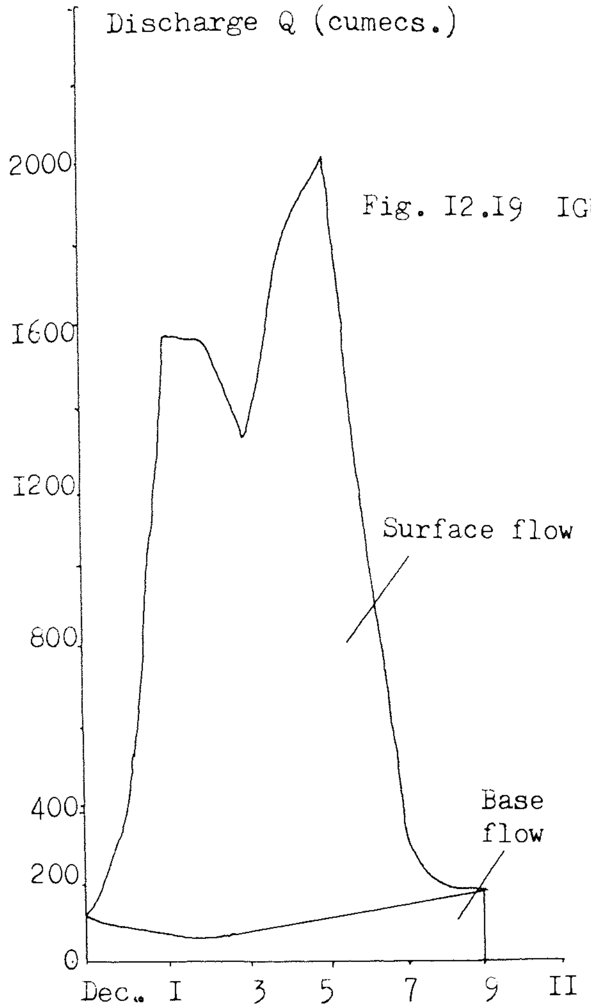
Figures 12.21 to 12.23 illustrate these calculations of losses to the floodplain.

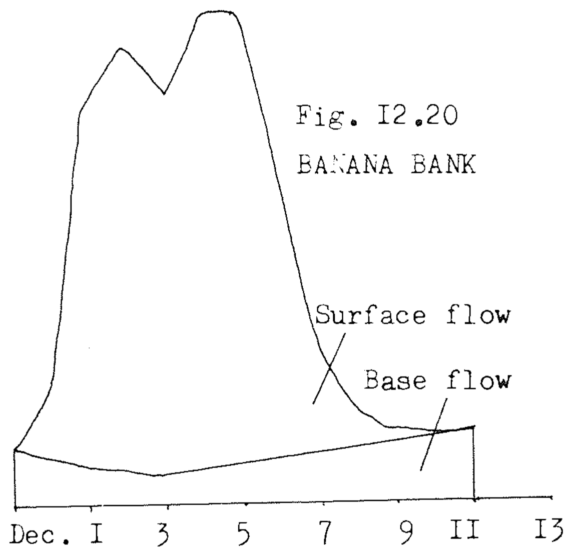
Table 12.13 ESTIMATED LOSSES TO THE FLOODPLAIN

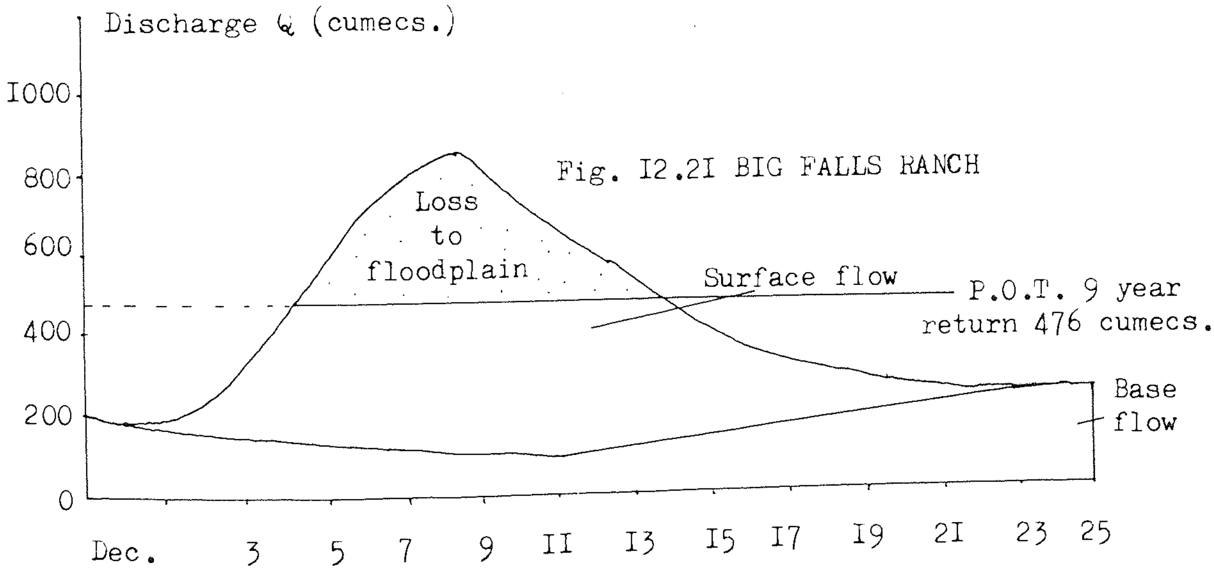
Station	Loss to floodplain (m^3)	(+15%)
B.F.R.	1.67×10^8	1.92×10^8
B.L.	2.03×10^8	2.33×10^8
D.B.	2.33×10^8	2.68×10^8
TOTAL LOSS	6.03×10^8	$6.93 \times 10^8\ m^3$

Consideration of the original hydrographs for the gauging indicated by extrapolation, that an increase of 15% of the total flow at the floodplain stations would account for the approximate underestimate of the hydrographs, as mentioned earlier. This gave an overall estimated total loss to the floodplain of $6.93 \times 10^8 m^3$.

With an estimate of the Belize river contribution to the 1979 flood, made from data independent of LANDSAT information, investigations of the floood event at the scale of 1:50,000 using c.c.t. slides were attempted.







Figures I2.I9,20,2I. I979 FLOOD HYDROGRAPHS

Figure 12.22 BERMUDAN LANDING

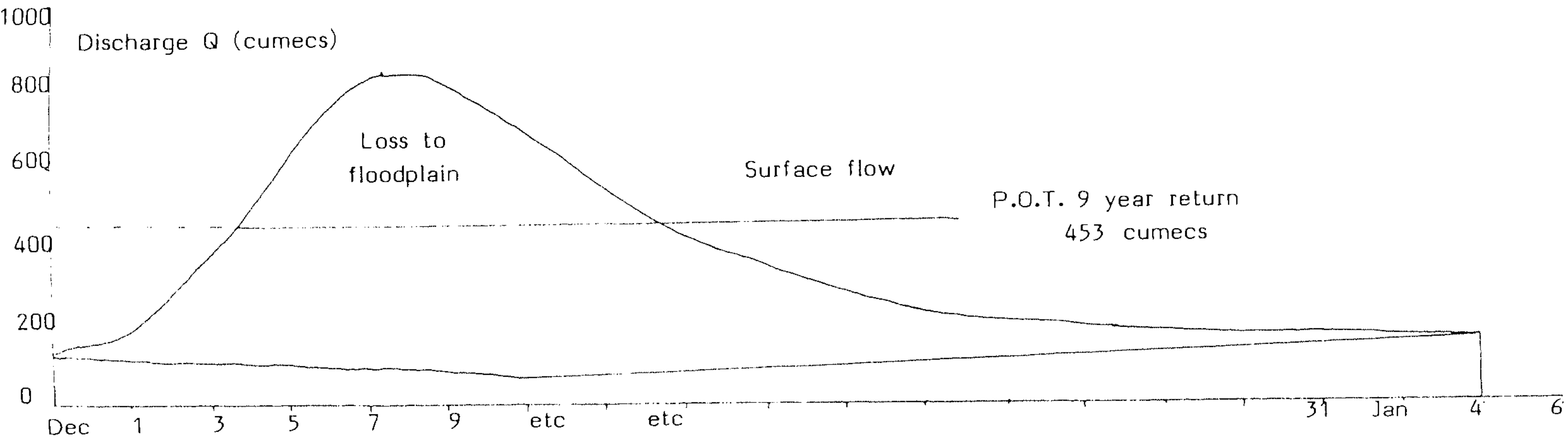
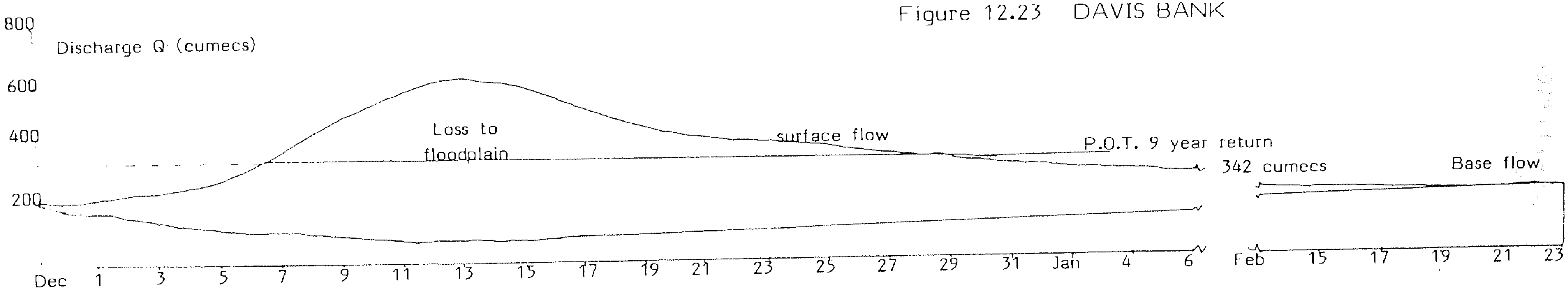


Figure 12.23 DAVIS BANK



Figures 12.22, 23 1979 FLOOD HYDROGRAPHS

CHAPTER 13 INVESTIGATIONS INTO THE 1979 FLOOD, 1:50,000 SCALE LANDSAT C.C.T. SLIDES

13.1 INTRODUCTION

The observation of 1:250,000 scale c.c.t. slide projections showed they contained useful information best exploited, if possible at 1:50,000 scale. The latter scale was used to identify if such projections were of significant value, and indeed possible.

A review of research literature indicates that a variety of regular and non-regular scales have been used in the interpretation of LANDSAT data. Land/water boundaries have been investigated at 1:250,000 (164). Catchment features have been mapped at 1:100,000 (165) while non-regular scales such as 1:84,000 have been used for convenience, later to be rendered to more conventional scales (166). The accuracy of these scales and any distortional inaccuracies are frequently not specified. Where LANDSAT imagery is processed directly by electro-mechanical printing equipment, scales such as 1:24,000 have been used for land use maps(167).

The simple projection of the c.c.t. slides covering the floodplain area was used. Distortions were expected to be similar as indicated by work in earlier chapters and to provide no serious difficulties. False colour composites in bands 4, 5, and 7, the same as used for 1:250,000 scale investigations, were used. Research literature indicates that the techniques used to identify flooding and land cover types are very diverse. Computer assisted processing is also very expensive. The main technique used in this research was therefore limited to the use of the f.c.c. slide projections, which need only minimal pre-processing, but chapter 14 illustrates two widely used techniques, that were attempted in addition to the work of this chapter.

The calculations of distortions for the slide projections were made by the use of ground control points. Some areas of the floodplain were not supplied with suitable features for use and distortions in these areas were unmeasured. They can be seen to be small (±3%) by consideration of table 13.1.

Table 13.1 SLIDE PROJECTION DISTORTIONS, 1:50,000 SCALE

Slide	Direction of distortion from slide centre/% distortion							
	N.	N.E.	E.	S.E.	S.	S.W.	W.	N.W.
1	NA	NA	NA	NA	NA	NA	NA	NA
2	NA	NA	NA	+1.3%	+0.8%	+1.4%	+1.6%	NA
3	+0.9%	NA	+1.6%	NA	+2.5%	+2,4%	+0.8%	+1.0%
4	+0.5%	+1.0%	-0.5%	-0.8%	-1.1%	NA	NA	NA
5	NA	-1.1%	NA	NA	NA	0.0%	-0.8%	+1.1%
6	NA	NA	NA	NA	NA	NA	NA	NA
Lower Floodplain	NA	-3.3%	NA	-2.5%	NA	0.0%	NA	NA

Positive values indicate distances on the imagery greater than topographic maps, negative values the reverse.

From these projections, a series of maps were copied with details of land/water boundaries on them.

13.2 GENERAL FEATURES OF THE 1:50,000 SCALE LANDSAT C.C.T. SLIDES

Slide 1

No visible contact between the New River drainage system and the Belize River was noticed, though large areas are unobservable due to dense vegetation. Spot height information is not available from topographic maps of this area.

Slide 2

An expansion of the Belize river, located on 1:250,000 scale projections was measured as being 5 km long by 1.5 km wide, the usual width of the Belize river being 50 to 100 metres at this point. The distribution of main water bodies is the same as identified by 1:250,000 scale slides and prints. Hydrological contact between the lagoon areas and the Belize river is more explicit than at these scales.

Slide 3

Bermudan Landing appears to be a focus of flooding, more clearly seen at this scale. Overspill from the Belize river to Mussel Creek, though indicated by low brightness values in all bands, could not be confirmed by observatiuon which was inhibited by thin cloud and dense vegetation. The lagoon areas of Labouring Creek show considerable expansion, but direct connection with Spanish Creek and the N.W. lagoon complex, cannot be identified.

Slide 4

No significant information.

Slide 5

Indications of local expansion upstream of Banana Bank are evident. However, widespread flooding is not present and such minor expansions probably explain the slight drop in river volume between Iguana Creek and Banana Bank.

Slide 6

Few significant features, except local ponding around Iguana Creek.

Lower Floodplain Slide

The main locations of overspill and inundation are clearly visible. Linear water bodies leading to the main areas of flooding define the channel features through which water is conducted. Areas of flooding that adversely affect the Western Highway are clearly visible. The internal drainage of the area and the expansion of river courses such as Hector Creek, are visible. A secondary route to the sea, near to the mouth of the Belize river at Haulover bridge, was also evident.

The descriptions listed above are relatively general and on the whole they relate closely to features identified at 1:250,000 scale. However, they do include features not easily seen at that scale and a summary of the main aspects of the 1979 flood may be given.

1. Between the confluence of the Macal and Mopan rivers above Iguana Creek and Big Falls Ranch, no widespread significant flooding took place.

2. Around Big Falls Ranch and downstream to Bermudan Landing flooding probably occurred providing water to Mussel Creek. Flooding to the west of the river did not occur.

3. At and downstream of Bermudan Landing, flooding of considerable extent took place, with the largest front of flooding being just above Davis Bank. Connection with the N.W. lagoonal area occurred.

4. A considerable amount of flooding took place downstream of Davis Bank. This occurred with water movement predominantly to the south and east.

5. The flooding of point 4 above was concentrated upon the central lower floodplain area and affected the Western Highway to a great extent.

Within this summary of conclusions are implicit descriptions of water movement and relative flood volumes. It was therefore necessary to see how 1:50,000 scale information can provide information relating to the points in table 11.1, the locations of overspill being already identified by descriptions of the slides. The focus of investigation may be moved to estimating the area extent of the 1979 flood.

13.3 SPECIFIC FEATURES OF THE 1:50,000 SCALE LANDSAT SLIDES

13.3.i Estimates of flood extent at the time of scene acquisition

The procedure of transferring spot height values from topographic maps to maps generated by the c.c.t. slides was followed as previously described. The procedures concentrated upon the upper and middle floodplain areas, upstream of Davis Bank, to facilitate the comparison of estimates of flood volumes. The contribution of the Belize river passing through the lower floodplain could not be estimated owing to the lack of discharge information and spot height elevations, the latter being totally restricted to roadways.

