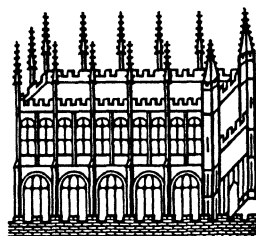


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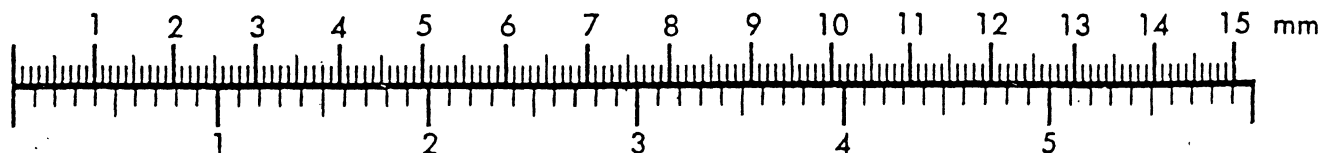
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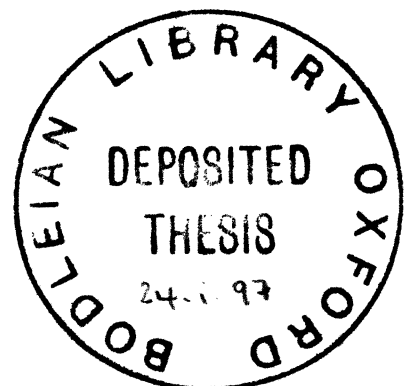
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**Late Holocene Environmental Change in the Basin of  
Pátzcuaro, Michoacán, México.**

**Thesis submitted for the Degree of  
Doctor of Philosophy  
in the Faculty of Anthropology and Geography**

by

**Sarah L. O'Hara  
St. Hilda's College, Oxford  
Trinity Term, 1991. [i.e. 1996]??**





Antiquar

Liechtenstein  
Herr von der Dorn...

ABSTRACT  
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D. Phil. Trinity 1991 [i.e. 1996]

Late Holocene Environmental Change in the Basin of  
Pátzcuaro, Michoacán, Mexico.

This thesis describes late Holocene environmental changes in the Basin of Pátzcuaro, Michoacán, Mexico. Using palaeolimnological, geomorphological, sedimentological and historical evidence it is possible to conclude that the Basin of Pátzcuaro has suffered at least three episodes of disturbance within the last 3,600 years. A minor episode of erosion began about 3,500 years ago and is believed to have been triggered by the onset of sedentary agriculture within the basin. A second, more severe phase of disturbance, occurred between about 2,500 and 1,200 years B.P. during which time there was extensive degradation in the northern part of the catchment; widespread gullying is believed to have occurred at this time. The recent, most intense period of erosion began about 850 years B.P., coinciding with the arrival of the Purépecha in the basin. There is no evidence to suggest that degradation within the catchment intensified after the arrival of the Spanish 470 years B.P. However, a change in the style of erosion from predominantly sheet-wash to gully erosion occurred at approximately 400-500 years B.P. and may reflect the introduction of new agricultural techniques by the Spanish.

Fluctuations in the level of Lake Pátzcuaro have been used to infer late Holocene climatic change. Prior to 4,000 years B.P. dry conditions prevailed. An abrupt change to wetter conditions occurred between about 3,600 and 3,200 years B.P. before becoming more arid. Wetter conditions between 2,500 and 1,200 years B.P. can be inferred from the lake sediment record. The driest period in the record occurred between 1,200 and 850 years B.P. Fluctuations in the level of the lake over the last 600 years have been determined from historical records. The lake rose between 600 and 470 years B.P. and remained high until approximately 300 years B.P. after which time the lake level fell once again.

## TABLE OF CONTENTS

|  | fPage  |
|--|--------|
| ABSTRACT   | i      |
| CONTENTS   | ii     |
| LIST OF TABLES   | vii    |
| LIST OF PLATES   | viii   |
| LIST OF FIGURES  | x      |
| ACKNOWLEDGEMENTS   | xv     |
| <br>CHAPTER ONE: INTRODUCTION  | <br>1  |
| <br>CHAPTER TWO: PHYSICAL BACKGROUND TO THE<br>BASIN OF PATZCUARO                                  | <br>4  |
| 2.1 LOCATION   | 4      |
| 2.2 GEOLOGY  | 4      |
| 2.3 MORPHOLOGY OF THE LAKE PATZCUARO BASIN   | 5      |
| 2.4 CLIMATE  | 6      |
| 2.5 SOILS  | 7      |
| 2.6 VEGETATION   | 9      |
| 2.7 PRESENT DAY LAND USE   | 10     |
| 2.8 HYDROLOGY  | 11     |
| 2.9 MORPHOMETRY AND BATHYMETRY OF THE LAKE   | 12     |
| 2.10 THE WATER BUDGET  | 13     |
| 2.11 MODERN LIMNOLOGY  | 14     |
| <br>CHAPTER THREE: BACKGROUND TO THE ARCHAEOLOGY OF<br>MEXICO                                      | <br>16 |
| 3.1 INTRODUCTION   | 16     |
| 3.1.1 The Archaic (ca 7,000-3,500 B.P)   | 16     |
| 3.1.2 The Preclassic (ca 3,500-1,700 B.P.)   | 18     |
| 3.1.3 The Classic (ca 1,700 - 1,100 B.P)   | 19     |
| 3.1.4 The Postclassic (ca 1,100 - 470 B.P.)  | 21     |
| 3.2 ARCHAEOLOGICAL AND HISTORICAL BACKGROUND<br>TO THE BASIN OF PATZCUARO                          | 22     |
| 3.2.1 The Purépecha  | 24     |
| 3.2.2 The Hispanic Period  | 25     |
| 3.2.3 Changes in the population since the Conquest   | 27     |
| 3.2.4 Pre- and Post Hispanic agriculture   | 28     |
| 3.2.5 Evidence of environmental degradation  | 31     |
| <br>CHAPTER FOUR: LATE QUATERNARY-EARLY HOLOCENE ENVIRONMENTAL<br>CHANGE IN MEXICO: A BRIEF REVIEW | <br>35 |
| 4.1 INTRODUCTION   | 35     |
| 4.2 RECONSTRUCTION OF LATE PLEISTOCENE-HOLOCENE<br>CLIMATES IN CENTRAL MEXICO                      | 36     |
| 4.3 SUMMARY OF LATE PLEISTOCENE/HOLOCENE CLIMATIC<br>CHANGE  | 43     |
| 4.4 LATE HOLOCENE ENVIRONMENTAL DEGRADATION IN<br>MEXICO   | 44     |