The transposition of spot heights could more conveniently and accurately be achieved at 1:50,000 scale. It presented one significant difference from the 1:250,000 scale investigations, which was the determination of a 7 metre maximum flood level, thus increasing the postulated average flood depth by 0.5 metres. The area at 1:250,000 scale was thus increased to 276.8 km^2 and the total flood volume estimate was increased to $6.92 \times 10^8 m^3$, a 36% difference with the previous 1:250,000 scale estimate. A difference directly contributable to investigations at a larger scale.

By comparison, the area indicated by the 1:50,000 scale maps of the c.c.t. slides was 285.1 km^2. With flood depths averaged at 2.5 metres, the total flood volume was estimated at 7.13×10^8. Overall, the precision and accuracy of working at 1:50,000 scale was very good, differences of location due to the small distortional inaccuracies were easily dealt with. Hydrological detail was much greater, in many ways not sufficiently exploitable by this research, with its emphasis on broad, regional hydrological aspects. One opportunity, indicative of the detail available at this scale, was the selecting of areas suitable for providing cross-sections of the flood depth. Limitations on this procedure reflected upon the lack of spot height information from maps. Three cross-sections were taken according to spot height distribution in the N.W. lagoonal area and are presented below in figure 13.1. Sections A-A', B-B' and C-C' had respective average depths of 3.6, 3.6 and 3.0 metres. Their overall average depth, weighted by length of section, was 3.49 metres. The location of these cross-sections in the N.W. lagoonal area indicates that they are taken in the part of greatest floodwater concentration and this is substantiated by the calculated depth values given above. While the results of this cross-section were not thought sufficiently representative of the floodplain as a whole, the procedure indicates the detail of methods that may be conveniently performed at 1:50,000 scale. Indeed it is the lack of topographic map detail that largely restricts investigations of this sort, though this fact indicates very well the necessity of other sources of information to be available for combination with LANDSAT imagery.

The possibility of using U.T.M. coordinates to accurately define spot height locations (related to pixel/line positions) was briefly considered. This

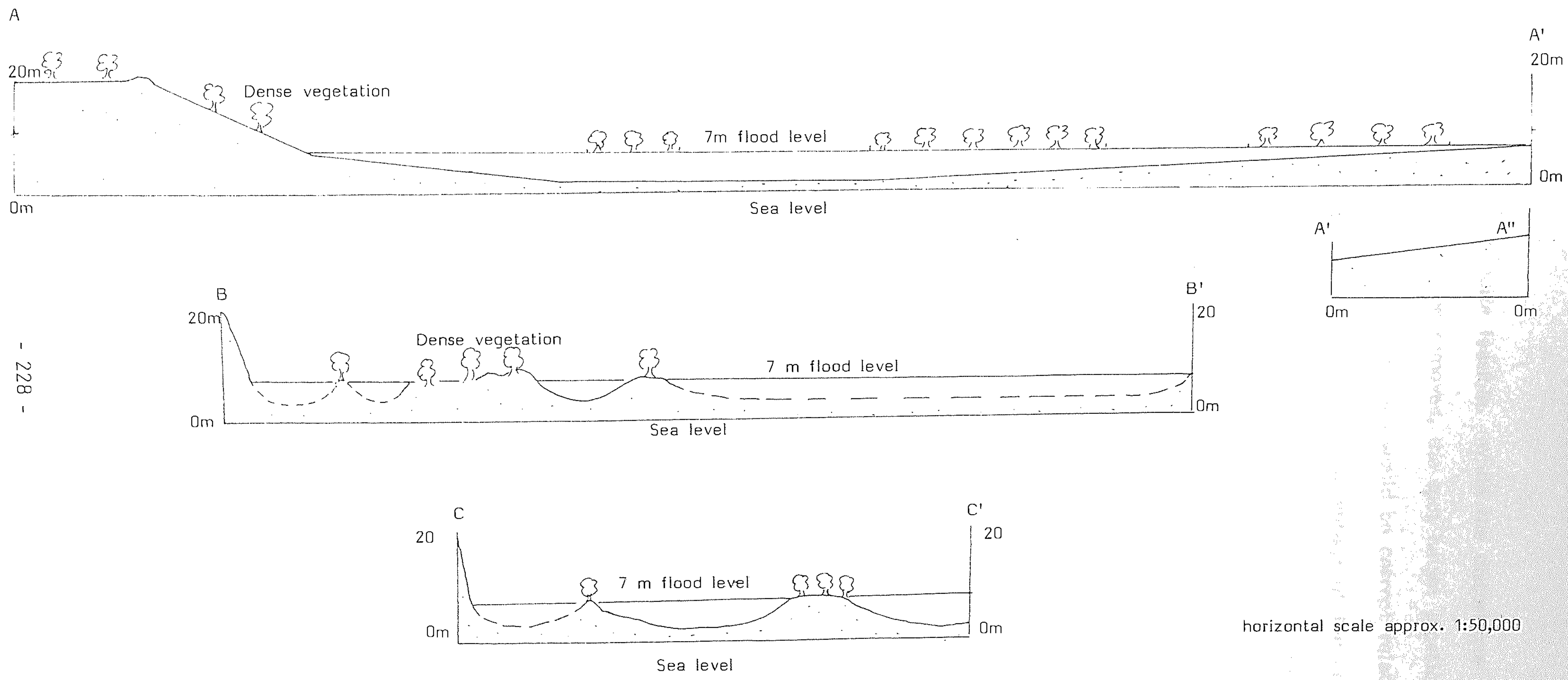


Figure 13.1 CROSS-SECTIONS THROUGH THE N.W. LAGOONAL AREA

procedure was found to be quite feasible. While the distortional elements of the resulting slides would not be removed, the spot height locations would be placed precisely on the monitor screen and would be correct relative to other scene features when projected. The main disadvantage of the procedure was cost. The image must necessarily be registered to U.T.M. coordinates by at least 30 ground control points, to provide a sufficient degree of accuracy of registration. The sampling time needed on three bands using 50 metre pixels would be approximately 24 hours, though reduction of the study area would give proportional reductions of sampling time. In cases where registration is necessary for earth rotation, this would be no disadvantage.

While the flooding of the upper and middle floodplain area was estimated at $7.13 \times 10^8 m^3$, that of the lower floodplain could be seen to be less. Depth estimates were impossible to attempt, but the area of coverage was only 27.5 km^2, giving a flood volume of $0.69 \times 10^8 m^3$ with a postulated flood depth of 2.5 metres.

13.3.ii The maximum flood extent

No specific details were observable to identify the maximum flood level and thereby the maximum flood extent. The nature of the study area prevented such details as tide marks from being observable, even if present. Other features, notably areas with apparently high soil moisture levels in the N.W. lagoon region, and the presence of many isolated ponds in parts of the lower floodplain, otherwise unflooded, suggested a receding flood, but their presence due to other reasons was possible and no conclusion to this matter could be attained.

13.4 RELATIONS BETWEEN BELIZE RIVER AND LOCAL CATCHMENT CONTRIBUTIONS AND LANDSAT OBSERVED FLOOD VOLUMES

It may be assumed that floodwater is derived from two sources; the local catchment and the flooded river. Calculations for the former have not yet been made.

13.4.i Floodplain catchment contribution

A method for calculating the contribution of the floodplain has been proposed and applied to a restricted area of it(168). The method proposes a simple but effective runoff model for storm runoff response in tropical catchments(169).

Runoff is calculated as a function of area, precipitation and catchment coefficients, the latter determined by generalised land/vegetation types and climatic conditions. It has been suggested that while the application of methods developed in one region may not be haphazardly used elsewhere, no empirical methods have been developed in Belize and this particular method is based on widely applicable hydrological principles. The similarity of catchments between the two regions is prominant and similar methods, developed in W.Africa, have proved successful(170).

The method developed is based on the following equation:

$$Ro = (P - Y)\ Ca.\ A.\ 10^3\ m^3 \tag{15.1}$$

where P = precipitation of storm runoff (m.m.)

Y = initial retention (m.m.)

Ca = contributing area coefficient

A = catchment area (km^2)

Although the method proceeds to determine peak and mean flows, base time and surface flow recession, the gross volume of surface runoff, given by equation 15.1 is sufficient for this research. Appendix F presents the tables from which the parameters of equation 15.1 are determined. Substitution of these values in the equation gives :

$$Ro = (364.8) - 0.0) \times 0.4 \times 710.6 \times 10^3\ m^3$$

$$= 1.037 \times 10^8\ m^3 = 1.04 \times 10^8\ m^3$$

Conditions of the catchment are assumed as being slopes between 1° and 4°, impeded drainage and located a wet zone with perennial streams. The rainfall value was for Belize International Airport, with the catchment area measured from 1:50,000 scale maps.

13.4.ii Correlations between hydrograph and LANDSAT flood estimates

The estimated total flooding from the Belize river is $6.93 \times 10^8 m^3$, with an addition of $1.04 \times 10^8 m^3$ from the local catchment the total is $7.97 \times 10^8 m^3$. This volume is equal to a depth of water averaging 2.80 metres over the flooded area.

By comparison the LANDSAT estimate is $7.13 \times 10^8 m^3$ or 2.5 metres over the catchment. The correlation between these values is very good; they differ by only 10.5%. Even though these estimates of the total flood volumes are unsupported by ground values, they are obtained by relatively straightforward methods, the weaknesses of which may be clearly seen and avoided. The similarity of the results, while possibly inaccurate in absolute terms, clearly indicate a common order of magnitude for flood events in the region and shows that LANDSAT information may provide valuable information relating to flood volumes.

The post flood nature of the imagery leads to the possibility of underestimating the true extent of the flood, due to its partial recession. At Big Falls Ranch, flooding appears to have started 16 days before scene acquisition, at Bermudan Landing 15 days and at Davis Bank 2 days. The flood scene indicates that the initial recession of the flood paobably led to little floodwater returning to the river. Outlets to the Belize river are few and small, and rising river levels as the floodwater passed downstream, would prevent floodwater return. Inevitably, losses due to infiltration and evapotranspiration would occur, but these would be small under the circumstances. It is likely then that estimates of the total flood volume given above reflect the magnitude of inundation experienced by the floodplain in 1979.

Investigations by 1:50,000 scale projection substantiate several important points about the flooding of the Belize river:

1. Hydrological connection between the Belize and New River systems does not appear to occur at times of severe flood.
2. The major contributor to the 1979 flood was the Belize river.

3. LANDSAT imagery, with supportive map information, can determine flood extents and depths, even in areas largely covered by vegetation.

4. The main characteristics of flooding may be obtained at least 16 days after flood inception.

5. LANDSAT imagery can provide extensive and highly detailed hydrological information at 1:50,000 scale, even by simple slide projection.

CHAPTER 14 IMAGE PROCESSING TECHNIQUES USED TO INVESTIGATE THE 1979 FLOOD

14.1 INTRODUCTION

The use of false colour composites, and to a lesser degree, band 4, 5, and 7 monochromatic LANDSAT imagery to quantify the flood of the Belize and Sibun rivers, can be seen to define most of its important features. The flood extent was identified and estimates of the flood volume and depth were made. It is important to look at the supplementary image processing techniques that may derive the maximum amount of information from the floodscene. It may in this way be possible to establish whether or not more detailed treatment of the imagery may improve the recognition of flood features, the areas susceptible to flooding and the routeways through which floodwater may pass.

Such processing techniques are expensive to undertake and their variety is wide - band ratioing, edge enhancement and principal components analysis have already been mentioned. Two methods were investigated however:

1. A type of density slicing termed 'piece-wise stretching'.
2. Supervised classification

14.2 PIECE-WISE STRETCHING

This technique is accomplished by selecting portions of the spectrum of pixel brightness values and exploiting tonal differences by the imposition of operator-specified contrast stretches. The technique employs single-band, undecimated images and was applied, as was supervised classification, to the lower floodplain area. Its main reason for use was to identify the location of possible flow channels within the floodplain(171).

A band 7 undecimated image was presented on the monitor screen, and of preliminary investigations including manual linear, logarithmic and exponential stretches, the former was recognised as providing the most useful method.

14.2.i Method of piece-wise stretching

Previous work has identified water and land boundaries by studies of image histograms, where the division has been placed at brightness value 40 (172). Although each scene may differ in this respect, it provides a useful preliminary indication of such land cover separation.

A histogram of the area was obtained (see figure 14.1). Its bimodal form was striking and the brightness values representing wetland were clearly in the extreme low range of brightness values. Indications were that despite the peak of intermediate values, the areas of deeper water could be recognised. A series of piece-wise stretches, based on the information relating to pixel b.vs. were made, each being more extreme in its separation of groups of brightness values. The details of the stretch parameters are given below in table 14.1.

Table 14.1 PARAMETERS OF PIECE-WISE STRETCHES

P.W.S. No.	Brightness values of pixels break point: Original b.v.		Redesigned b.v.
1	0	respecified as	0
	20		200
	21		201
	55		255
2.	0	respecified as	0
	15		170
	16		171
	55		255
3.	0	respecified as	0
	10		170
	11		171
	55		255

This procedure effectively compresses high brightness values into a very small range, thereby allowing the subtle differences with low brightness values to be displayed in a wide range of grey tones, more visibly perceptible. Figure 14.2 illustrates this, Appendix G shows histograms of the stretches.

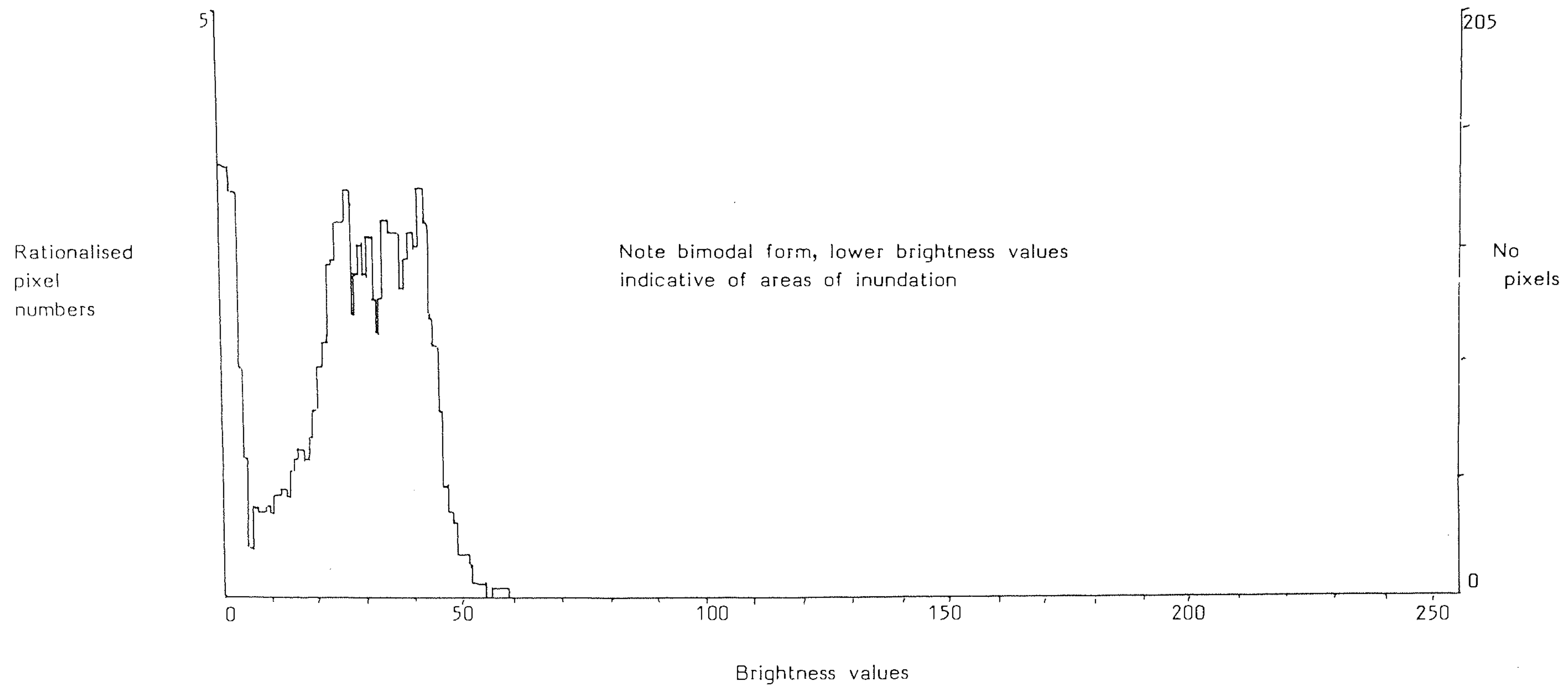


Figure 14.1 HISTOGRAM OF LOWER FLOODPLAIN AREA, BAND 7. PRIOT TO PROCESSING

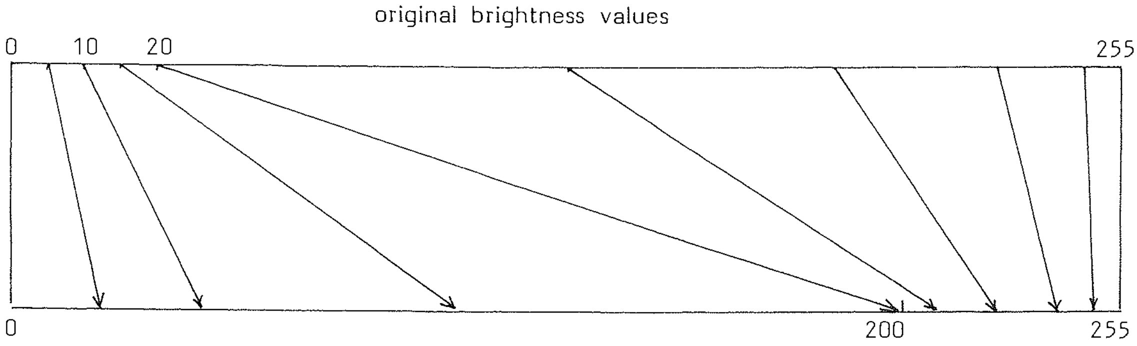


Figure 14.2 OPERATION OF PIECE-WISE STRETCHES

The stretches effectively "white out" high brightness values. Map figures 14.3 to 14.5 show the details of hydrological features of the lower floodplain area. It will be seen that the shallower water areas, of brighter tones are gradually eliminated until only the deep channel routes are presented. These clearly show the frontal expansion of the Belize river and its subsequent movement in two main N. - S. channels across the floodplain area. A third subsidiary channel route is aligned approximately E. - W., with floodwater movement toward the coast. These channels, in the final figure, can be seen to be broad (over 1 km in parts) and lead directly to the Almond Hill and Straight Lagoon area. The locations of inundation likely on the western highway can be pinpointed clearly. Such information is extremely valuable, not only to understanding the hydrological processes of the floodplain, but also relates to aspects of highway surveying in terms of flood damage and/or economic disruption.

This sort of information is extremely useful and is quite clearly seen when piece-wise stretching is used. By contrast, the observation of the general flooded area of the lower floodplain by unprocessed band 7 prints, is far less informative, with flood movement and directions largely hidden by extensive inundation.

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Figure 14.3 PIECE-WISE STRETCH No.1, LOWER FLOODPLAIN

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Figure 14.4 PIECE-WISE STRECH No.2, LOWER FLOODPLAIN

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Figure 14.5 PIECE-WISE STRETCH No.3 LOWER FLOODPLAIN

14.3 SUPERVISED CLASSIFICATION

The operation of image processing methods to achieve supervised classification, is relatively simple, but the bases of statistical analysis upon which it is founded, are complex. In essence, it is a process where sample 'training areas' of known land cover categories are identified and assessments of their spectral identities are applied across the whole image, automatically.

The statistical nature of spectral identification varies, but as land cover groups tend to cluster, their identity can be discovered. Figure 14.6 below shows this clustering by a two waveband diagram, though in practice it is possible to analyse more than two bands at once.

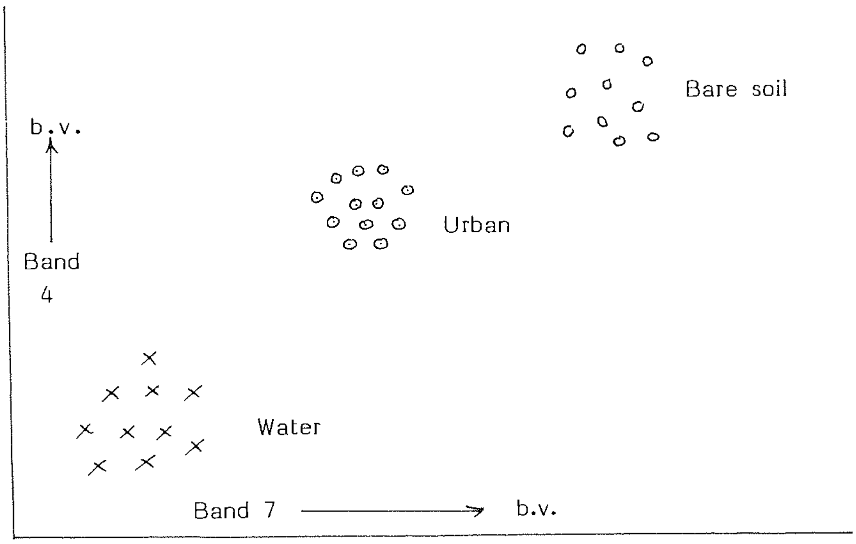


Figure 14.6 CLUSTERING OF LAND COVER TYPES

The grouping of unidentified pixels may be achieved by the self explanatory 'nearest neighbour' technique or by drawing hypothetical boundaries according to their group distributions ('parallel piped' classification). The classification may alternatively be determined by the analysis of the pixels' variance and correlation, and the derivation of the probability density function of the known land cover groups ('maximum likelihood' classification). The essential difference between these techniques is that they become progressively more accurate, but computational time and expense also increases. The details of these techniques are available from relevant textbooks(173), (174).

The primary choice, that of the use of supervised classification, was then superseded by the selection of suitable training areas. The value of the information generated depends to a great extent upon the quality of the training procedure and a thorough geophysical knowledge of the area is necessary(175). The first step involves identifying the spectral response, usually on a particular image (usually, as in this case, in all bands) and may be redefined for other images. The image must be undecimated. The land cover groups were selected by reference to vegetational maps and the flooded areas, a number of training areas were identified as representing these land cover groups. As many examples of training areas as possible, within practical limits, are best used, with n + 1(where n = the number of channel bands) being essential. As it is necessary to determine that the distribution of pixel brightness values is 'normal', histograms in all bands are necessary, for work with maximum likelihood classifiers. Further categorisation may be investigated by the use of a divergence matrix, indicating the statistical 'distance' of one group from another. Section 14.3.i below follows the procedures followed for the processing of Belize imagery.

14.3.i Supervised classification of the lower floodplain area

An undecimated, f.c.c. image was used on the video monitor. Consultation with vegetational and topographic maps allowed the identification of areas of relatively homogeneous cover. Since the distinction of land/water relationships was the primary goal, groupings did not relate directly to the identification of specific vegetational types. A series of eight training areas were selected.

The image showed a high degree of heterogeneity throughout the floodplain area and the selected training areas, covering five groups (or 'themes') were found with difficulty after atmospheric haze reductions had been made. The use of water bodies as primary classification targets was not successful due to the wide range of brightness values within such areas of inundation. Histograms of each band (4, 5, 6 and 7) showed a normal distribution for the 'wet land' theme, the most important group. A confusion matrix, identifying the classification accuracies of the training areas was obtained and is presented below in table 14.2.

Table 14.2 CONFUSION MATRIX OF TRAINING AREAS - CLASSIFICATION ACCURACY

Theme	1	2	3	4	5	unclassified	Total
1	12863	65	282	74	2775	477	16536
2	85	22966	309	1129	223	90	27587
3	328	1884	45034	1357	784	1165	50552
4	41	745	447	15778	99	41	17151
5	1420	193	738	223	25797	862	29233

Themes: 1 = Forest 2 = Scrubland 3 = Bare soil + wetland
4 = Wetland 5 = Palm Forest

In table 14.2 above, the horizontal axes are the classifier themes, vertical axes are the manually classified themes. Values give the number of pixels classified.

The matrix shows that a reasonably large number of pixel values were used, and that theme 4 does not share classification to any great extent. The closest themes are 2 (scrubland) and 3 (bare soil and wetland), both transitionary groupings associated with small bodies of water that could not be excluded from the training areas. With these classifications made in all four bands, a single run Bayesian maximum likelihood classification was made for unclassified pixels to be placed. Table 14.3 below provides details for classification after a subsequent second run of the classifier.

Table 14.3 CLASSIFICATION SUMMARY 1

Theme	Pixels	Hectares	Percent of Area
1	15263	6872.9	6.0
2	26745	12043.3	10.5
3	51647	23256.6	20.3
4	19447	8757.0	7.6
5	30954	13938.0	12.1
Unclassified	110874	49926.6	43.5
Totals	254930	64868.4	100.0

The large percentage remaining unclassified relates mostly to the large sea area present on the image. The Bayesian classifier weights the probability of pixel classification by two factors and is an extension of the normal maximum likelihood classifier by equiprobability contours. These weights are calculated first by the overall frequency of occurrence (infrequent pixels weighted lighter, frequent pixels more heavily) and second by the 'cost' of misclassification of a pixel type; together this results in theoretical optimum classification (176). Figures 14.7(a), (b) and (c) show the progressive presentation of all five themes on the monitor screen in the following sequence, before the use of the Bayesian classifier.

14.7(a): wetland (yellow).

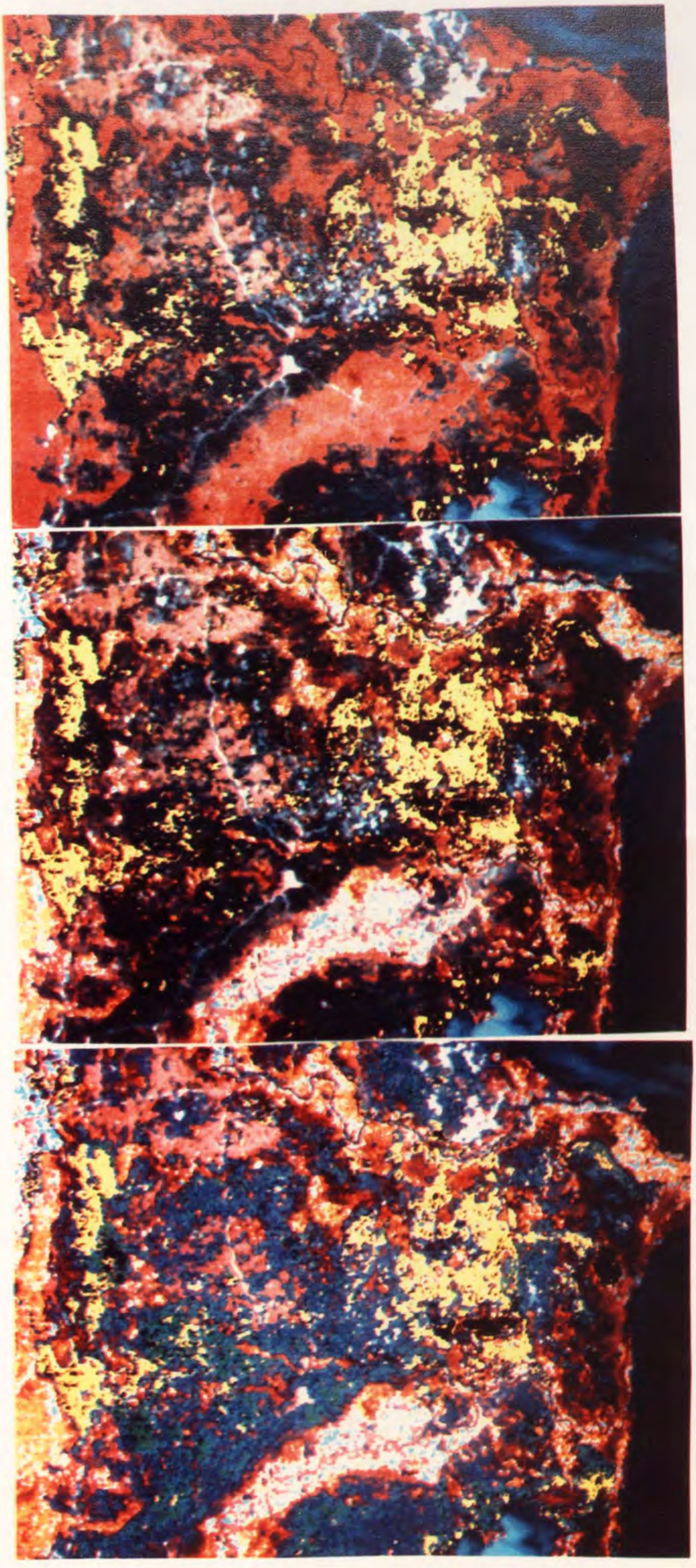
14.7(b): wetland (yellow), palm forest (orange), forest (pale blue).

14.7(c): wetland, palm forest, forest, scrubland + wetland (green), bare soil and scrub (dark blue).

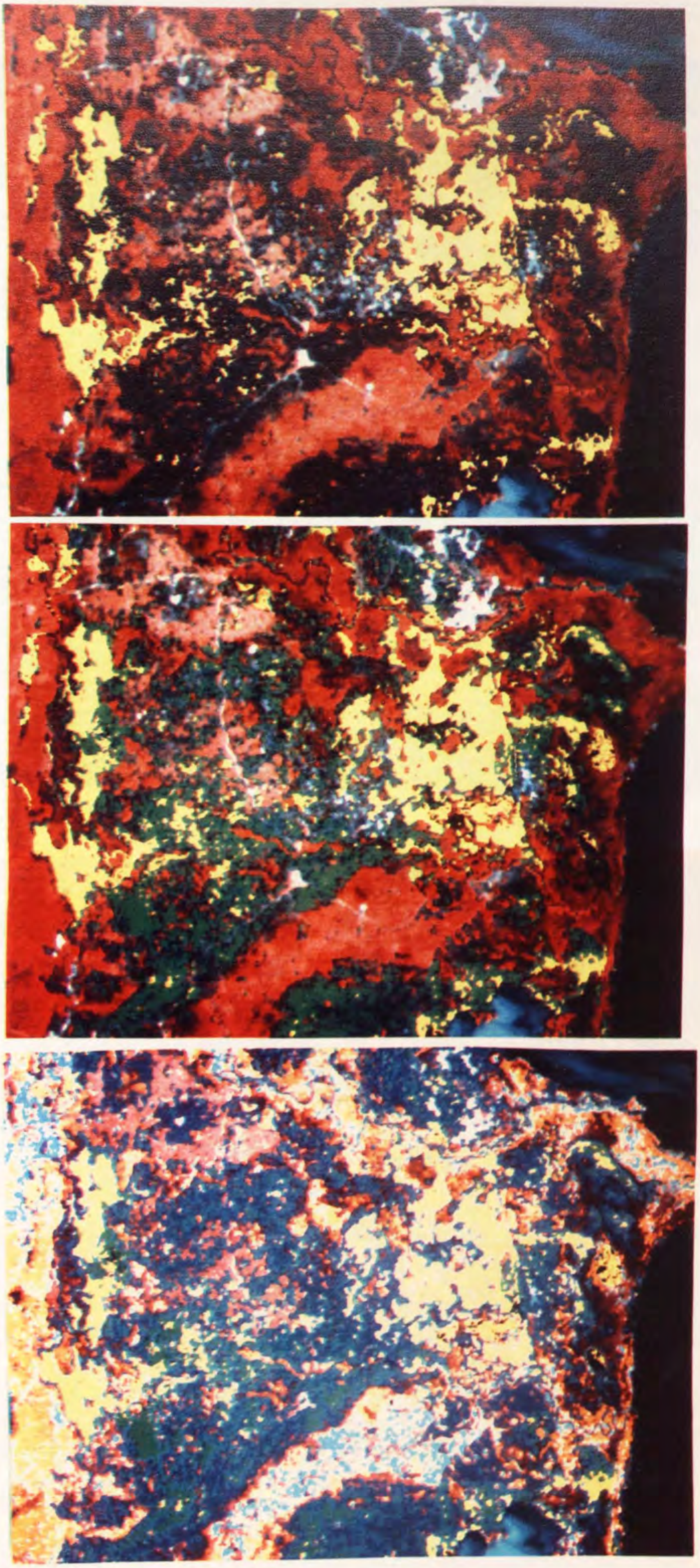
Where classified themes are not displayed, the colours of the f.c.c. image are retained. Figures 14.8(a), (b) and (c) show the same scenes after use of the Bayesian classifier.