|  |   |     |
|--|---|-----|
| 4.5  | HOLOCENE ENVIRONMENTAL CHANGE IN THE BASIN OF PATZCUARO | 49  |
| 4.6  | ENVIRONMENTAL DEGRADATION IN MEXICO: A SUMMARY          | 52  |
| CHAPTER FIVE: RESEARCH METHODOLOGY   |   | 53  |
| 5.1  | INTRODUCTION  | 53  |
| 5.2  | ARCHIVAL AND HISTORICAL RESEARCH                        | 53  |
| 5.3  | THE LACUSTRINE AND TERRESTRIAL RECORD                   | 54  |
| 5.3.1  | Field Work  | 54  |
| 5.3.2  | Terrestrial Record                                      | 54  |
| 5.3.3  | Lacustrine Record                                       | 54  |
| 5.4  | LABORATORY ANALYSES                                     | 57  |
| 5.4.1  | Stratigraphy  | 57  |
| 5.4.2  | Bulk Density  | 58  |
| 5.4.3  | Organic matter  | 58  |
| 5.4.4  | Magnetic mineral analyses                               | 58  |
| 5.4.5  | Grain size Analysis                                     | 60  |
| 5.4.6  | Sediment Chemistry                                      | 61  |
| 5.4.7  | Sample Preparation                                      | 62  |
| 5.4.8  | Element Analysis  | 63  |
| 5.4.9  | Radiocarbon dating                                      | 64  |
| 5.5  | STATISTICAL ANALYSES                                    | 64  |
| 5.5.1  | Correlation   | 64  |
| 5.5.2  | Simultaneous R- and Q-Mode Factor Analysis              | 65  |
| 5.6  | DETERMINATION OF SEDIMENT ACCUMULATION                  | 66  |
| CHAPTER SIX: VARIATIONS IN THE LEVEL OF LAKE PATZCUARO DURING HISTORICAL TIMES |   | 68  |
| 6.1  | INTRODUCTION  | 70  |
| 6.2  | THE CASE OF LAKE PATZCUARO                              | 69  |
| 6.3  | METHODOLOGY   | 70  |
| 6.4  | THE PRE HISPANIC RECORD                                 | 71  |
| 6.5  | THE EARLY COLONIAL PERIOD                               | 73  |
| 6.6  | THE EIGHTEENTH CENTURY                                  | 76  |
| 6.7  | THE NINETEENTH CENTURY                                  | 77  |
| 6.8  | THE TWENTIETH CENTURY                                   | 80  |
| 6.9  | DISCUSSION  | 82  |
| 6.10   | CONCLUSIONS   | 85  |
| CHAPTER SEVEN: THE TERRESTRIAL RECORD  |   | 86  |
| 7.1  | INTRODUCTION  | 86  |
| 7.2  | THE SOUTHERN BASIN                                      | 87  |
| 7.2.1  | San Francisco Uricho (SFU)                              | 87  |
| 7.2.2  | Ajuno   | 89  |
| 7.2.3  | Tzentzencuaro (Tzz)                                     | 91  |
| 7.2.4  | Pátzcuaro   | 95  |
| 7.2.5  | Tzurumútaró   | 97  |
| 7.2.6  | La Ciénaga De Tzurumútaró                               | 97  |
| 7.2.7  | Ihuatzio  | 100 |
| 7.2.8  | Summary and interpretation of the Southern Basin        | 101 |

|   |   |     |
|---|---|-----|
| 7.3   | THE CENTRAL BASIN   | 102 |
| 7.3.1   | San Pedro Cucuchuchu (SPC)  | 102 |
| 7.3.2   | Napizaro  | 103 |
| 7.3.3   | Summary and interpretation of the Central Basin                                   | 104 |
| 7.4   | THE NORTHERN BASIN  | 104 |
| 7.4.1   | Tzintzuntzan  | 105 |
| 7.4.2   | Tzocuio   | 106 |
| 7.4.3   | Quiroga(Q)  | 106 |
| 7.4.4   | San Jerónimo Purenchécuaro (SJP)  | 107 |
| 7.4.5   | Summary and interpretation of the Northern Basin                                  | 108 |
| 7.5   | SUMMARY OF THE TERRESTRIAL RECORD   | 109 |
| CHAPTER EIGHT: PHYSICAL PROPERTIES OF THE LAKE SEDIMENT RECORD. |   | 111 |
| 8.1   | INTRODUCTION  | 111 |
| 8.2   | THE SOUTHERN BASIN  | 111 |
| 8.2.1   | Stratigraphy  | 112 |
| 8.2.2   | Radiocarbon Dates And Sediment Accumulation Rates                                 | 113 |
| 8.2.3   | Moisture Content And Bulk Density   | 113 |
| 8.2.4   | Carbonate content (CaCO <sub>3</sub> )  | 114 |
| 8.2.5   | loss-on-ignition  | 115 |
| 8.2.6   | Magnetic Susceptibility (X)   | 115 |
| 8.2.7   | Grain Size  | 116 |
| 8.2.8   | Summary of The Southern Basin   | 116 |
| 8.3   | THE CENTRAL BASIN   | 118 |
| 8.3.1   | Stratigraphy  | 119 |
| 8.3.2   | Radiocarbon Dates And Sediment Accumulation Rates                                 | 120 |
| 8.3.3   | Moisture Content And Bulk Density   | 121 |
| 8.3.4   | Carbonate Content   | 121 |
| 8.3.5   | Loss-on-ignition  | 122 |
| 8.3.6   | Magnetic Susceptibility (X)   | 123 |
| 8.3.7   | Grain Size  | 124 |
| 8.3.8   | Summary and interpretation of The Central Basin Sediments                         | 125 |
| 8.4   | THE NORTHERN BASIN  | 126 |
| 8.4.1   | Stratigraphy  | 127 |
| 8.4.2   | Radiocarbon Dates And Sediment Accumulation Rates                                 | 127 |
| 8.4.3   | Moisture Content And Bulk Density   | 127 |
| 8.4.4   | Carbonate Content   | 128 |
| 8.4.5   | Loss-on-ignition  | 128 |
| 8.4.6   | Magnetic Susceptibility (X)   | 128 |
| 8.4.7   | Grain Size  | 129 |
| 8.4.8   | Summary and interpretation of the Northern Basin Sediments                        | 130 |
| 8.5   | SUMMARY AND INTERPRETATION OF THE PHYSICAL PROPERTIES OF THE LAKE SEDIMENT RECORD | 130 |
| 8.6   | CONCLUSIONS   | 132 |
| 8.6.1   | Zone I (approximately 5,000-4,200 years B.P.)                                     | 132 |
| 8.6.2   | Zone II (approximately 4,200-3,600 years B.P.)                                    | 133 |

|       |   |     |
|-------|---|-----|
| 8.6.3 | Zone III ( approximately 3,600-3,200 years B.P) | 133 |
| 8.6.4 | Zone IV (approximately 3,200-2,500 years B.P.)  | 133 |
| 8.6.5 | Zone V (approximately 2,500-1,200 years B.P.)   | 133 |
| 8.6.7 | Zone IV (approximately 1,200-850 years B.P.)    | 134 |
| 8.6.7 | Zone VII (approximately 850-0 years B.P.)       | 134 |

## CHAPTER NINE: SEDIMENT CHEMISTRY RECORD OF LAKE PATZCUARO

|       |  |     |
|-------|--|-----|
| 9.1   | INTRODUCTION   | 135 |
| 9.2   | LAKE PATZCUARO 11  | 136 |
| 9.2.1 | Sediment chemistry   | 136 |
| 9.2.2 | Correlation  | 137 |
| 9.2.3 | Factor Analysis  | 138 |
| 9.2.4 | Summary of Lake Patzcuaro 11   | 140 |
| 9.3   | THE MASTERCORE (MC)  | 141 |
| 9.3.1 | Sediment Chemistry   | 141 |
| 9.3.2 | Correlations   | 143 |
| 9.3.3 | Factor Analysis  | 143 |
| 9.3.4 | Summary of the Mastercore  | 145 |
| 9.4   | LAKE PATZCUARO 10  | 146 |
| 9.4.1 | Sediment Chemistry   | 146 |
| 9.4.2 | Correlations   | 147 |
| 9.4.3 | Factor Analysis  | 147 |
| 9.4.4 | Summary of Lake Patzcuaro 10   | 149 |
| 9.5   | LAKE PATZCUARO 19  | 150 |
| 9.5.1 | Sediment Chemistry   | 150 |
| 9.5.2 | Correlations   | 151 |
| 9.5.3 | Factor Analysis  | 151 |
| 9.5.4 | Summary of Lake Pátzcuaro 19   | 153 |
| 9.6   | SUMMARY OF THE SEDIMENT CHEMISTRY RECORD OF LAKE PATZCUARO                     | 153 |
| 9.7   | CHANGES IN THE RATE OF SEDIMENT INFLUX INTO THE LAKE OVER THE LAST 3,500 YEARS | 155 |
| 9.7.1 | Zone V (2,500-1,200 years B.P.)  | 156 |
| 9.7.2 | Zone VI (1,200-850 years B.P.)   | 156 |
| 9.7.3 | Zone VII (850-0 years B.P.)  | 157 |
| 9.7.4 | Summary  | 157 |