At this point several comments may be made upon the results of classification:

1. A total of 7.6% of the scene is classified in the 'wetland' (water) theme.
2. The distribution of the wetland classification corresponds well with that from other images (f.c.c. and band 7) and the major features of floodwater routing across the floodplain can be seen, if not in such detail as afforded by the techniques of piece-wise stretching.
3. Areas of permanent standing water - Almond Hill and Straight lagoons, are not classified except at their extreme peripheries, showing that their separate classification can identify inundative shallow water from that of a permanent nature.
4. Shortcomings of the classification technique are shown by areas still unclassified, some obviously flooded by observation of the f.c.c. image.



Figures 14.7 (a), (b), (c) PROGRESSIVE CLASSIFICATION OF LANDCOVER TYPES, LOWER FLOODPLAIN



Figures 14.8 (a), (b), (c) PROGRESSIVE CLASSIFICATION AFTER USE OF MAXIMUM LIKELIHOOD FILTER

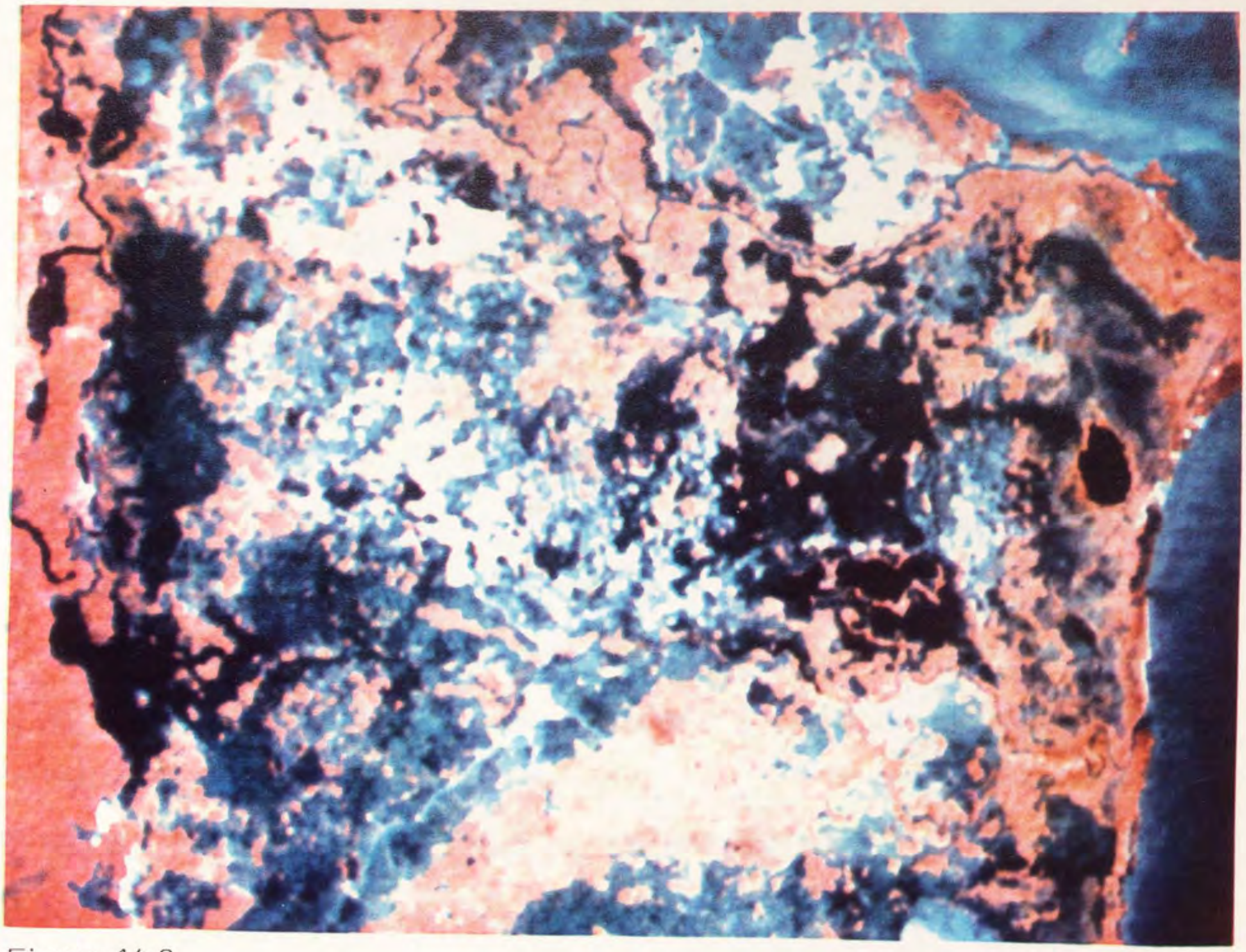


Figure 14.9

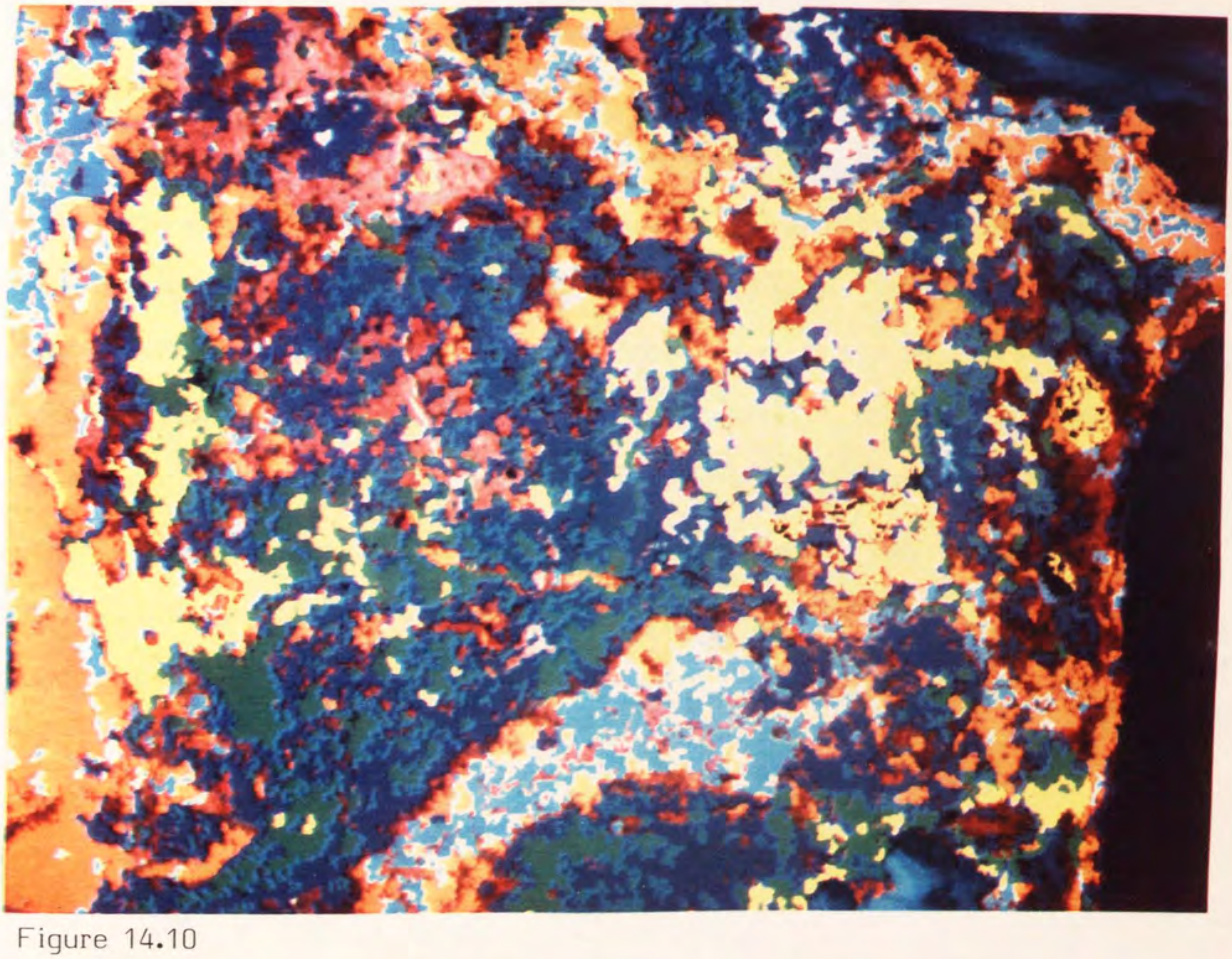


Figure 14.10

Figures 14.9, 14.10. LOWER FLOODPLAIN, FALSE COLOUR COMPOSITE AND FINALLY CLASSIFIED IMAGE

This in particular illustrates difficulties of suitable training area selection.

5. With increasing use of the Bayesian classifier, the areas of classification become more coherent and visually more easy to identify. This visual enhancement gives a good indication of transition from true wetland through scrubland/wetland to areas of bare soil/scrub.

6. Areas of cultivated land, not included in the theme groups, is clearly indicated by its distinctive appearance in f.c.c. colouration.

7. In the final, fully classified image, the quantity of visual interpretations of the theme groups, tends to overwhelm the nature of floodwater distribution.

14.4 CONCLUSIONS REGARDING IMAGE PROCESSING TECHNIQUES

While the two techniques discussed above do not represent the fullest range of processing techniques, they do illustrate two frequently used methods of investigation. Conclusions as to the usefulness of each technique are implicit within the relevant sections of this chapter. Specific conclusions are presented in the next chapter, Chapter 15, where they can be compared more directly to the conclusions relating to more straightforward image presentation. It may be stated quite clearly, however, that the subjective influence of the research field will determine the general effectiveness of any such processing methods and generalised conclusions are therefore difficult to identify, though the overriding need to obtain the maximum amount of data from the image is paramount. Chapter 15 not only presents such conclusions, but also presents the costs of these techniques, in terms of the use of time and expenditure imposed on this research.

CHAPTER 15 CONCLUSIONS

15.1 INTRODUCTION

The conclusions of this research thesis divide naturally into three parts. Two of these parts represent the interconnected main aspects of the research, the investigations of flood flows obtained from catchment characteristics and the study of the 1979 flood. The third part is a presentation of costs of remote sensing materials and their use.

The questions attached to the two main aspects of the research are these :

1. Can LANDSAT data be used wholly or partly in the place of map data to obtain flood formulae by regression analysis?
2. Can LANDSAT data be used to obtain quantitative assessments of flood volumes and understand the behaviour of a flood event?

It is clear that many qualifying conditions may be attached to these questions and it is the discussion of these qualifications that will provide much of the substance of this chapter. They relate to the use of LANDSAT photographic prints since other remotely sensed information does not provide sufficient areal coverage to encompass the whole Belize and Sibun catchments and values of catchment characteristics for these sources cannot be applied in regression. In terms of flooding, both LANDSAT print material and c.c.t. slides, especially the latter, were used and comparisons are made. The comparisons of the differing information sources made in Chapter 7 provide the basis by which their usefulness may be estimated, both according to data obtainable from same scale topographic maps and by cross comparisons of the information sources. The details of such comparisons are provided by the use of subcatchment studies.

The suitability of investigation methods, the advantages and disadvantages of procedures are noted and explained within each relevant section of the thesis and it is not the aim of this chapter to discuss them further. Rather, it is to present the main conclusions of the research in a methodical manner, describing the relative merits of the remote sensing sources to provide accurate and useful information and to set this, by the provision of typical costs, into a financial perspective. While it is inevitable that some repetition of implicit conclusions contained within the text may occur necessarily, generally this is for emphasis.

15.2 THE USE OF REMOTELY SENSED DATA IN QUANTIFYING CATCHMENT CHARACTERISTICS

15.2.i Background

Specific conclusions relating to the measurement of catchment characteristics are given below in section 15.2.ii, at this point it is important to place these details within a general background.

Only LANDSAT data provides virtually global coverage, this is extremely important. In addition it provides a very high theoretical frequency of scene acquisition (18 days), and though practical limitations of data collection and storage prevent the attainment of this theoretical frequency, stockpiles of imagery covering many years and seasons are available. By comparison, SIR-A and Metric Camera material may be regarded almost as 'one off' opportunities, though a second flight of SIR-A (SIR-B) has been made and provides digitally processable material. These two information sources were part of the payload of the space shuttle flights, lasting only a few days, whereas LANDSAT is a series of permanently orbiting satellites. When considering seasonal flow regimes, variations in vegetation growth and the collection of ground data, these frequent monitoring capabilities are extremely important.

LANDSAT data provides 'photographic' material and computer compatible tape data and this ability to provide both formats is very important. Within the confines of this research, it is clear that each format has its own suitable niche of application and this double provision is very useful, especially since it is presented in terms of discrete wavebands, each with its own specific advantages and use. SIR-A 'photographic' material is generally more difficult to relate to conventional air photography, but ground resolution is finer than LANDSAT. So is that of Metric Camera material, which not only has the advantage of utilising conventional photographic processes, but also provides a high degree of stereoscopic coverage. Of all the information sources only SIR-A can collect information through cloud and at night.

As stated previously, each information source has its own unique but general advantages and while 'the more information the better' may be a suitable axiom in many circumstances, it is important for the researcher to use these general differences to identify the most appropriate information source. The improvement of remotely sensed material in terms of data quantity and resolution size, provided by the eleven channel LANDSAT thematic mapper and its French equivalent S.P.O.T., will vastly increase the volume of data generated, and the careful primary selection of material will become increasingly important.

15.2.ii Conclusions regarding catchment characteristic evaluation

These conclusions are provided under the subheadings of the characteristic being investigated, to facilitate the recognition of the most important results.

1. Areal measurement

No significant difference was found between any of the remotely sensed information sources. The direct implication is that the most freely available, easily utilised and cheapest material should be used for such investigation. More significant than information source is the environmental setting of the feature measured and no hard and fast rules could be identifed regarding this. Generally, large, individual areas were most accurately measured. Areas of topographic complexity proved difficult to subdivide internally because of this complexity, while being immediately recognisable in regional terms. By contrast areas of low topographic variety were surprisingly easy to subdivide internally, so long as sufficient features for this were evident. The underlying element of recognition and definition is contrast and this must be sought wherever possible.

The corollary of this is that inaccuracies of internal subdivision tend to be high (+19.9% to -20.8% in this research) whereas those attached to the definition of contrasting regional areas were lower (+6.4% to -11.8%). It must also be stated that the base by which these values are obtained - 1:250,000 scale topographic maps - left much to be desired regarding drainage networks and contours and the accuracy of estimates from this source cannot be unconditionally guaranteed. Area is an important regression variable closely related to river flow and the inaccuracies of both map and remotely sensed information must be carefully considered, though the conclusion of this research is that the latter may provide reasonably accurate values for use in regression analysis.

2. Mainstream slope

While, as stated previously, mainstream slope values have proved useful in regression analysis this research has shown that a very high correlation exists (-0.959) between mainstream slope and mainstream length. They are quite interchangeable within regression formulae and the fact that LANDSAT and SIR-A data cannot provide such information is not a serious disadvantage. Metric Camera provided mainstream slope values but these did not correlate highly with those values obtained from maps, though it must also be stated that different methods of slope calculation provided differences almost as great. It may well be expected that the stereoscopic facility of Metric Camera data is more important relating to altitude evaluation and basin slope than to mainstream slope.