## CHAPTER 10: DISCUSSION

|        |   |     |
|--------|---|-----|
| 10.1   | HUMAN DISTURBANCE RECORD  | 159 |
| 10.1.1 | Techniques  | 159 |
| 10.2.2 | Summary of the history of environmental degradation in the Basin of Patzcuaro           | 160 |
| 10.1.3 | The human disturbance record from the Basin of Patzcuaro in the Central Mexican context | 162 |
| 10.2   | LATE HOLOCENE CLIMATIC CHANGE IN THE BASIN OF PATZCUARO                                 | 166 |
| 10.2.1 | The Lake Pátzcuaro climatic record in the Central Mexican context                       | 167 |
| 10.3   | HUMAN AND CLIMATE INTERACTION   | 169 |
| 10.4   | CONCLUSIONS   | 170 |

|   |     |
|---|-----|
| BIBLIOGRAPHY  | 172 |
| APPENDIX A: Worked example of simultaneous R- and Q<br>mode factor analysis (from Walden, 1990) | 186 |
| APPENDIX B: PHYSICAL PROPERTIES OF THE CORES  | 193 |
| APPENDIX C: DATA FROM LAKE SEDIMENT RECORD  | 208 |

## LIST OF TABLES.

|           | Following page  |
|-----------|---|
| Table 2.1 | Main climatic parameters for the Lake Pátzcuaro Basin, 1921-1942 and 1970-1986. 6                   |
| Table 2.2 | Variations in the climate between the southern and northern portions of the Lake Pátzcuaro Basin. 6 |
| Table 2.3 | Major physical and chemical properties of the main soils types in the Basin of Pátzcuaro. 8         |
| Table 2.4 | Secchi disc readings reported from previous limnological surveys in Lake Pátzcuaro 15               |
| Table 3.1 | Main cultural groups of Mesoamerica. 16   |
| Table 3.2 | Population changes in the Basin of Pátzcuaro since the time of the Spanish Conquest. 28             |
| Table 7.1 | Radiocarbon dates from the lake sediments and terrestrial sections 86                               |
| Table 7.2 | Elevations of the major breaks in slope in the Basin of Pátzcuaro 101                               |
| Table 8.1 | Results of moisture content and bulk density analyses for selected cores from Lake Pátzcuaro        |
| Table 9.1 | Correlation matrix from sediment data set from LP11 137   |
| Table 9.2 | Correlation matrix from sediment data set from Mastercore 143                                       |
| Table 9.3 | Correlation matrix from sediment chemistry data set from LP10 147                                   |
| Table 9.4 | Correlation matrix from sediment chemistry data set from LP19 151                                   |
| Table 9.5 | Variations in clastic input into Lake Pátzcuaro between 2,500 and 1,200 years ago 156               |
| Table 9.6 | Variations in clastic input into Lake Pátzcuaro between 1,200 and 850 years ago 156                 |
| Table 9.7 | Variations in clastic input into Lake Pátzcuaro over the last 850 years 157                         |

## LIST OF PLATES

|           |  |    |
|-----------|--|----|
| Plate 2.1 | The birth of Paracutín ca 1943   | 5  |
| Plate 2.2 | The Island of Jarácuaro ca. 1945   | 6  |
| Plate 2.3 | The Island of Jarácuaro ca. 1988.  | 6  |
| Plate 3.1 | Prehispanic terracing on the slopes surrounding Tzintzuntzan.  | 30 |
| Plate 3.2 | Terracing on the steep slopes near Icupio  | 30 |
| Plate 3.3 | Scenes from the Relacion de Michoacan.   | 31 |
| Plate 6.1 | The Beaumont Map of Lake Pátzcuaro from the time of the Conquest.  | 72 |
| Plate 6.2 | The Seler map of Lake Patzcuaro from the time of the Spanish conquest.   | 72 |
| Plate 6.3 | Overlooking Tzentzencuaro  | 73 |
| Plate 6.4 | Lake Pátzcuaro depicted on a map ca. 1579  | 74 |
| Plate 6.5 | Lake Pátzcuaro depicted on a map ca. 1748.   | 74 |
| Plate 6.6 | The walled fortification surrounding the Island of La Pacanda believed to have been constructed by General Epitacio Huerta ca 1850.                  | 73 |
| Plate 6.7 | Lake Pátzcuaro depicted on a map ca. 1906  | 74 |
| Plate 6.7 | El Vado (de Apupuato) ca 1930 at the time when the lake flanked this former island. Today the lake is situated approximately 1.5 km from this point. | 74 |
| Plate 6.8 | The Jetty on the Island of Jaracuaro constructed when the lake was at a higher level in 1938.  | 81 |
| Plate 6.9 | The steam boat used unti the 1930s arriving at Muelle 1. Today it is impossible to bring even canoes to this point.                                  | 81 |
| Plate 7.1 | Gullying behind San Francisco Uricho   | 88 |
| Plate 7.2 | Diatomite exposes on the southern margin of the lake   | 92 |
| Plate 7.3 | Colluvium exposed at the brick-pit at Tzurumuataro   | 97 |
| Plate 7.4 | Lacustrine sediments underlying colluvium at   |    |

|  |     |
|--|-----|
| LC7  | 97  |
| Plate 7.5 Badlands forming in the upper reaches of Ihuatzio embayment  | 100 |
| Plate 7.6 The road cut at San Pedro Cucuchuchu   | 100 |
| Plate 7.7 Gullied terrain in the northern part of the Basin of Pátzcuaro   | 105 |
| Plate 7.8 Exposure of core-stones after the complete removal of the top soil commonly seen in the northern part of the catchment | 105 |

## LIST OF FIGURE

|   | Following page |
|---|----------------|
| Figure 2.1 Location of the study area.  | 4              |
| Figure 2.2 The Basin of Pátzcuaro.  | 4              |
| Figure 2.3 Simplified geology map of the study area   | 4              |
| Figure 2.4 Main sub-basins within the catchment showing the drainage density.               | 5              |
| Figure 2.5 The distribution of the major soil types in the Basin of Patzcuaro.              | 8              |
| Figure 2.6 Simplified diagram of the main vegetation assemblages in the Basin of Pátzcuaro. | 9              |
| Figure 2.7 The drainage network in the Basin of Patzcuaro.                                  | 11             |
| Figure 2.8 Variations in the shoreline gradients of Lake Patzcuaro.                         | 13             |
| Figure 2.9 Bathymetric map of Lake Pátzcuaro.   | 13             |
| Figure 2.10 Observed and expected lake level variations for Lake Patzcuaro, 1970-1986.      | 13             |
| Figure 2.11 Main water currents of Lake Pátzcuaro.  | 14             |
| Figure 2.12 Water chemistry of Lake Pátzcuaro.  | 15             |
| Figure 2.13 Variations in suspended sediment concentrations of Lake Pátzcuaro.              | 15             |
| Figure 2.14 Variations in the trophic status of Lake Pátzcuaro.                             | 15             |
| Figure 3.1 Early human occupation sites in the Americas.                                    | 16             |
| Figure 3.2 Major Archaic and Preclassic archaeological sites in Mesoamerica.                | 17             |
| Figure 3.3 Location of major Classic and Postclassic archaeological sites in Mesoamerica    | 19             |
| Figure 3.4 Major archaeological sites in the vicinity of the study area.                    | 21             |
| Figure 3.5 Limits of the Purépecha empire at the time of the Spanish Conquest.              | 24             |

|            |   |    |
|------------|---|----|
| Figure 3.6 | Uses of the Coa in Prehispanic agricultural practices.  | 29 |
| Figure 4.1 | Location of the main palaeolimnological investigations in Central México  | 37 |
| Figure 4.2 | Paleolimnological stages in the Basin of México during the last 35,000 years BP.                                    | 38 |
| Figure 4.3 | Palaeolimnological record of the Upper Lerma Basin  | 39 |
| Figure 4.4 | Palaeolimnological record of Lake Zacapu  | 39 |
| Figure 4.5 | Palaeolimnological record of La Piscina de Yuriria  | 39 |
| Figure 4.6 | Palaeolimnological record of La Hoya San Nicolas de Parangueo   | 39 |
| Figure 4.7 | Palaeolimnological record of Lake Pátzcuaro (see envelope)  |    |
| Figure 4.8 | Colluvial stratigraphy of section described by Street-Perrot <u>et al.</u> (1989)                                   | 51 |
| Figure 5.1 | The coring device constructed for this project.   | 56 |
| Figure 6.1 | The location of the sites used to determine variations in the level of Lake Pátzcuaro                               | 70 |
| Figure 6.2 | Fluctuations in the level of Lake Pátzcuaro over the last 600 years   | 81 |
| Figure 7.1 | Location of the terrestrial sites investigated in the Basin of Pátzcuaro.   | 86 |
| Figure 7.2 | Location of the reconstructed slope profiles.   | 87 |
| Figure 7.3 | Location of the profiles investigated at SFU.   | 88 |
| Figure 7.4 | The stratigraphy of the SFU profiles  | 88 |
| Figure 7.5 | The slope profile of the Ajuno valley showing positions and simplified stratigraphy of the main sites investigated. | 89 |
| Figure 7.6 | Location of the sites investigated in the Ajuno valley.   | 89 |