3. Stream frequency

Almost without exception, remotely sensed information provided more data relating to stream density and drainage patterns than 1:250,000 scale maps. In general terms they provided 2.5 times more information but only about one third of that provided by 1:50,000 scale maps. Details regarding the specific relationships can be found in Chapter 7, though there were significant differences between information sources, linked not only to ground resolution and manipulability but also to terrain type.

4. Soil/Slope index

Generally, this variable did not prove so important as in the F.S.R. regressions. Metric Camera gave accurate and useful evaluations of basin slope which was highly correlated to the soil/slope index. In these circumstances it is evident that basin slope itself is a suitable regression variable, most especially in areas where details of soil type and soil structure are not available. The process of determination of the soil/slope index is a lengthy one and it is important in terms of time that such a detailed treatment of soil/runoff response, generalised to extreme limits may be unnecessary.

5. Floodplain areas

Large differences were noted between map and LANDSAT values of this variable, such differences related mostly to the lack of features on both map and imagery. The evaluation of the 'gross' floodplain was the most promising alternative since larger scale features could be introduced into the delineation of the area and regional divisions were most accurately estimated from both information sources.

6. Mainstream length

The evaluation of this characteristic was easily performed in all cases. Accuracies of mainstream length were good with an average of 6.3% difference from map values. Different accuracies of estimations within different regional types, moreover, are not seen and its direct substitution for mainstream slope, a relatively time consuming variable, is a great advantage.

Multiple regression analysis

It has been found that the subjective interpretation of LANDSAT data has a fundamental effect upon the quantification of catchment characteristics

(177), but this is also true of the drawing of topographic maps. 1:50,000 scale sheets used in this research presented one particularly important instance of this - the different notation regarding drainage channels. While the conclusions of this research cannot be expected to provide relationships in absolute terms, the accuracies of the regression formulae that are derived from the evaluations are clearly defined, standard errors of the formulae give these accuracies in terms of the 68% and 95% confidence levels.

The correlation of map and LANDSAT variables was seen to be extremely high and this is the fundamental basis that explains the useful nature of remotely sensed evaluations. LANDSAT data provides a sufficient number of variables for regression despite correlation between variables. The F.S.R.(178) found a full variable set of seven characteristics provided estimates at the 95% confidence level of -58% to +148%, using 533 catchment cases. These estimates are closely in line with the estimates given by Belize data, both map and LANDSAT, where only three or four variables were used. Other research has found only two variables (area and mainstream slope) adequate(179). It is evident from both this research and that by the F.S.R. and other workers, that the addition of many variables to the regression set does not necessarily give a proportional increase in accuracy and that a limited number of variables provides adequate coverage. This is important in that first, areas with few gauging stations may provide an adequate basis for regression and second, that highly correlated variables may be dismissed where necessary.

Table 15.1 below provides a comparison of standard errors of various regression equations from several world regions, with a variety of number and type of regression variables, to illustrate the points made above.

The statement that 'the predictions of the equations are crude and give little more than the order of magnitude'(180) is clearly true. However, the value of such results should not be underestimated. These results may not be

Table 15.1 COMPARISONS OF REGRESSION FORMULAE PREDICTIONS

Regression Source	Dep. Variable	Indep.Variable	R2	s.e.e.	95% confidence level
F.S.R. (1972)	Best estimate of Mean Annual Q	AREA	0.880	0.229	-65% to +187%
(553 cases)		STMFQ			
		1085%			
		SAAR			
F.S.R. (1972)	Mean Annual Q	AREA	0.914	0.194	-59% to +144%
(553 cases)		STMFQ			
		1085%			
		SOIL			
		URBAN			
		LAKE			
		SAAR			
Benson (1962)	Mean Annual Q	AREA	0.841	0.194	-59% to +144%
Benson (1962)	Mean Annual Q	AREA	0.922	0.142	
		1085% slope			
Belize Data	Exponential flow	A.A.R. - AREA	0.947	0.177	-56% to +126%
(LANDSAT)	growth factor B	STFQ			
		GFLPN			
Belize Data	B	A.A.R. - AREA	0.934	0.197	-60% to +148%
(LANDSAT)		GFPN			
		CIRC			

important in areas such as the U.K., but in developing countries they may be very significant indeed. In the case of Belize, this research presents the first attempt to evaluate flood flows and provide regression formulae for application throughout the country. Estimates of flows that may be ±100% are extremely useful where catchments are ungauged and return periods for flood events are unknown. Especially useful was the finding that Q(T) P.O.T. parameters could be substituted for those of M.A.F. with no significant loss of accuracy.

It may be concluded therefore that LANDSAT data specifically and remotely sensed information in general can provide not only the basic information for regression formulae, but also accuracies as great as map information. It provides a useful and possibly unique insight into the discharge regions of poorly documented rivers. In addition, the peaks-over-threshold method of flood flow extension can be seen to operate in the most difficult and diverse of circumstances.

15.3 THE USE OF LANDSAT IMAGERY IN THE EVALUATION OF FLOODING

The particular circumstances of the 1979 flood event are adequately covered in Chapters 11 and 13. It was clearly evident that the facilities afforded by the use of computer compatible tape imagery, clearly outweighed those provided by LANDSAT prints. The c.c.t imagery gave greater detail and provided a far more flexible opportunity for the enlargement of scale, by which this extra detail could be exploited. However, it must also be recognised that in terms of basic flood inventory, the provision of LANDSAT print data was adequate to provide a good estimate of flood extent and depth and the inventory of water bodies. It can be seen from Chapters 13 and 14 that while this is true, the use of c.c.t. imagery provides the opportunity to explore the more subtle behavioural patterns of the flood process and to obtain important, extra information. The immediate conclusion is that print material gives an accurate overall synopsis of conditions, and that the costly use of image manipulation should be concentrated upon important detail.

This research shows that remotely sensed information should not be viewed in isolation and that its value increases proportionally with the supplementary data that is available. Altitude and vegetation cover information is particularly important in this respect. Since the circumstances of the Belize and Sibun floodplains obviate the possibility of extensive ground surveys, the importance of the LANDSAT post flood image must be recognised in the quantification of the flood volume and the location of its economically damaging effects. The estimates of flood volume, while both derived from secondary methods of evaluation, were extremely similar and the ease and simplicity by which the LANDSAT value was obtained, compared to that by hydrological investigations, cannot be overstated. Variations of flood depth, flood distribution, overspill and floodwater movement, were aspects of the 1979 flood that could hardly be documented in any other way, and certainly not at such a cost.

The LANDSAT image has shown that the New River and Belize river systems appear to remain separate at times of flood, while the connections with the Sibun river are strong. The main areas through which the Belize and Sibun rivers provide floodwater have been identified and the proportional increase downstream of this contribution has been recognised. Implications regarding transport and communications have been seen and the importance of a new breach to the sea of the river in times of flood is relevant to the drainage canal systems of Belize city if, as a result, suspended material is dropped upstream of its normal depositional locations. The significance of the 1979 flood scene is that it captures a rare event - a severe flood, and allows its detailed study that otherwise could not be accomplished.

15.4 COSTS OF PURCHASE AND USE OF REMOTE SENSING MATERIALS

When considering the cost of purchase and use of remote sensing material, one fact is readily recognisable. The purchase of photographic negatives is cheap and so is their enlargement. By contrast, the purchase of computer compatible tapes and their use is very expensive. The most explicit way to present this contrast is to compare the expenditure for this research as a typical example.

Table 15.2 COSTS OF MATERIAL PURCHASE AND USE

R.S.Source	Purchase cost	Utilisation cost
LANDSAT negatives	U.S. $30 per negative	Approx. £30 per 1:250,000 print.
LANDSAT c.c.ts.	U.S. $650 per tape	Machine time £12 per hour (bona fide university rates) Commercial rates approx. £100 per hour
Metric Camera diapositives	£15 per diapositive	Approx. £10 per inter negative and £30 per 1:250,000 print
SIR-A	No cost to bona fide institutions	Approx. £17 per 1:250,000 scale print

The purchase and use of photographic material is cheap and easy. The distortional inaccuracies of this format are not significant. Generally, the time expended upon all sources in this format are the same since the procedures of investigation are largely similar. The selection of catchment characteristics is a more important factor when determining labour/time costs and such substitutions as mainstream length for slope and basin slope for the soil/slope index prove to be economically expedient choices for regression analysis. The derivation of all catchment characteristics from LANDSAT print data can take several days, depending upon the precise definition of the characteristics and the facilities available for measurement. The use of digitiser and microcomputer facilities obviate the need for mechanical manual computations, but in developing countries such facilities may not be available.

Similar dispensations of time and effort can be expected to apply to any other photographic material of similar size and scale, in direct proportion to the number of characteristics and areas being studied. The Metric Camera stereoscopic investigation costs were similar to those of c.c.t. studies at the bona fide institution rate of £60 per day. The analysis of material took 1.5 days with the aid of supervisory technicians, the total cost being more than the total cost of purchase and use of any of the print material.

It is the cost effectiveness of c.c.t. image processing that provides the most difficult assessment. Chapter 14 provides some insight of the ability of image manipulation to provide detailed information regarding natural phenomena. Piece-wise stretching was seen to identify flood routes in circumstances whereby they are not easily recognisable. The method was relatively quick and easily effected but depended upon vegetation cover. Techniques of supervised classification provided land cover categories in an area of heterogeneous land cover types, presenting a greater and greater visually enhanced image by selection. The total machine time used was approximately 46 hours, costing a total of about £550. By comparison, the commercial cost of such investigation would be £5,500 and added to this is the purchase cost of three tapes, in all a commercial total of approximately £6,800.

The initial selection of imagery itself is an important factor determining the cost of image processing. Tapes from LANDSAT 1 are not corrected for earth rotation and must be so by registration to ground control points. At least 20 or 30 of these are necessary and this procedure will take perhaps 3 to 4 hours. The image will have to be resampled, a single undecimated monitor image in all bands perhaps taking 8 hours or so depending upon the processing equipment used. Thus the purchase of tapes that have been geometrically corrected for first order distortions is a considerable advantage.

The use of simple band or f.c.c. imagery has been shown to be an effective method of hydrological investigation. Little time is taken in preprocessing and further manipulation is unnecessary. It is the cheapest and most cost-effective method that can be used for investigation, but does not allow the discovery of information beyond that which is straightforwardly observable. The use of the piece-wise stretching for this research took approximately 5 hours of machine time. The supervised classification discussed in Chapter 14 took approximately 8 hours basic organisation plus a further 8 hours in gathering the statistical nature of the imagery, filtering, etc. The cost of this therefore was three times that of piece-wise streching, with little extra hydrological advantage to show. It must be remembered also that after a suitable image has been arrived at, it is necessary to photograph the image. While the cost of this is minimal it occupies further machine time in retaining the image. In addition, maps have then to be obtained by slide projection and observation or by the use of laser line printers. In either case, additional expenditure, not easily assessed, is necessary, perhaps as much as the total time used in print investigation.

Clearly, such costs are negligible when compared to project planning, though in terms of research expenditure they may be considerable. The information derived from the multiplicity of image processing techniques and the combination of varied data sources (for example merging LANDSAT with SIR-A imagery) can provide a powerful investigative tool and one which will be increasingly developed in the future. The final conclusion of this thesis is that the selection of remote sensing information sources and the manner in which they may best be exploited is dependent directly upon the aims of the proposed investigation and the facilities available to it, for which this research is a guide.

Aston University

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APPENDIX A.I. LANDSAT CARIBBEAN SCENE COVERAGE

APPENDIX A.2. LIST OF LANDSAT SLIDE, C.C.TAPES

The lists below provide details relating to the photographic slides taken of c.c.t. 020/48, 26 December 1978. The number of slides is approximately one third that of the total taken, and provides an example of the photographic material obtained and investigated after approximately 15 hours machine processing time. In almost all cases, duplicate photographs at different aperture/exposure settings were taken to ensure that the valuable monitor images were not lost.

C.C.TAPE 3 - 020/48 26 December 1979 (TAPE CODE BZI FF BND, 4, 5, 6, 7)

Slide No.	Band description	Area details
1	Preprocessed f.c.c.	Full image including cloud
2	Preprocessed Band 7	as above
3	Preprocessed Band 5	as above
4	Preprocessed f.c.c.	General floodplain area
5	f.c.c. with BFN and BFS training areas	North and south floodplain locations of land cover training areas
6	Band 7	General floodplain area
7	f.c.c. with training areas	S.F. floodplain area
8	Band 7 with training areas	as above
9	Band 5 with training areas	as above
10	Band $^7/_5$ ratio	as above
11	Band 7 piece-wise stretch 1	Lower floodplain
12	Band 7 piece-wise stretch 2	as above
13	Band 7 piece-wise stretch 3	as above
14	Band 7 p.w.s. 3 x 15 zoom	as above
15	F.c.c. full image x 1.3 zoom	full image
16	Band 7 River section 1	(N.) section of inundated floodplain
17	F.c.c. River section 1	as above
18	F.c.c. River section 2	as above
19	Band 7 River section 2	as above
20	F.c.c. River section 3	as above

APPENDIX A.2 continued

Slide No.	Band description	Area details
21	Band 7 River section 3	(N.) section of inundated floodplain
22	Band 5 River section 3	
23	F.c.c. River section 4	Section of inundated floodplain
24	Band 7 River section 4	as above
25	F.c.c. River section 5	as above
26	Band 7 River section 5	as above
27	F.c.c. River section 6	as above
28	Band 7 River section 6	as above
29	Band 5 River section 7	as above
30	Band 7 River section 7	as above
31	F.c.c. River section 7	as above
32	F.c.c. Theme classifications training areas	Lower floodplain with landcover training area 1
33	F.c.c. classification 65%	Land cover themes of Lower floodplain
34	F.c.c. 65% Wetland,	as above
35	F.c.c. 65% Wetland, Palm forest	as above
36	F.c.c. 95% Wetland	as above
37	F.c.c. 95% Wetland, Scrub	as above
38	F.c.c. 95% All cover classified	as above
39	F.c.c. 95% All cover except forest	as above

The slides 16 to 31 provided basic data for Maps, 11 to 13 data for image processing by piece-wise stretching and 32 to 39 data for landcover classification.