|             |   |     |
|-------------|---|-----|
| Figure 7.7  | The stratigraphy of the sections investigated in the Ajuno valley with X where available.                           | 89  |
| Figure 7.8  | The slope profile of the Tzentzénquaro embayment showing the position and simplified stratigraphy of selected sites | 91  |
| Figure 7.9  | Location of the sites investigated in the Tzentzénquaro embayment.  | 92  |
| Figure 7.10 | The main features of the diatom record from TZZ1.   | 92  |
| Figure 7.11 | The stratigraphies of the sites investigated in the Tzentzénquaro embayment.  | 93  |
| Figure 7.12 | Locations of the sites investigated in the Pátzcuaro embayment.   | 95  |
| Figure 7.13 | The stratigraphies of the sites investigated in the Pátzcuaro embayment.  | 95  |
| Figure 7.14 | The slope profile of the Pátzcuaro embayment showing the positions and simplified stratigraphies of selected sites. | 95  |
| Figure 7.15 | Locations of the sites investigated at Tzurumútaro, La Cienaga embayment and Ihuatzio.                              | 97  |
| Figure 7.16 | Slope profiles from La Cienaga embayment  | 98  |
| Figure 7.17 | Simplified stratigraphies of La Cienaga embayment in their relative heights and positions.                          | 98  |
| Figure 7.18 | Selected stratigraphies from La Cienaga embayments showing variations in X.   | 99  |
| Figure 7.19 | Location of the sites investigated in the SPC embayment.  | 102 |
| Figure 7.20 | Selected stratigraphical sections from the SPC embayment.   | 103 |
| Figure 7.21 | Location of the sites investigated at Tzintzuntzan, Tzocorio and Quiroga.   | 105 |
| Figure 7.22 | The slope profile from the Quiroga embayment showing simplified stratigraphies for selected sites.                  | 107 |
| Figure 7.23 | Stratigraphies of sites investigated  |     |

|             |   |     |
|-------------|---|-----|
|             | in the Quiroga embayment.   | 107 |
| Figure 7.24 | Location of the sites investigated in the SPJ embayment.  | 108 |
| Figure 7.25 | Slope profile from the SPJ embayment showing simplified stratigraphies.   | 108 |
| Figure 7.26 | Stratigraphies of the SPJ embayment showing X measurements where available.   | 108 |
| Figure 8.1  | Location of the cores used in the investigation of the Lacustrine record.   | 111 |
| Figure 8.2  | The stratigraphy and results of X, $X_{fd}$ , $CaCO_3$ , L.O.I and grain size for cores sites from the Southern Basin (in separate envelope). |     |
| Figure 8.3  | The stratigraphy and results of X, $X_{fd}$ , $CaCO_3$ , L.O.I and grain size for cores sites from the Central Basin (in separate envelope).  |     |
| Figure 8.4  | The stratigraphy and results of X, $X_{fd}$ , $CaCO_3$ , L.O.I and grain size for cores sites from the Northern Basin (in separate envelope). |     |
| Figure 9.1  | Down-profile changes in sediment chemistry from LP11 (in separate envelope)   |     |
| Figure 9.2  | Plot of variables and samples on Factor 1 versus Factor 2 for LP11 showing stratigraphy and position of sample                                | 138 |
| Figure 9.3  | Plot of variables and samples on Factor 2 versus Factor 3 for LP11 showing stratigraphy and position of sample                                | 138 |
| Figure 9.4  | Down-profile changes in the factor loadings for LP11  | 140 |
| Figure 9.5  | Down-profile changes in sediment chemistry from the MC (see separate envelope)  |     |
| Figure 9.6  | Plot of variables and samples on Factor 1 versus Factor 2 for MC showing stratigraphy and position of sample                                  | 143 |
| Figure 9.7  | Plot of variables and samples on Factor 2 versus Factor 3 for MC showing stratigraphy and position of sample                                  | 145 |
| Figure 9.8  | Down-profile changes in the factor loadings for MC  | 145 |

|             |   |     |
|-------------|---|-----|
| Figure 9.9  | Down-profile changes in sediment chemistry of LP10 (see separate envelope)                                      |     |
| Figure 9.10 | Plot of variables and samples on Factor 1 versus Factor 2 for LP10 showing stratigraphy and position of sample  | 148 |
| Figure 9.11 | Plot of variables and samples on Factor 2 versus Factor 3 for LP10 showing stratigraphy and position of samples | 148 |
| Figure 9.12 | Down-profile changes in the factor loadings for LP10  | 148 |
| Figure 9.13 | Down-profile changes in sediment chemistry of LP19 (see separate envelope)                                      |     |
| Figure 9.14 | Plot of variables and samples on Factor 1 versus Factor 2 for LP19 showing stratigraphy and position of sample  | 151 |
| Figure 9.15 | Plot of variables and samples on Factor 2 versus Factor 3 for LP19 showing stratigraphy and position of sample  | 151 |
| Figure 9.16 | Down-profile changes in the factor loadings for LP19  | 151 |
| Figure 9.17 | Lake Pátzcuaro divided into polygons were used for determining sediment accumulation rates                      | 155 |
| Figure 10.1 | The main periods of disturbance inferred from lake sediment records from Central México                         | 163 |
| Figure 10.2 | Relative lake level curves for selected lakes in Central México   |     |

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## CHAPTER ONE: INTRODUCTION

Soil erosion is one of the most severe environmental problems facing México with approximately 75% of the country classified as eroded (Tamayo, 1964). Although much of the Mexican landscape is susceptible to erosion, the problem has been exacerbated by the recent huge increase in population and the need to farm more marginal lands. It is widely assumed, however, that the problem of erosion in México is a legacy of the Spanish. Chevalier (1963), for example, concluded that:

*'Overgrazing of hillslopes, plowing of the lower slopes and deforestation through the heavy cutting of timber for colonial building and for the production of charcoal... resulted in sheet erosion and gulying which quickly turned the highland areas of Central México ... into an agricultural wasteland'.*

while Eckholm (1976) suggested that the:

*'European conquerors competing for empires in the New World took environmentally destructive habits with them. Oversized herds of cattle, sheep and goats bought from the Old World have helped destroy needed woodlands, create deserts and degrade rangeland throughout much of ... México...'*

The assumption that soil erosion and colonialism in México go 'hand-in-hand' has been questioned since in the 1940s (eg. Vaillant, 1944; Cook, 1949), although it has only been in recent years that concrete evidence of Prehispanic environmental degradation in México has been obtained (eg. Deevey et al. 1979, 1983; Metcalfe et al., 1989).

The relationship between environmental change and cultural development in México has been of interest to researchers since the turn of the century (Huntington, 1913, 1914). Attempts to establish links between, climate, palaeoecology and human activity began in the 1940s, and traditionally have been based on palaeolimnological investigations (Deevey, 1944; Sears and Clisby, 1955; Clisby and Sears, 1955; Bradbury, 1971, 1989; Watts and Bradbury, 1982; Ohnegmach and Straka, 1983; Metcalfe, 1985; Gonzales Quintero, 1986; and Leyden, 1987). The main aim of many of

these studies has been to establish the history of climatic change based on pollen and diatom analyses. Attempts to reconstruct the late Holocene record have proved difficult, however, as many lake basins in México have a long history of settlement. Consequently, it is has been almost impossible to distinguish the impact of climate from the impact of humans on the sediment record.

It has only been in the last decade that investigators working on Mexican palaeolimnological records have realised the potential of these lake sediment records for assessing the long term human impact on the environment (Deevey et al, 1979, 1983; Leyden, 1987; Metcalfe et al., 1989, 1991). By adopting a similar approach to palaeolimnologists in Europe (Mackereth, 1966; Pennington, 1978; Oldfield et al, 1978) and North America (Bradbury, 1975; Engstrom et al, 1991), researchers have been able to establish that many areas of México have experience periods of environmental degradation which can be associated with the development of Prehispanic cultures (Deevey et al, 1979, 1983; Leyden, 1987; Metcalfe et al., 1989, 1991).

Many of these investigations have reported periods of increased lake sediment accumulation that have been used to infer accelerated erosion. While these studies have added substantially to our understanding of late Holocene environmental change, and provide additional information which have helped clarify changes in the climate, they are unfortunately of limited value for assessing the extent of past environmental degradation. One of the main reasons for this has been the reliance of these studies on a single core. Liken and Davis (1975) and Edwards and Rowntree (1980), have inferred relative changes in sediment yields from changes in sediment accumulation at a single lake core, and it has been suggested by Lehman (1975) that using such data it is possible to estimate rates of sediment accumulation using theoretical models. The use of a single core for determining sediment accumulation rates and hence rates of erosion within a catchment have been criticised by a number of studies (eg. Bloemendal et al, 1979; Dearing et al, 1981; Davis et al, 1984), who have demonstrated that sediment accumulation proceeds in a complex and shifting manner, and that maximum deposition

occurs at different positions at different times. Moreover, Hakanson (1977) noted that because of density dependent sedimentation the chemical composition of sediments can vary spatially throughout a lake further limiting the representivity of a single core.

The aim of this study is to reconstruct late Holocene environmental change in the Basin of Pátzcuaro, Michoacán, México. This small intermontane basin, has been the subject of a number of previous palaeolimnological investigations (Deevey, 1944; 1957; Hutchinson *et al.*, 1957; Saporito, 1975; Watts and Bradbury, 1982), which together with the study of Street-Perrott *et al.* (1989), on terrestrial sediments, indicates that there is a long history of settlement and human disturbance within this catchment. The questions to be addressed are:

- i) can periods of accelerated erosion, as inferred from the lacustrine and terrestrial record, be associated with Prehispanic cultures within the basin?
- ii) is it possible to determine spatial and temporal variations in sediment accumulation using multiple cores, and using this information determine the source of sediment input into the lake?
- iii) by using a number of different lines of investigation and a variety of complimentary analytical techniques, is it possible to separate the human disturbance record from the climate record?

## CHAPTER TWO: PHYSICAL BACKGROUND TO THE BASIN OF PATZCUARO

### 2.1 LOCATION

The Basin of Pátzcuaro is a small intermontane basin situated in the highlands of the Tarascan Neovolcanic sub-province of Michoacán, México. It is located approximately 250 km west of México City, mid-way between the towns of Morelia and Uruapan (Fig. 2.1). The catchment is one of a series of closed lake basins created by the disruption of the drainage of an ancient tributary of the Río Lerma by volcanic activity in the Pleistocene (De Buen, 1943; Waitz, 1943; Barbour, 1973). This tributary is believed to have drained northwards from Zirahuén, entering Lake Pátzcuaro *via* the valley of Ajuno, and exiting through the valley of Chapultepec. The river then flowed north-eastwards to the Valley of Morelia following the drainage of the Río Grande, and passing through Lake Cuitzeo finally draining into the Río Lerma.

The 1990 census (INEGI, 1990) gave the population of the basin as 111,341 located in four municipios; Pátzcuaro, Quiroga, Tzintzuntzan and Erongarícuaro (Fig. 2.2). Today as in the past the Basin of Pátzcuaro forms the focal point of the indigenous Purépecha (Tarascans), who have lived in this region since Prehispanic times. The area is a major tourist centre attracting a large number of visitors each year. At the festival of the 'Day of the Dead' an estimated 150,000-200,000 people visit the area.

### 2.2 GEOLOGY

A simplified diagram of the geology of the study area is shown in Figure 2.3. The oldest features are large composite volcanoes which probably formed during the Cenozoic period, the most important being *Cerro El Zirate* located in the northern part of the basin. These features have certain characteristics similar to the vulcanism of the north-eastern part of Michoacán, and consist of andesites and dacites rich in olivine, albite, biotite, augite and hypersthene (Villarello, 1909). Their craters have suffered

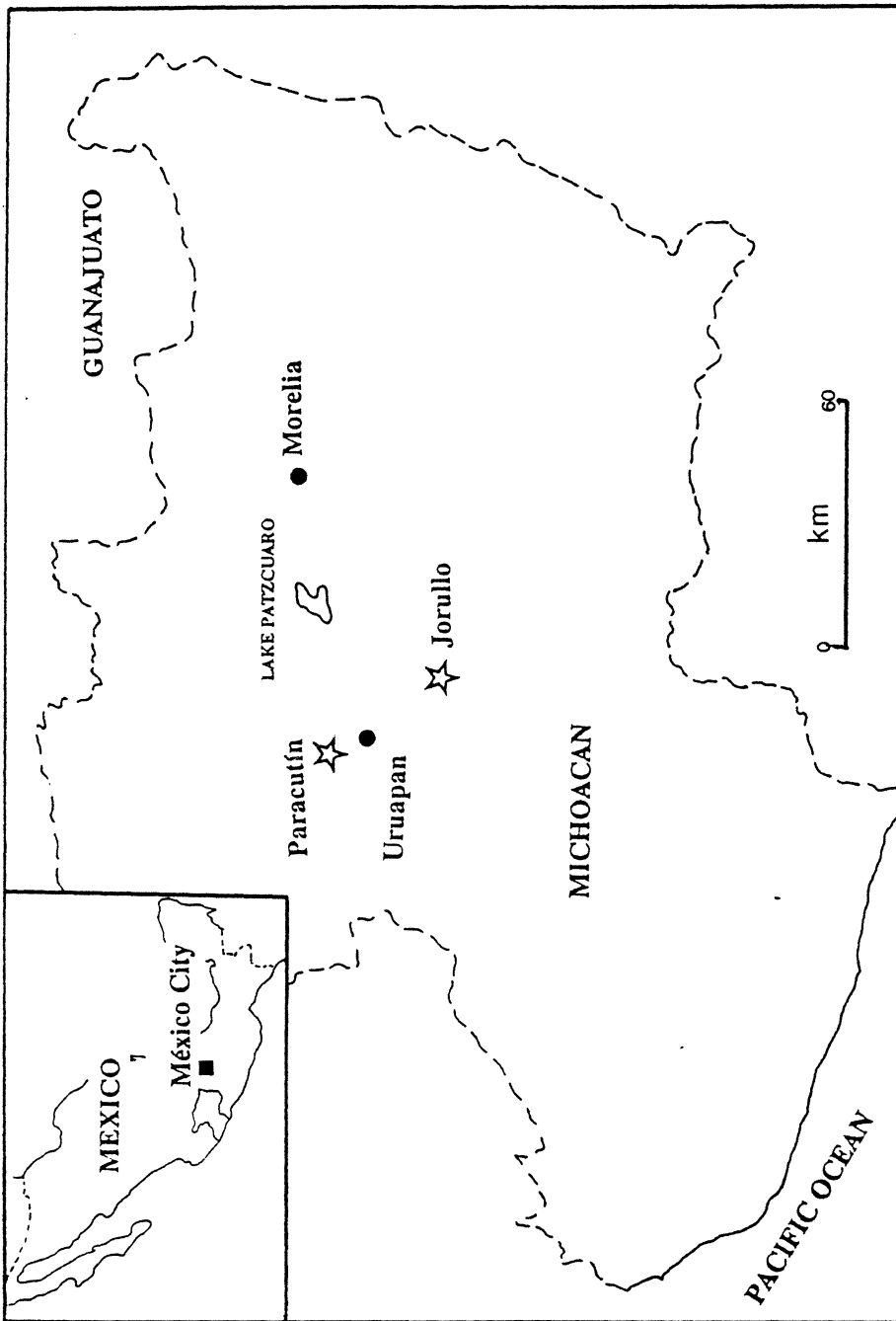


Figure 2.1 Location of the study area.