APPENDIX B METRIC CAMERA PHOTOGRAPHIC AND FLIGHT DETAILS

STS9/SPACELAB METRIC CAMERA EXPERIMENT

Mission/Parameter:		
Launching	:	28 November, 1983
Landing	:	8 December 1983
Altitude	:	240-257 Km
Inclination	:	57°
Velocity	:	7.7 km/sec
Scale of Image	:	about 1:820,000
Ground coverage of one image	:	approx. 189 km x 189 km
Image motion	:	at 1/500 sec exposure time 18 um (=16m on the ground)
Film	:	Kodak Double-X Aerographic film 2405 (B/W). Kodak Aerochrome infrared Film 2443 (Colour)
Camera :		
Type	:	Modified Zeiss RMK A 30/23
Lens	:	TOPAR A 1 with 7 lens elements
Calibrated	:	305.128 mm
Focal length max. distortion	:	6 um (measured)
Resolution	:	39LP/MM AWAR on AVIPHOT Pan 30 film
Film Flattening	:	By blower motor incorporated in the camera body
Shutter	:	Aerotop rotating disk shutter (between the lens shutter)
Exposure	:	1/250 to 1/1000 sec in 31 steps
F/Stops	:	5.6 to 11.0 in 31 steps
Exposure	:	4 to 6 sec and 8 to 12 sec
Frequency Image Format	:	23 cm x 23 cm
Film width	:	24 cm
Film length	:	150 m = 550 image frames
Dimensions :		
Camera	:	46 x 40 x 52 cm
Magazine	:	32 x 23 x 47 cm
Mass		
Camera	:	54.0 kg
Magazine	:	24.5 kg (with film)
Field of view	:	diagonal 56°, across 41.2°

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APPENDIX C.SIR-A RADAR CARIBBEAN COVERAGE

APPENDIX D

PROGRAM FOR THE CONVERSION OF GAUGE HEIGHT TO

Below is given the short computer program used to convert Belize and Sibun river stage values to discharge values. The program was used in preference to direct reading of the stage:discharge rating curves for all hydrological stations. Values R and Z represent the upper and lower limits of the rating curve for which curve coefficient 'A' and the constant C are related to Y, the gauge height by line 190 conversions to cumecs are made in line 200. The program lists gauge height, discharge in cumecs and cusecs at optional intervals of stage for the limits R and Z.

```
10    Print "Input R"
20    Input R
30    Print "Input Z"
40    Input Z
50    Print "Input coefficient A"
60    Input A
70    Print "Input constant C"
80    Input C
90    Print "Input station name"
100   Input N
110   Open 4.4 : CMD4
120   Print "Rating table 4";N
130   Print "Limits are=";R;" to Z=",Z,"Metres"
140   Print" "
150   Print" "
160   Print "Y metres", "XCumec", "XCusec"
170   Print" "
180   For Y=R to Z step 0.02
190   X=(Y/C)  (1/A)
200   Q=X*35.315
210   Print Y, X, Q
220   Next Y
230   End
```

APPENDIX E

GENERAL LANDCOVER TYPES OF THE BELIZE RIVER CATCHMENT

COMPUTER COMPATIBLE TAPES

Landcover type	special band F.C.C. (i.e.combined 4,5 and 7)	spectral band 5 (see overleaf for band 7 descriptions
Dense vegetation	Colour red. Different specific vegetational types may vary from bright scarlet to crimson, but such vegetational types distinctions were not classified unless specifically noted. Vegetation associated with the margins of clearly identified water bodies has a clearly identifiable purple/magenta colour.	Appears in dark and mid grey tones. Vegetation marginal to water has very dark grey to black tones. Thin vegetation is lighter toned.
Water	Clear water appears black. No confusion is possible with other land cover types.	Clear water appears black. Confusion is not likely but the specific boundaries with vegetation may not be clear.
Water with suspended material	Water in these circumstances appears mid blue. Distinctive features such as river are clearly identifiable but water bodies with suspended material may not be so, if distinctive vegetational or soil features are not present.	Water in these circumstances appears mid or dark grey. River features are identifiable, but water bodies with suspended material may not be distinct from vegetation.
Bare soil	Appears white or very pale blue.	Appears as bright white tones.
Cultural features	Appear white or pale blue. Proximity to vegetation may impose a pink tinge.	Appear white or pale grey according to the proximity of vegetation and water.
Pine forest and orchard savannah	Appears pale grey blue with red areas of denser vegetation. White areas occur where soil shows through. A speckled texture is often evident.	Appears as a mixture of light and mid greys. Speckled texture.

APPENDIX E continued

GENERAL LANDCOVER TYPES OF THE BELIZE RIVER CATCHMENTS :

LANDSAT PRINTS (black and white presentation

Landcover	Spectral band	description of appearance
Dense vegetation	7	White to very pale grey. Variations of exact tone may vary due to the varying admixtures of vegetational type, as may textural appearance. Confusion with other landcover types unlikely.
Water	7	Water bodies appear black. Confusion with other landcover types unlikely.
Water with suspended material	7	Water with suspended material appears dark grey. While obvious features such as clearly defined rivers are easily identifiable, confusion may occur where water bodies are in an agitated condition such as during a flood. Sometimes this feature may identify the sources of water impact to a water body.
Bare soil	7	Appears as bright white tones. Confusion may occur with dense vegetation, more likely with cloud, but areas of bare soil are rare and small in the floodplain area of the Belize river.
Cultural features	7	Appear white or pale grey, due to high reflectance, but the reflectance of linear features, especially dirt roads common in the floodplain area may be highly affected by the reflectance of neighbouring features. Cultural features are few in the Belize floodplain.
Pine forest and orchard savannah	7	Appears mixed light and mid grey. The unique textural mixture of these areas enable them to be relatively easily identified despite their mid tone values. They form a distinctive vegetational type.

APPENDIX F

TABLES USED FOR THE CALCULATION OF CATCHMENT RUNOFF

Table 4 below presents the runoff factor 'contributing coefficient' according to Fiddes (ref. 149) used in Chapter 13, to determine the local catchment contribution to flooding. Tables 5 to 8 present factors involved in runoff distribution for channel flow and while not used directly in the calculations of the thesis, indicate the physiographic factors upon which the method is based. Table 9 gives flow result comparisons between the method and computer generated predictions.

TABLE 4

Standard contributing area coefficients
(Wet zone catchment, short grass cover)

Catchment slope		Soil type		
		Well drained	Slightly impeded drainage	Impeded drainage
Very Flat	<1.0%		0.15	0.30
Moderate	1–4%	0.09	0.38	0.40
Rolling	4–10%	0.10	0.45	0.50
Hilly	10–20%	0.11	0.50	
Mountainous	>20%	0.12		

Note: The soil types are as in Fig. 16 and are based on the soils map contained in the Handbook of Natural Resources of East Africa (see ref. 13).

TABLE 5

Catchment wetness factor

Rainfall zone	Catchment wetness factor (C_W)	
	Perennial streams	Ephemeral streams
Wet zones	1.0	1.0
Semi arid zone	1.0	1.0
Dry zones (except West Uganda)	0.75	0.50
West Uganda	0.60	0.30

TABLE 6

Land use factors (C_L)
(Base assumes short grass cover)

Largely bare soil	1.50
Intense cultivation (particularly in valleys)	1.50
Grass cover	1.00
Dense vegetation (particularly in valleys)	0.50
Ephemeral stream, sand filled valley	0.50
Swamp filled valley	0.33
Forest	0.33

TABLE 7

Catchment lag times

Catchment type	Lag time (K) hrs
Arid	0.1
Very steep small grassed or bare catchments (slopes > 15%)	0.1
Semi arid scrub (large bare soil patches)	0.3
Poor pasture	0.5
Good pasture	1.5
Cultivated land (down to river bank)	3.0
Forest, overgrown valley bottom	8.0
Papyrus swamp in valley bottom	20.0

TABLE 8

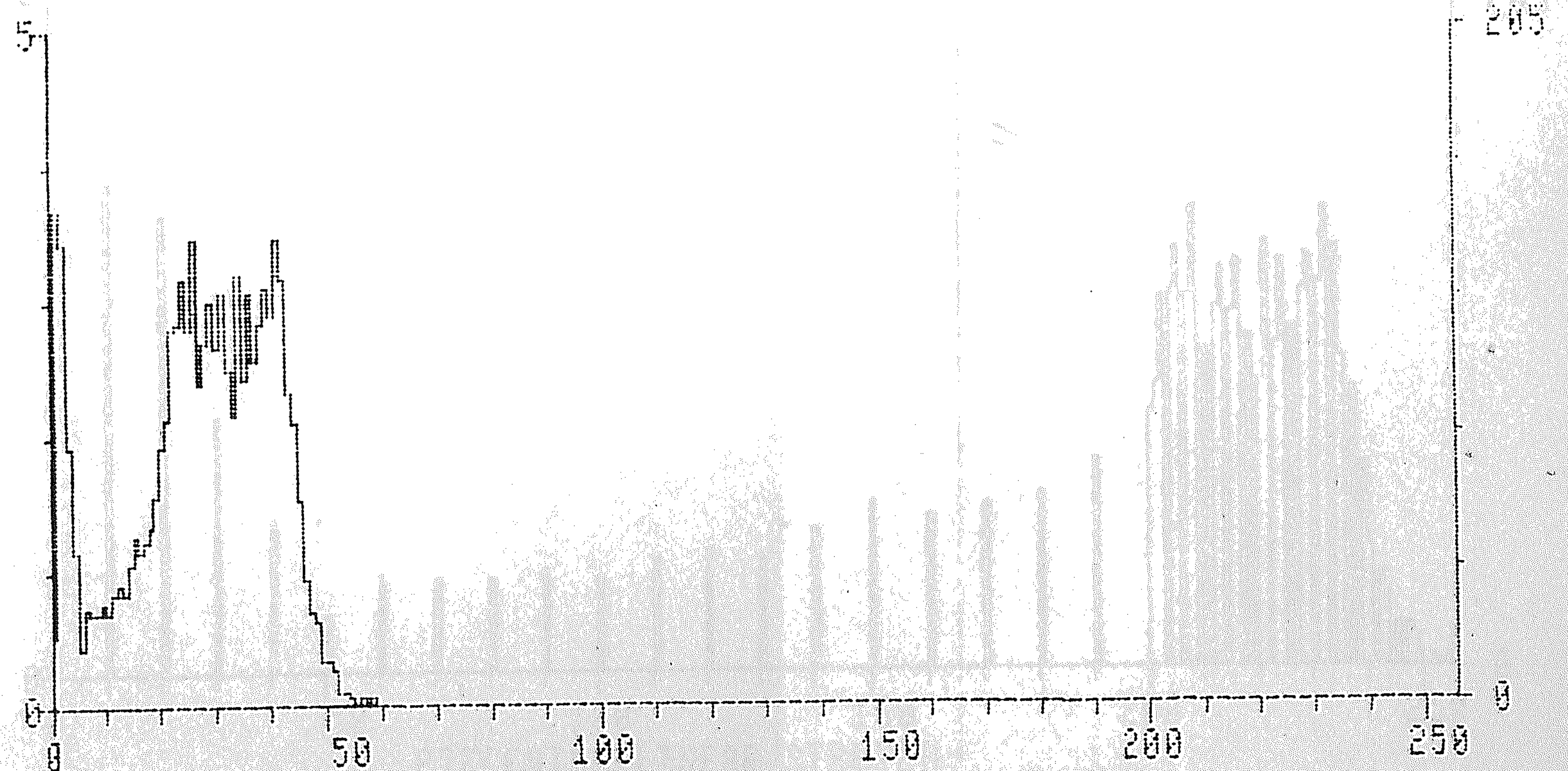
Rainfall time (T_p) for East African 10 year storms

Zone	Index "n"	Rainfall time (T_p) (h)
Inland zone	0.96	0.75
Coastal zone	0.76	4.0
Kenya-Aberdare Uluguru Zone	0.85	2.0

TABLE 9

Comparison between predicted 10 year floods using computer and short methods

Catchment	Storm rainfall (mm)	Assumed Catchment Parameters									10 Year Peak Flows	
		Ca	CL	Cw	y(mm)	K (hr)	Area (km^2)	Land slope %	Channel slope %	Channel length (km)	Computer method (m^3/sec)	Short method (m^3/sec)
Tiwi	122	0.09	0.75	1.00	0	1.0	6.7	2.2	1.2	5.08	5.7	6.6
Mudanda	89	0.10	1.50	1.00	5.0	0.3	1.7	8.2	5.0	2.67	6.8	8.0
Migwani	105	0.38	1.00	1.00	0	1.0	83.5	3.0	1.3	19.05	377.0	430.2
Kajiado	68	0.50	1.00	1.00	0	1.5	3.6	8.8	2.7	3.43	9.0	12.0
Eseret	57	0.12	0.50	1.00	0	0.1	3.2	22.0	9.2	3.70	3.0	3.1
Kiambu I	112	0.10	0.50	0.75	0	8.0	2.0	4.0	3.6	2.75	0.14	0.27
Kiambu II	112	0.10	1.50	1.00	0	3.0	5.2	6.6	2.8	6.03	3.6	4.5
Barabili	96	0.15	0.50	0.75	0	8.0	3.9	0.7	0.3	2.03	0.67	0.61
Munyere sub	54	0.11	1.00	0.60	5.0	0.1	0.5	27.0	23.5	0.83	1.11	1.12
Rubaare	65	0.10	1.00	0.30	5.0	1.0	13.7	6.0	4.9	6.99	4.6	4.3
Lugula	103	0.45	0.50	0.75	0	8.0	3.1	9.0	0.7	2.29	2.27	1.74
Saosa	103	0.11	0.33	0.75	0	8.0	6.8	12.0	3.4	4.54	0.63	0.55