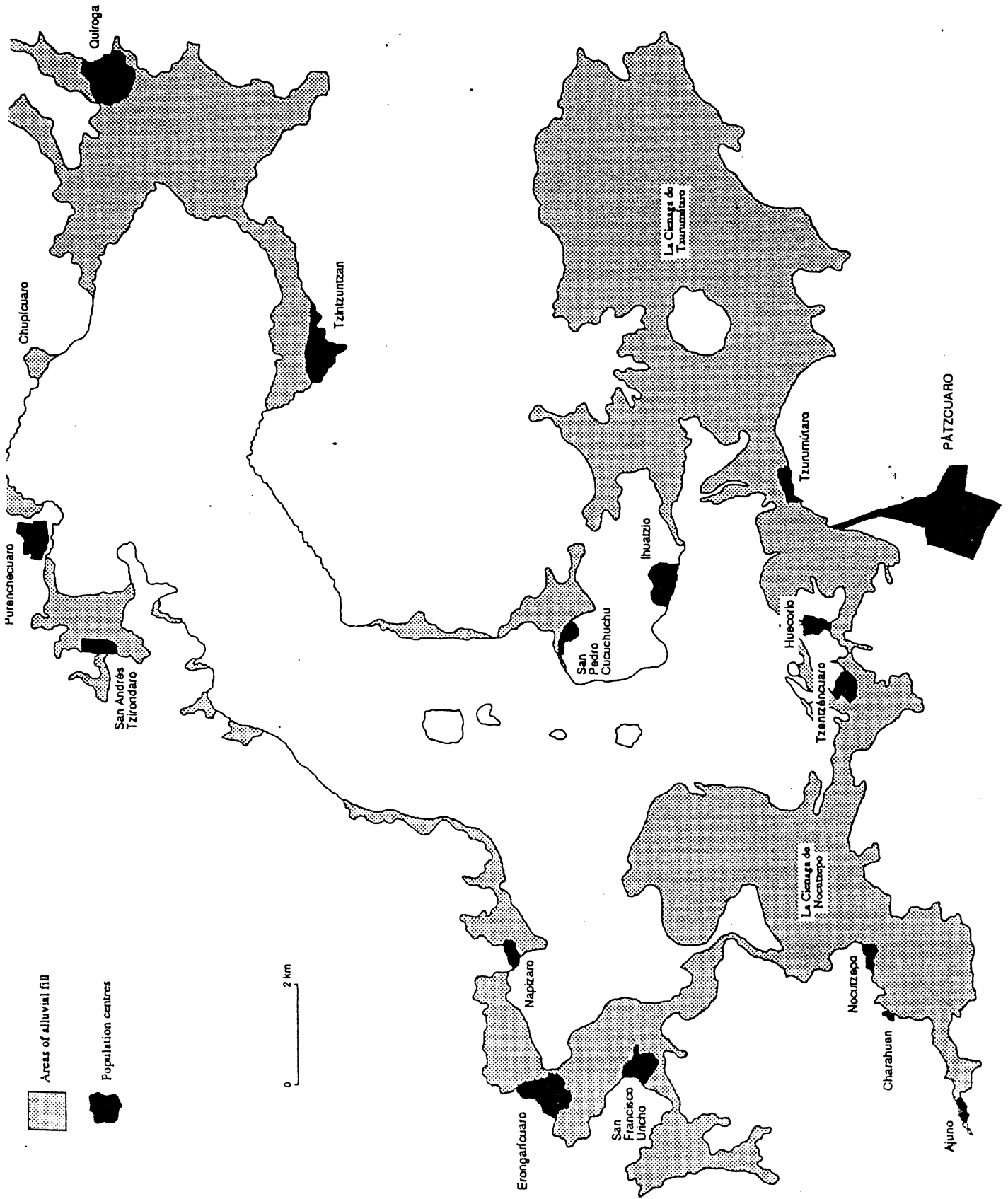


Figure 2.2 The Basin of Pátzcuaro.

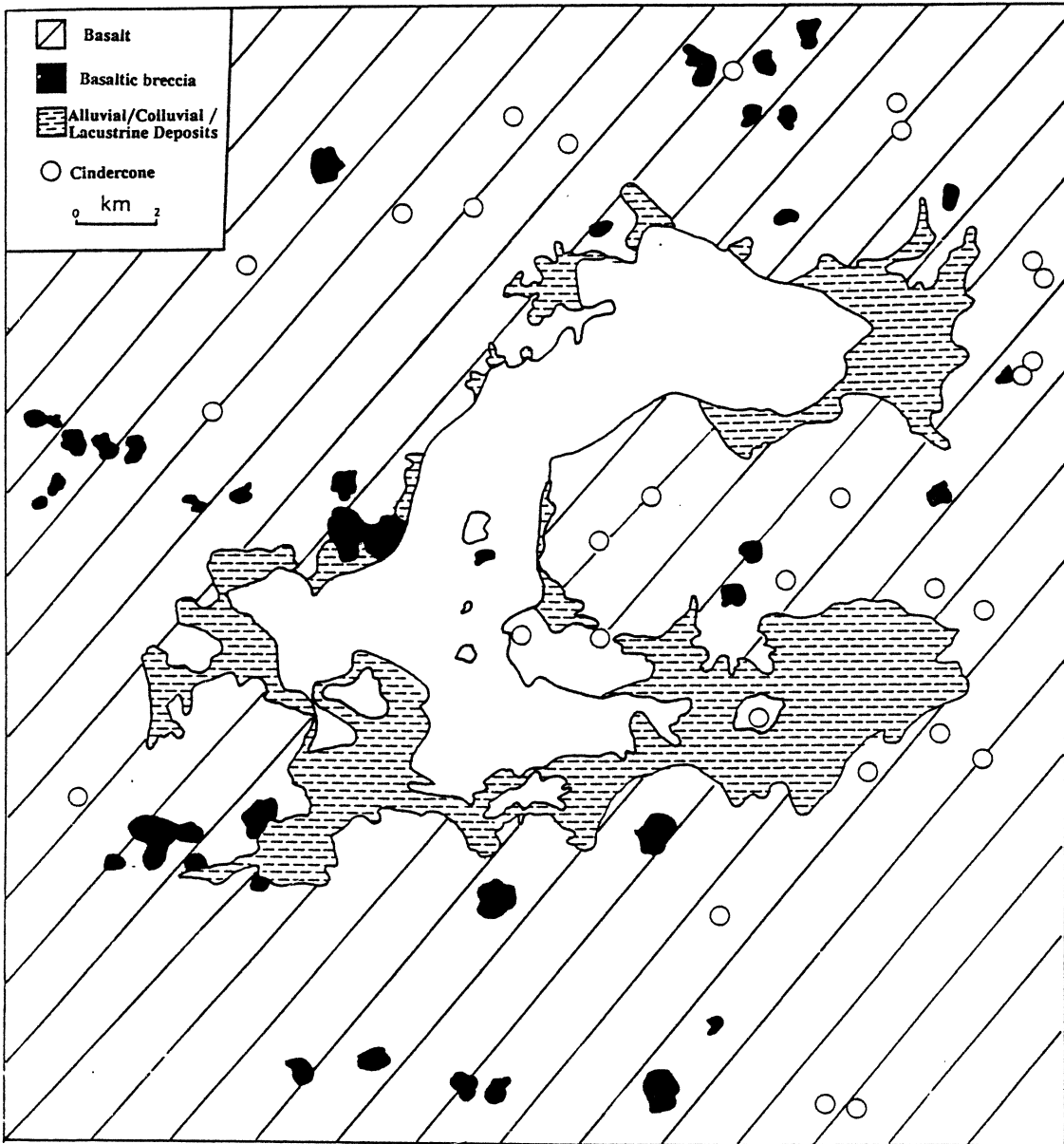


Figure 2.3 Simplified geology map of the study area

intense erosion and are dissected by many deep gullies (barrancas) that often form a radial pattern (Barrera, 1986).

Barrera (1986) reported the presence of 130 volcanic cones within the basin. These are composed of semi-consolidated ash and cinder blocks; in general those of greatest altitude and volume represent the oldest features. They are similar in morphology to Paracutín (Plate 2.1) and have generally been formed in a single period of activity. Their well-preserved form attests to their relative youth. Two types of cone are observed: symmetrical cones with well developed flat floored crater and breached cones with one side generally blown away.

Numerous small lava flows have been recognised within this area. The majority are confined to the southern portion of the drainage basin and are the product of solidification of very fluid degassed lavas (Barrera, 1986). They are locally called *zacapurhu* or *malpaises* ('badlands') as their highly porous character causes water to drain through them rendering such regions useless for agricultural purposes.

### 2.3 MORPHOLOGY OF THE LAKE PATZCUARO BASIN

Lake Pátzcuaro is one of the most important water bodies in Central México. Standing at an elevation of 2,036 m a.s.l. the distinct C-shaped lake has an area of 126.4 km<sup>2</sup> (Chacón Torres, 1989) and drains a catchment of 927 km<sup>2</sup> (Gorenstein and Pollard, 1983, Chacón Torres, 1989). The catchment can be divided into eight major sub-basins which vary in area from 33 to 301 km<sup>2</sup> (Fig. 2.4). The lake has no surficial outlet and is fed by ephemeral streams, rainfall and groundwater seepage.

The lake is surrounded by a number of volcanic cones. To the north and west these form the steep slopes of the mountains of Comanja, Tigre and El Zirate. The last, rising to an elevation of 3,330 m a.s.l. (DETENAL, 1978) is the highest peak in the area. To the south, the catchment is delimited by the mountains of Tingambato and Santa Clara del Cobre while to the east the lake is bordered by the relatively gentle slopes of the Sierras of Prieto and Gachupin.



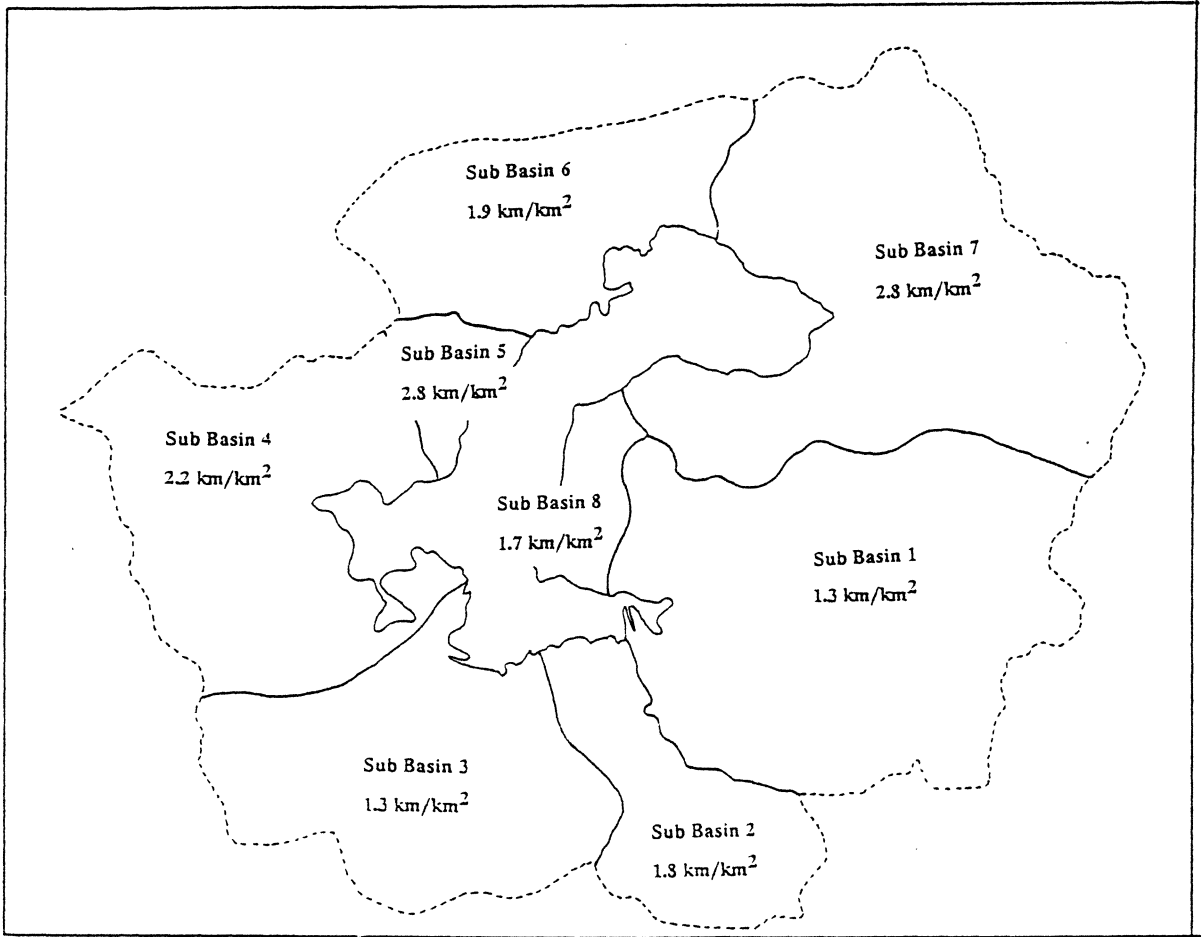


Figure 2.4 Main sub-basins within the catchment showing the drainage density.

Gently sloping alluvial, colluvial and lacustrine deposits, border the lake. These areas are most extensive in the southern part of the basin although large expanses of sediment are also found around Quiroga (Fig. 2.3). The extent of these deposits depends on the level of the lake and even quite small lake level variations can result in a considerable change in their dimensions. In recent years the large drop in the level of the lake (ca. 4 m) has caused quite extensive areas of relatively flat land to be uncovered (Plates 2.2 and 2.3) which have been immediately utilised for agricultural purposes.

## 2.4 CLIMATE

Although the Basin of Pátzcuaro lies in the tropics, its altitude and distance from the sea have modified the climate considerably. The region experiences humid temperate conditions and falls into the Köppen category Cwb. Data from the two weather stations that currently operate within the basin, 'Estacion Pátzcuaro' and 'Estacion Santa Fé de la Laguna' (Fig. 2.2), demonstrate that there are quite significant climatic variations within the basin.

There is little variation in mean monthly temperatures for the Pátzcuaro region (Table 2.1). The mean temperature for May, the warmest month, is  $19.1^{\circ}\text{C}$  and for January, the coldest month,  $12.4^{\circ}\text{C}$ . The mean maximum temperature varies between  $31^{\circ}\text{C}$  in May and  $24.4^{\circ}\text{C}$  in December and the mean minimum temperatures range from  $12.9^{\circ}\text{C}$  in June and  $4^{\circ}\text{C}$  in January. Differences are also noted in the temperatures experienced in the north and south of the area, with slightly higher temperatures recorded in the north (Table 2.2).