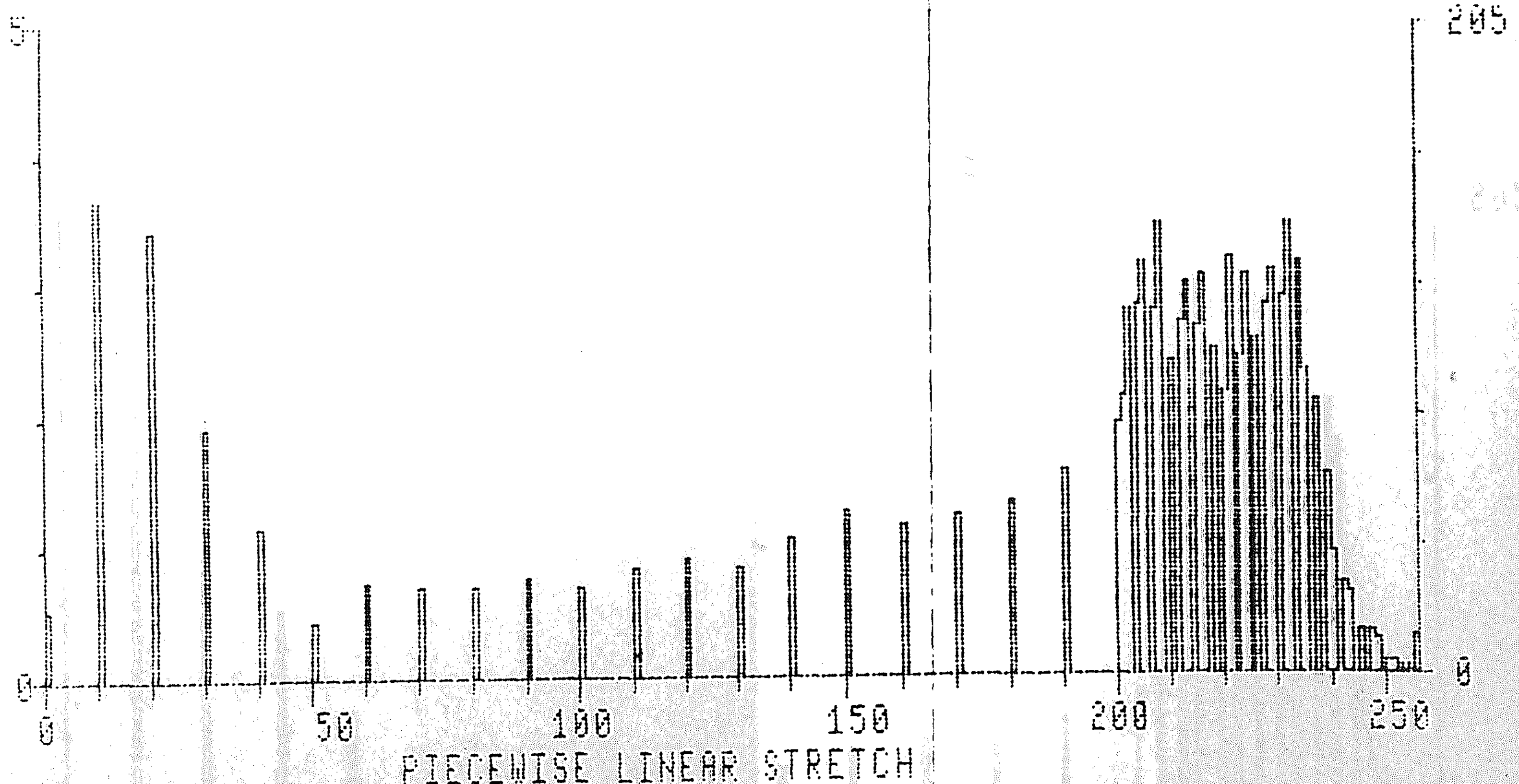


HISTOGRAM OF THE DISPLAY OF BFSFFBND7

LT TYPE 'X' TO CONTINUE (X) =

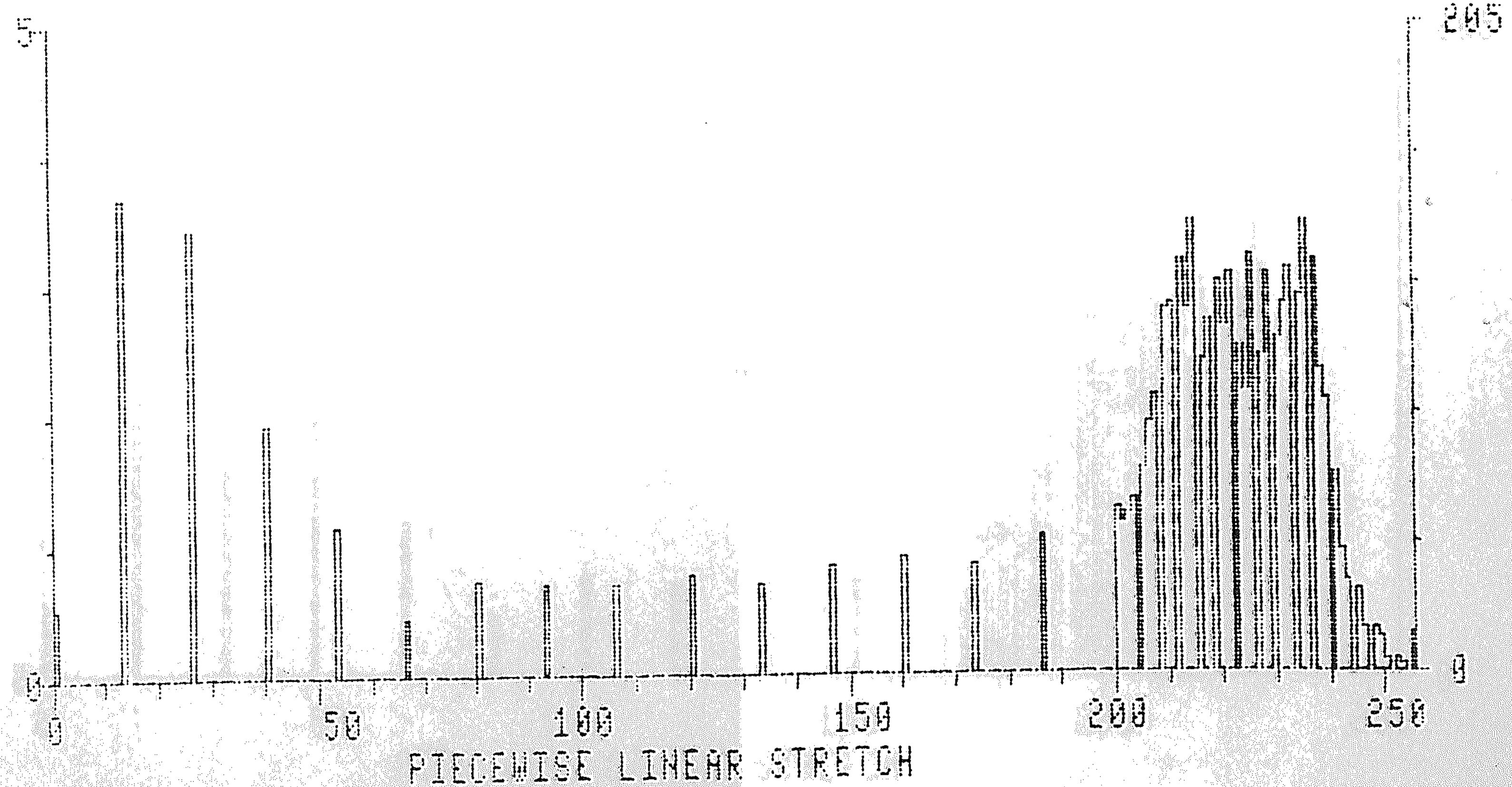
APPENDIX G BAND 7 HISTOGRAM OF PIXEL BRIGHTNESS VALUES BEFORE STRETCHING

The following histograms represent values for a trial piece-wise stretch and for stretches 1 and 3



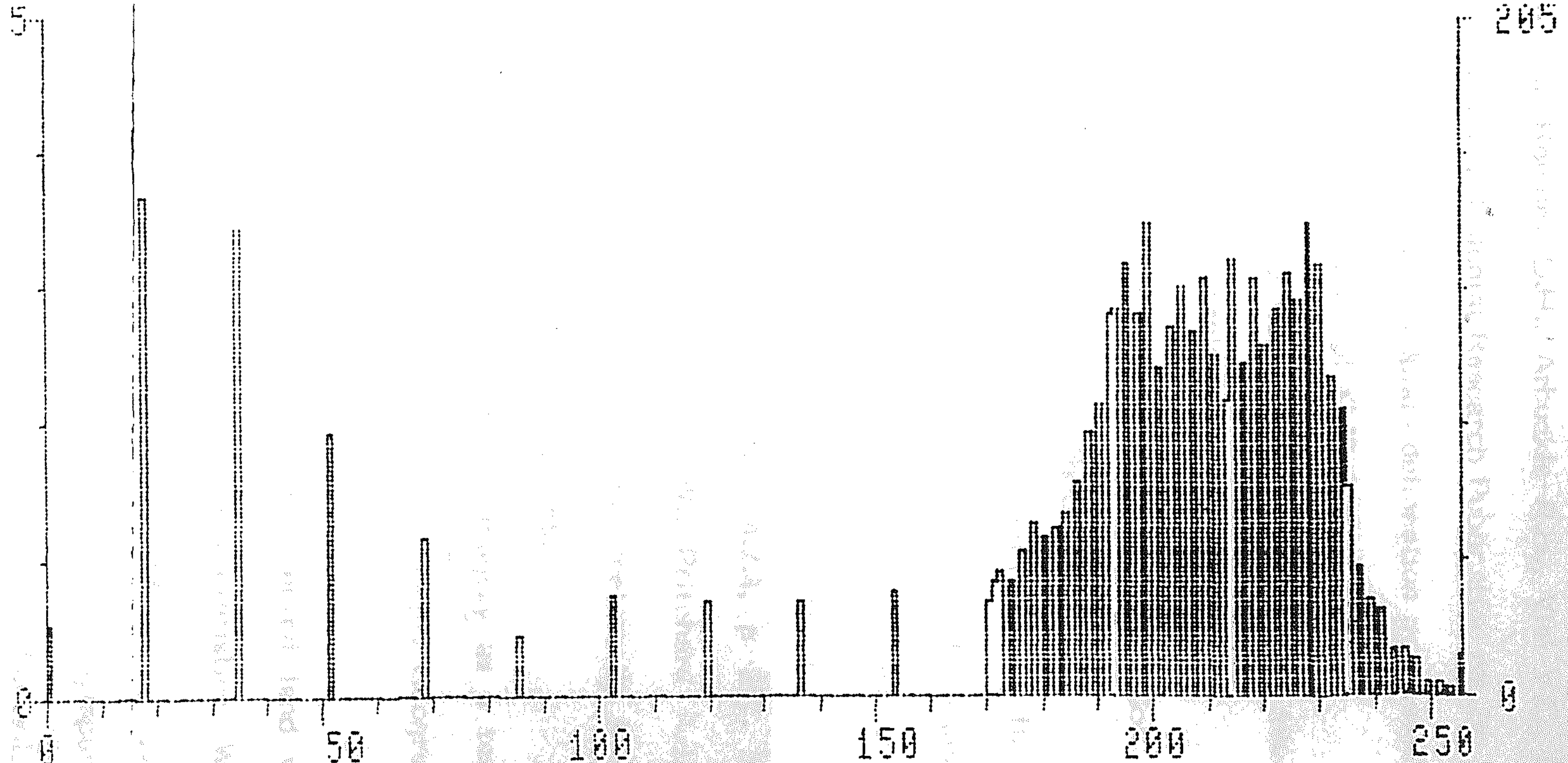
LT   TYPE 'X' TO CONTINUE (X) =

TRIAL



LT TYPE 'X' TO CONTINUE (X) =

P.W.1.



PIECEWISE LINEAR STRETCH

LT TYPE 'X' TO CONTINUE (X) =

P.W.3

REFERENCES

1. Wright A.G.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O., Colonial Research Publication No.24, 1959.

2. Wright A.G.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O., Colonial Research Publication No.24, 1959.

3. Harker G.R., Rouse J.W., Floodplain delineation using multispectral data analysis, P.E. and R.S., Vol XLIII, No. 1, 1977

4. Miller S.T., Report on the flooding of the Belize and Sibun rivers, 1980, Belize National Hydrometeorological Unit, 1981.

5. Manual of Remote Sensing, Colwell R.N. (ed.), Am. Soc. Photogram, 1983; R.S. and P.E. (journal) Am. Soc. Photogram.

6. Benson M.A., Factors influencing the occurrence of floods in a humid region of diverse terrains, U.S.G.S. Water Supply paper 1580-B, 1962

7. Wolfe P.O., Comparison of methods of flood estimation, Session A, Symposium on river flood hydrology, Proc. Inst. Civ. Eng. p 1-23, 1966.

8. Flood Studies Report, Vol II. 4.2.1. - 4.2.4, p 292, N.E.R.C., 1975.

9. Drayton R., Chidley T.R.E., Rees S.W., Pritchard A.J., Visual interpretation for the estimation of key parameters in hydrologic models (paper), Annual Meeting of the I.G.B., 1986.

10. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, Univ. Kansas, Dept. Geography, Lawrence, Kansas, 1967.

11. Pluhowski E.J., Applications of remotely sensed land use information to improve estimates of streamflow characteristics, Water Resources Division, Open file report 77-632, U.S.G.S., 1977.

12. Dowman I.J., Report on Metric Camera workshop, Symposium on experiences with photography from space (paper), D.F.V.L.R. Oberfaffenhofen, 1985.

13. Lillesand T.M., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, 1979.

14. Leopold L.B., Wolman M.G., Miller J.P., Fluvial processes in Geomorphology, Freeman Press, San Francisco, 1964

15. Mintzer O., Askari F.A., A remote sensing technique for estimating watershed runoff, Report No. 712508, Ohio Water Resources Center, Columbus, Ohio, 1980.

16. Castruccio P.A., Loats H.L., Fowler T.R., Applications of remote sensing to the development and formulation of hydrologic planning models, NA58 - 30539, Eco Systems International, Maryland, 1976.

17. Drayton R., Chidley T.R.E., Rees S.W., Pritchard A.J., Visual interpretation of satellite imagery for the estimation of key parameters in hydrologic models, (paper), Annual Meeting of the I.G.B., 1986.

18. Rose P.W., Rosendhal P.C., Classification of LANDSAT data for hydrologic application, Everglades National Park, P.E. and R.S., Vol.XLIX, No.4, p 505-511, 1983.

19. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating flooding, P.E. and R.S., Vol.XLVII, No. 4, p 1351-1356, 1981.

20. Rose P.W., Rosendhal P.C., Classification of LANDSAT data for hydrologic application, Everglades National Park, P.E. and R.S., Vol.XLIX, No. 4, p 505-511, 1983.

21. Ferguson H.L., Deutch M., Kruus J., Applications to floods of remote sensing from sattelites. C.S.O.W.R.M. '80, Pergamon Press, Oxford, 1980.

22. Morrison R.B., White P.G., Monitoring flood inundation, U.S.G.S. Professional Paper 929, 1982

23. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating river flooding, P.E. and R.S., Vol.XLVII, No.9, p 1351 - 1356, 1981

24. Nash J.E., Shaw B.L., Flood frequency as a function of catchment characteristics, Session C., Symposium on river flooding, Proc. Inst. Civ. Eng. 1965.

25. Flood Studies Report, Vol.II, 4.2.2., p 292, N.E.R.C., 1975.

26. Flood Studies Report, Vol.II, 4.2.6., p 312, N.E.R.C., 1975.

27. Chow V.T., Statistical and probability analysis of hydrologic data, Part IV, Handbook of Applied Hydrology, McGraw-Hill, New York, 1964.

28. Flood Studies Report, Vol.II, 4.2.6., p 313, N.E.R.C., 1975.

29. Flood Studies Report, Vol.II, 4.3.4., p 318, N.E.R.C., 1975.

30. Flood Studies Report, Vol.II, 4.2.2, N.E.R.C., 1975.

31. Horton R.E., Drainage basin characteristics, Trans. A.G.U. 13, p 35--361

32. Nash J.E., A unit hydrograph study with particular reference to British catchments, Proc. Inst. Civ. Eng. Vol.17, p 249-282, 1960.

33. Flood Studies Report, Vol.II, 4.2.3, N.E.R.C., 1975.

34. Nash J.E., A unit hydrograph study with particular reference to British catchments, Proc. Inst. Civ. Eng. Vol.17, p 249-282, 1960.

35. Horton R.E., Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology, Bull. Amer. Soc. 56, p 275-330, 1945.

36. Schumm S.A., Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey, Bull. Amer. Geol. Soc. 67, p 597-646, 1956.

37. Flood Studies Report, Vol.II, 4.3.4. - 4.3.7, p 316-328, N.E.R.C., 1975.

38. Flood Studies Report, Vol.II, 4.2.6., p 312, N.E.R.C., 1975.

39. Fiddes D., Paper 5, T.R.R.L. Supplementary Report 259, p 284-324, T.R.R.L., 1975.

40. Emmot C., Airphoto interpretation for measurement of landuse change (Ph.D. thesis), Aston University, I979.

41. Fiddes D., Paper 5, T.R.R.L. Supplementary Report 259, p 284-324, T.R.R.L., 1975.

42. Wright A.C.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O. Colonial Research publication, No. 24, 1959.

43. Flood Studies Report, Vol.II, 4.3.4., p 317, N.E.R.C., 1975.

44. Johnson D.G., Vetlow I.P., The role of satellites in the 1980's, W.M.O. No.494, W.M.O. Geneva, 1977.

45. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating river flooding, P.E. and R.S., Vol.XLVII, No.9, 1981.

46. Benson, M.A., Factors affecting floods in the south west U.S.A., U.S.G.S., Water Supply Paper, 1580 - D, p 72, 1964.

47. Miller V.C., A quantitative geomorphic study of drainage basin characteristics in the Clinch Mountain area, Virginia and Tennessee, Technical Report 3, Dept. of Geography, Columbia University, New York 1953.

48. Schumm S.A., Evaluation of drainage systems and slopes in the badlands at Perth Amboy, New Jersey, Bull. Amer. Geol. Soc. 67, p 597-646, 1956.

49. Morisawa M., Quantitative geomorphology of some watersheds in the Appelation Plateau, Bull. Amer. Geol. Soc., 73, p 1025-1046, 1967.

50. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, University of Kansas, Dept. Geography, Lawrence, Kansas, 1967.

51. Lillesand TM., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, 1979.

52. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating river flooding, P.E. and R.S., Vol.XLVII, No.9, p1351 - 1356, 1981.

53. Klemas V. et al, Inventory of Delaware's wetlands, P.E. and R.S., Vol. XL, No. 4, 1974.

54. Lillesand TM., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, 1979.

55. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating river flooding, P.E. and R.S., Vol.XLVII, No.9, p1351 - 1356, 1981.

56. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, University of Kansas, Dept. Geography, Lawrence, Kansas, 1967.

57. Dowman I.J., Report on the Metric Camera Workshop, D.F.V.L.R. Paper 2, Symposium on experiences with photography from space, Photogram Soc., 1985.

58. Dowman I.J., Report on the Metric Camera Workshop, D.F.V.L.R. Paper 2, Symposium on experiences with photography from space, Photogram Soc., 1985.

59. Schroeder M., Flight performance of the Metric Camera experiment, Paper 1, Symposium on experiences with photography from space, Photogram Soc., 1985.

60. Dowman I.J., Report on the Metric Camera Workshop, D.F.V.L.R. Paper 2, Symposium on experiences with photography from space, Photogram Soc., 1985.

61. Meneguette A.A.C., Evaluation of Metric Camera photography for mapping and coordinate determination, Paper 6, Symposium on experiences with photography from space, Photogram Soc., 1985.

62. Snowsill D., Ordnance Survey experience with space photography, Paper 4, Symposium on experiences with photography from space, Photogram Soc., 1985.

63. SIR-A information package 81-11A-01A, N.A.S.A., Goddard Space Center, Green Belt, Maryland, 1983.

64. Manual of Remote Sensing, Vol.I, 10, p 429-473. , Am. Soc. Photogram., Sheridan press, Virginia, I983.

65. Lillesand R.M., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, 1979.

66. Elachi C., Radar images of the Earth from space, New Scientist, Vol. p 46 - 53, December 1983.

67. Wright A.C.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O., Colonial Research publication No. 24, 1959.

68. Manual of Remote Sensing, Vol. I, 10, p 443-457

69. Schmugge T.J., Microwave approaches in hydrology, P.E. and R.S. Vol.XLVI, No. 4, 1080.

70. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, University of Kansas, Dept. Geography, Lawrence, Kansas, 1967.

71. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, University of Kansas, Dept. Geography, Lawrence, Kansas, 1967.

72. Manual of Remote Sensing, Vol.I, 12, p 517-570. , Am. Soc. Potogram. , Sheridan press, Virginia, I983.

73. Dowman I.J., Report on the Metric Camera Workshop, D.F.V.L.R. Paper 2, Symposium on experiences with photography from space, Photogram Soc., 1985.

74. SIR-A information package 81-11A-01A, N.A.S.A., Goddard Space Center, Green Belt, Maryland, 1983.

75. Manual of Remote Sensing, Vol. I, 17, p 753-767 , Am. Soc. Photogram., Sheridan press, Virginia, I983.

76. Flood Studies Report, Vol.II, 4.3.4., p 316, N.E.R.C., 1975.

77. McCoy R.M., The evaluation of radar imagery as a tool for drainage basin analysis, Ph.D. Thesis, University of Kansas, Dept. Geography, Lawrence, Kansas, 1967.

78. Wright A.C.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O., Colonial Research publication No. 24, 1959.

79. Walker S.H., Summary of climatic records for Belize, L.R.D., Supplementary report 3, 1973.

80. Walker S.H., L.R.D., Supplementary report 105, Vol.2, 1973.

81. Wright A.C.S., Romney D.H., Arbuckle R.H., Vial V.E., Land in British Honduras, H.M.S.O., Colonial Research publication No. 24, 1959.

82. Walker S.H., Summary of climatic records for Belize, L.R.D., Supplementary report 3, p.10, 1973.

83. Nash J.E., Shaw B.L., Flood frequency as a function of catchment characteristics, Paper 6, Session C., Inst. Civ. Eng. Symposium of river flood hydrology, p.115-135, 1966.

84. Reve W.T.N., Edmonds D.T., Zambezi river flooding and its effects on design and operation of the Kariba Dam, Paper 8, Session D., Inst.Civ. Eng. Symposium of river flood hydrology, p 12 - 187, 1966.

85. Flood Studies Report, Vol.II, 4.2.4., p.305-311, N.E.R.C., 1975.

86. Hydrology for soil and water conservation in coastal regions of North Africa, Examples of hydrological technique for small basins, Hydrology Branch Engineering division Soil Conservation Service, U.S.D.A., 1974.

87. Potter D., Rainfall and topographic factors affecting runoff, Trans. A.G.U., Vol.34, No.1, p 67 - 71, 1953.

88. Langbein W.B., Topographic characteristics of drainage basins, U.S.G.S. Water supply paper 968-C, p 125-157, 1947.

89. Wolfe P.O., Comparison of flood estimation, Paper 1, Session A, Inst. Civ. Eng. Symposium of river flood hydrology, p 1-23, 1966.

90. Flood Studies Report Vol.II, 4.3.1 - 4.3.3, p 20-27, N.E.R.C., 1975.

91. Flood Studies Report Vol.II, 4.2.4, p 306, N.E.R.C., 1975

92. Beran M.A., Sutcliffe J.V., An index of flood producing rainfall, Jour. Hyd. Vol.17, p 229-236, 1972.

93. Flood Studies Report Vol.II, 4.3.4, p 318, N.E.R.C., 1975.

94. Thiessen A.H., Precipitation averages for large areas, Mon. Wea. Rev., Vol.39, p 1082-1084, 1911.

95. Potter K., Report on the Belize Meteorological Service, unpublished internal report, 1980.

96. U.S. Weather Bureau, Hydrometeorological Report No. 5, N.O.A.A., 1947.

97. Ward R.C., Principles of Hydrology, McGraw Hill Book Company (U.K.) Ltd., London, 1967.

98. Whitmore J.S., Agrohydrology South African Dept. of Water Arrairs, Technical report 22, 1966.

99. Chidley T.R.E., Keys K.M., A rapid method of computing areal rainfall, Jour. Hyd. 12, p 15-24, 19.

100. Walker S.H., Summary of climatic records for Belize, L.R.D. Supplementary report 3, 1973.

101. Ward R.C., Principles of Hydrology, McGraw Hill Book Company (U.K.) Ltd., London, p 47, 1967.

102. Flood Studies Report, Vol.II, 4.2.4., p 305-312, N.E.R.C., 1975.

103. Flood Studies Report, Vol.II, 4.2.4., p 307, N.E.R.C., 1975.

104. Flood Studies Report, Vol.II, 5.1, p 38, N.E.R.C., 1975.

105. Flood Studies Report, Vol.II, 5.1, p 38, N.E.R.C., 1975.

106. Rodier J.A., Paper 3, T.R.R.L., Supplementary Report 259, p 284-324, T.R.R.L., 1975

107. Hershfield D.K., Wilson W.I., A comparison of extreme rainfall depths from tropical and non-tropical storms. Fiddes D., paper 5 , T.R.R.L. Sup. report 259, T.R.R.L., I975.

108. Walker S., Records of River Stage, discharge and water quality for the Belize and Sibun rivers 1968-71, L.R.D., Miscellaneous report No. 126.

109. Penman H.L., Natural evaporation from open water, bare soil and grass, Proc. Roy. Soc. Ser.A., Vol.193, p 120-145, 1948.

110. Chidley T.R.E., Pike J.G., A generalised computer program for the solution of the Penman equation for evapotranspiration, Jour.Hyd. Vol.10, p 75-89, 1970.

111. Chidley T.R.E.,Assessments in groundwater recharge, Case studies in groundwater res. evaluation, Clarendon press, Oxford, I98I.

112. Tables of the Smithsonian Institute, Contributions to Earth Sience,I969.

113. Walker S., Records of River Stage, discharge and water quality for the Belize and Sibun rivers 1968-71, L.R.D., Miscellaneous report No. 126. 1972.

114. Hydrological yearbook 1981-82 of the National Hydrometeorological Service of Belize, Belize, 1982.

115. Walker S., Records of River Stage, discharge and water quality for the Belize and Sibun rivers 1968-71, L.R.D., Miscellaneous report No. 126. 1972.

116. Hudson, H.E., Hazen R., Droughts and low stream flow, Section 18, Handbook of applied hydrology, McGraw-Hill, New York, 1964.

117. Report on the Western highway, Belize, Richards and Dumbleton International, Birmingham, 1981.

118. Flood Studies Report, Vol.II, 4.3.5., p 322, N.E.R.C., 1975.

119. Flood Studies Report, Vol.II, 2.7.1., p 185, N.E.R.C., 1975.

120. Langbein W.B., Annual floods and the partial duration series, Trans. A.G.U. , 30, p. 878-88I, I949.

121. Flood Studies Report, Vol.II, 2.7.1., p 185, N.E.R.C., 1975.

122. Flood Studies Report, Vol.II, 2.7.5., p 193, N.E.R.C., 1975.

123. Flood Studies Report, Vol.II, 2.7.3., p 187, N.E.R.C., 1975.

124. Flood Studies Report, Vol.II, 2.7.3., p 187, N.E.R.C., 1975.

125. Flood Studies Report, Vol.II, 2.7.5., p 194, N.E.R.C., 1975.

126. Flood Studies Report, Vol.II, 2.7.11., p 210, N.E.R.C., 1975.

127. Flood Studies Report, Vol.II, 2.7.11., p 210, N.E.R.C., 1975.

127. Flood Studies Report, Vol.II, 2.7.11., p 210, N.E.R.C., 1975.

129. Flood Studies Report, Vol.II, 2.7.11., p 212, N.E.R.C., 1975.

130. Flood Studies Report, Vol.II, 2.7.11., p 214, N.E.R.C., 1975.

131. Flood Studies Report, Vol.II, 2.7.5., p 193, N.E.R.C., 1975.

132. Nash J.E., Shaw B.L., Flood frequency as a function of catchment characteristics, Paper 6, Session C., Inst. Civ. Eng. Symposium on river flood hydrology, p.115-135, 1966.

133. Flood Studies Report, Vol.II, 4.3.5., p 322, N.E.R.C., 1975.

134. Gumbell E.J., Statistical theory of floods and droughts, Jour.Inst. Water Engineers, Vol.12, p 157, 1958.

135. Flood Studies Report, Vol. II, 2.7.9., p 204, N.E.R.C., 1975.

136. Flood Studies Report, Vol. II, 4.3.1., p 313, N.E.R.C., 1975.

137. Flood Studies Report, Vol. II, 4.3.1., p 314, N.E.R.C., 1975.

138. Flood Studies Report, Vol. II, 4.3.1., p 314, N.E.R.C., 1975.

139. Flood Studies Report, Vol. II, 4.3.4., p 318, N.E.R.C., 1975.

140. Rose P.W., Rosendhal P.C., Classification of LANDSAT data for hydrological application, Everglades National Park, P.E. and R.S., Vol.XLIX, No.4, p 505-511, 1983

141. Philipson W.R., Hafker W.R., Manual versus digital LANDSAT analysis for delineating river flooding, P.E. and R.S., Vol.XLIII, No.9, p 1351 - 1356, 1981.

142. Harker G.R., Rouse Jnr. J.W., Flood-plain delineation using multispectral data analysis, P.E. and R.S., Vol.XLIII, No. 1, p 81-87, 1977.

143. McLeester J.N., Philipson W.R., Developing in situ flood estimates using multidate LANDSAT imagery. Proc. 45th Ann. Meeting Am. Soc. Photogram, p 625-637, 1979.

144. Wright A.CS., Romney D.H., Arbuckle R.A., Vial V.E., Land in British Honduras, vegetation map No.1, H.M.S.O. Colonial Research Publication No. 24, 1959.

145. Hallberg G.R., Hayer B.E., Rango A., Application of ERTS-1 imagery to flood inundation mapping, Proc.Symposium significant results obtained from ERTS-1, NASA sp-327, p 745-753, NASA, Washington D.C., 1973.

146. Lamprey R., The Masai : A remote sensing approach, Ph.D. thesis, University of Aston, Birmingham, 1985.

147. Gray D.M., Wigham J.M., Peak flow-rainfall events, section VIII, Handbook on the principles of hydrology, National Research Council of Canada, Ottawa, 1970.

148. Chow V.T., Runoff, Section 14, Handbook of applied hydrology, McGraw-Hill, New York, 1964.

149. Flood Studies Report, Vol.II, 6.1.4., p 375, N.E.R.C., 1975.

150. Linsley R.K., Kohler M.A., Paulhus J.L.H., Hydrology for Engineers, McGraw-Hill, New York, 1958.

151. Linsley R.K., Kohler M.A., Paulhus J.L.H., Hydrology for Engineers, McGraw-Hill, New York, 1958.

152. Flood Studies Report, Vol.II, 6.1.5, p 377, N.E.R.C., 1975.

153. Flood Studies Report, Vol.II, 6.1.5, p 378, N.E.R.C., 1975.

154. Flood Studies Report, Vol.II, 6.4.2, p 388, N.E.R.C., 1975.

155. Flood Studies Report, Vol.II, 6.4.2, p 389, N.E.R.C., 1975.

156. Linsley R.K., Kohler M.A., Paulhus J.L.H., Hydrology for Engineers, McGraw-Hill, New York, 1958.

157. Flood Studies Report, Vol.II, 6.4.2, p 388, N.E.R.C., 1975.

158. Flood Studies Report, Vol.II, 6.4.1, p 388, N.E.R.C., 1975.

159. Flood Studies Report, Vol.II, 6.4.3, p 389-390, N.E.R.C., 1975.

160. Flood Studies Report, Vol.II, 6.4.4, p 390, N.E.R.C., 1975.

161. Walker S.H., Records of river stage, discharge and water quality for the Belize and Sibun rivers, 1968-71, L.R.D., Miscellaneous Report No. 126, 1972.

162. Walker S.H., Records of river stage, discharge and water quality for the Belize and Sibun rivers, 1968-71, L.R.D., Miscellaneous Report No. 126, 1972.

163. Chidley T.R.E., private communication, 1985.

164. White M.E., Reservoir surface area from LANDSAT imagery, P.E. and R.S., Vol.XLIV, 1978.

165. Pluhowski E.J., Applications of remotely sensed land use information to improve stream flow characteristics, Final Report, U.S.G.S. Open file report 77-632, 1977.

166. Odanyo V.A.O., Pettry D.E., Land use mapping by machine processing of LANDSAT data, P.E., and R.S., Vol.XLIII, No. 1., 1979.

167. Odanyo V.A.O., Pettry D.E., Land use mapping by machine processing of LANDSAT data, P.E., and R.S., Vol.XLIII, No. 1., 1979.

168. Fiddes D., Paper 5, T.R.R.L. Supplementary Report 259, p 284-324, T.R.R.L., 1975.

169. Richards and Dumbleton International, Report on the Western highway, Belize, Birmingham, 1981.

170. Radier J.A., Paper 3, T.R.R.L., Supplementary report 259, p 244-254, T.R.R.L. 1975.

171. Manual of Remote Sensing , Colwell R.N.(ed.), Am. Soc. Photogram., Sheridan press, Virginia, I975.

172. Rose P.W., Rosendhal P.C., Classification of LANDSAT data for hydrologic application, Everglades National Park, P.E. and R.S., Vol. XLIX, No. 4, 1983.

173. Manual of Remote Sensing, Vol.I, 17, p 719-788.

174. Lillesand T.M., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, 1979.

175. Lillesand T.M., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, p 461-470, 1979.

176. Lillesand T.M., Kiefer R.W., Remote sensing and image interpretation, John Wiley and Sons, New York, p 471, 1979.

177. Drayton R., Chidley T.R.E., Rees S.W., Pritchard A.J., Visual interpretation of satellite imagery for the estimation of key parameters in hydrologic models, (paper), Annual meeting I.B.G., 1986.

178. Flood Studies Report, Vol. II, 4.3.11, p.346, N.E.R.C., 1975.

179. Benson M.A., Factors influencing the occurrence of floods in a humid region of diverse terrain, U.S.G.S. Water Supply paper 1580-B, 1962.

180. Flood Studies Report, Vol.II, 4.3.4., p 318, N.E.R.C., 1975.

ABBREVIATIONS

Am. Soc. Photogram.	American Society of Photogrammetry
A.G.U.	American Geophysical Union
Bull. Am. Geol. Soc,	Bulletin of the American Geological Society
c.c.t.	computer compatible tapes (LANDSAT)
CSOWRM'80	The contribution of space observations to Water Resources Management, Soloman and Bhavsar, Pergamon Press, Oxford.
D.F.V.L.R.	
f.c.c.	false colour composite (bands 4, 5, 7 image (LANDSAT)
F.S.R.	Flood Studies Report
H.M.S.O.	His/Her Majesty's Stationery Office, London
I.B.G.	Institute of British Geographers
Inst.Civ.Eng.	Institution of Civil Engineers
Jour.Hyd.	Journal of Hydrology
L.R.D.	Land Resources Division, Overseas Development Administration, Tolworth, Surrey.
m.s.s.	Multispectral Scanner (LANDSAT)
Mon.Wea.Rev.	Monthly Weather Review (U.S.A.)
N.A.S.A.	National Aeronautics and Space Administration (U.S.A.)
N.E.R.C.	Natural Environment Research Council
N.O.A.A.	National Ocean (U.S.A.)
P.E. and R.S.	Photogrammetric Engineering and Remote Sensing (Journal of the American Society of Photogrammetry)

Photogram. Soc.	Photogrammetrical Society (U.K.)
Proc.	Proceedings (of)
Trans. A.G.U.	Transactions of the American Geophysical Society
T.R.R.L.	Transport and Road Research Laboratory (U.K.)
U.S.D.A.	United States Department of Agriculture
U.S.G.S.	United Stated Geological Society
U.T.M.	Universal Transverse Mercator (map projection)
W.M.O.	World Meteorological Organisation