Precipitation exhibits a marked seasonal distribution with over 80% of the total annual rainfall falling between May and October as intense, convective rainstorms of short duration. The wettest month is July with an average of 225.5 mm (1970-1986). Between November and April little rain falls, the driest month being April which has an average of 9.6 mm (Table 2.1). There is a considerable difference in the amount of precipitation received annually in the southern and northern part of the basin. The mean



Main Climatic parameters for the Basin of Patzcuaro; 1921-1944 and 1970-1986

| PERIOD                | JAN   | FEB   | MAR   | APR   | MAY   | JUN   | JUL   | AUG   | SEP   | OCT   | NOV   | DEC   | ANNUAL |
|-----------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| <b>TEMPERATURE</b>    |       |       |       |       |       |       |       |       |       |       |       |       |        |
| MEAN (CELSIUS)        | 12.4  | 14.1  | 16.2  | 18.2  | 19.9  | 19.5  | 17.7  | 17.3  | 17.1  | 16.4  | 14.9  | 12.8  | 18.3   |
|                       | 12.8  | 13.7  | 15.8  | 17.7  | 19.1  | 18.8  | 17.6  | 17.6  | 17.5  | 16.6  | 14.9  | 13.5  | 18.3   |
| MEAN MAX (CELSIUS)    | 20.2  | 23.0  | 24.7  | 27.0  | 28.0  | 25.4  | 23.6  | 22.7  | 22.4  | 22.7  | 21.6  | 20.4  | 23.5   |
|                       | 24.6  | 25.8  | 20.1  | 30.2  | 31.0  | 29.2  | 26.3  | 25.4  | 25.4  | 23.6  | 24.8  | 24.4  | 20.7   |
| MEAN MIN (CELSIUS)    | 4.5   | 5.6   | 7.7   | 9.6   | 12.1  | 13.6  | 12.4  | 12.6  | 12.1  | 10.2  | 7.2   | 5.5   | 9.4    |
|                       | 4.0   | 5.0   | 6.4   | 8.7   | 10.7  | 12.9  | 12.4  | 12.2  | 12.0  | 10.1  | 6.3   | 5.8   | 0.8    |
| RAINFALL (mm)         | 14.3  | 12.0  | 9.6   | 4.0   | 35.2  | 176.0 | 236.6 | 236.9 | 190.1 | 76.6  | 29.1  | 19.8  | 1040.8 |
|                       | 13.8  | 6.7   | 5.5   | 9.6   | 38.9  | 144.9 | 224.5 | 198.5 | 164.8 | 63.2  | 16.0  | 14.0  | 900.7  |
| MAX. RAINF. IN 24 HRS | 35.0  | 27.0  | 25.0  | 19.7  | 33.8  | 50.0  | 48.7  | 75.7  | 61.5  | 51.5  | 44.7  | 52.5  | 75.7   |
|                       | 52.0  | 15.7  | 16.5  | 57.7  | 28.0  | 57.0  | 62.5  | 56.0  | 64.0  | 60.1  | 20.3  | 28.0  | 64.0   |
| EVAPORATION (mm)      | 100.6 | 124.4 | 158.7 | 203.1 | 197.9 | 112.5 | 125.1 | 112.6 | 91.7  | 101.7 | 89.5  | 96.5  | 1524.5 |
|                       | 89.8  | 115.6 | 168.7 | 187.3 | 180.9 | 134.9 | 115.5 | 112.1 | 89.2  | 96.3  | 86.6  | 77.6  | 1437.0 |
| WIND SPEED (m/s)      | 2.2   | 3.8   | 3.8   | 2.2   | 2.2   | 0.8   | 2.2   | 2.2   | 2.2   | 2.2   | 2.2   | 2.2   | 2.2    |
|                       | 4.4   | 9.4   | 9.4   | 4.4   | 4.4   | 2.2   | 2.2   | 2.2   | 4.4   | 4.4   | 4.4   | 4.4   | 4.4    |
| DIRECTION (DEGREES)   | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 25.0  | 225.0 | 225.0 | 225.0 | 225.0  |
|                       | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0 | 225.0  |

Source: Chacon Torres, 1989.

Table 2.1

| Average rainfall | Station   | # of years<br>of observation | Average rainfall (mm) |      |      |      |      |       |       |       |       |       |      |      | Annual<br>Year |        |
|------------------|-----------|------------------------------|-----------------------|------|------|------|------|-------|-------|-------|-------|-------|------|------|----------------|--------|
|                  |           |                              | J                     | F    | M    | A    | M    | J     | J     | A     | S     | O     | N    | D    |                |        |
|                  | PATZCUARO | I-15                         | 14.3                  | 14.9 | 17.0 | 18.7 | 20.3 | 19.5  | 18.2  | 18.2  | 18.2  | 18.1  | 17.2 | 15.8 | 14.7           | 17.3°C |
|                  |           | P-16                         | 19.8                  | 9.6  | 6.2  | 10.0 | 65.7 | 179.  | 234.4 | 256.6 | 176.5 | 136.2 | 13.9 | 16.6 | 1124.5 mms.    |        |
|                  | SANTA FE  | T-12                         | 13.1                  | 14.2 | 15.9 | 18.0 | 19.3 | 18.9  | 17.9  | 1.78  | 17.6  | 16.9  | 14.8 | 13.5 | 16.5°C         |        |
|                  |           | P-12                         | 7.2                   | 4.1  | 21.6 | 17.2 | 34.4 | 148.3 | 215.7 | 214.2 | 169.7 | 63.6  | 12.2 | 14.3 | 922.5 mms.     |        |

Source Bassols (1986)

**Table 2.2 Variations in temperature and precipitation between the northern and southern part of the Basin of Pátzcuaro.**

annual rainfall for the period 1968-1980 at 'Estacion Pátzcuaro' was 1124 mm while at 'Estacion Santa Fé de la Laguna', for the period 1965-1978 it was 922 mm. Thus, on average, the northern part of the Basin of Pátzcuaro receives about 13% less rain than the southern portion of the basin.

Although 'Estacion Pátzcuaro' has been collecting meteorological data intermittently since 1886, much of the information has been lost. The most complete set of data obtained to date is that of Chacón Torres (1989) who presented an analysis (of the available information) for the periods 1921-1944 and 1970-1986 (Table 2.1). He found little difference between the mean annual temperatures of these periods, but noted a considerable reduction in the mean annual precipitation. In 1921 and 1944 the mean annual precipitation was 1040 mm compared to 900 mm for the period 1970-1986. A decrease in the amount of precipitation in the warm season, June to September, accounts for most of this variation (Table 2.1).

South-westerly and south-easterly winds predominate in this area with an average of 40.2% of winds from the former and 25.5% for the latter direction. During the winter months, outbreaks of cold polar air '*nortes*' bring lower temperatures and increased wind speeds. Maximum average wind speeds are  $6.7 \text{ ms}^{-1}$ , mostly blowing from the southwest and southeast (Chacón Torres, 1989), with high winds occurring more frequently during the winter months.

The Basin of Pátzcuaro experiences a moisture deficit over the year, evaporation being considerably greater than precipitation. Evaporation rates are lowest in the winter months, but are still greater than precipitation, and reach their highest in April and May, during the warmest months. Only during the period June-September are precipitation amounts in excess of evaporation (Table 2.1).

## 2.5 SOILS

Soils in the Basin of Pátzcuaro fall into a number of distinct types. Their formation is influenced by a number of factors, the most important being recent volcanic

activity, climate, proximity to the lake, vegetation cover and human interference. The main physical and chemical characteristics of the most important soil types in the basin are shown in Table 2.3.

Andosols, covering over 50% of the basin, represent the most important soil type in this region. In general, these are confined to the upper mountain slopes in particular those that border the eastern shore of the lake (Fig. 2.5). These soils have developed on recent volcanic deposits and retain certain characteristics of their parent material. Because the andosols are moisture-retentive it is possible to plant crops two months before the onset of the rains and consequently these soils are referred to as '*tierra de humedad*' (West, 1948). As these are relatively young soils, they contain large quantities of weatherable material and on the whole are extremely fertile. However, once the natural vegetation is removed they tend to be very susceptible to erosion (Toledo and Barrera, 1984).

The soils in the western portion of the basin are dominated by luvisols. These differ from andosols in that they exhibit a much greater degree of leaching. Luvisols dominate the more gently-sloping areas of the southern and eastern parts of the basin, and in general have developed on surfaces that have remained relatively undisturbed by erosion. Luvisols are frequently found in association with other soil types, the relation depending on microclimate and topography.

Acrisols account for approximately 9 % of the soils in the study area (CRAC, 1981) and are confined to the southern and eastern parts of the basin where the slopes are between 15-25° (Fig. 2.5). Acrisols have developed on old parent material under conditions much more humid than are currently experienced in this region (Barrera, 1986). They are particularly important in the vicinity of Tzintzuntzan where the soils covering the mountains of *Tariaqueri* and *Yahuarato* consist entirely of acrisols.

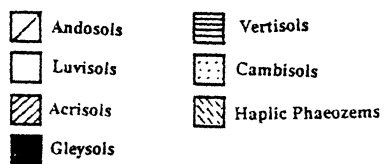
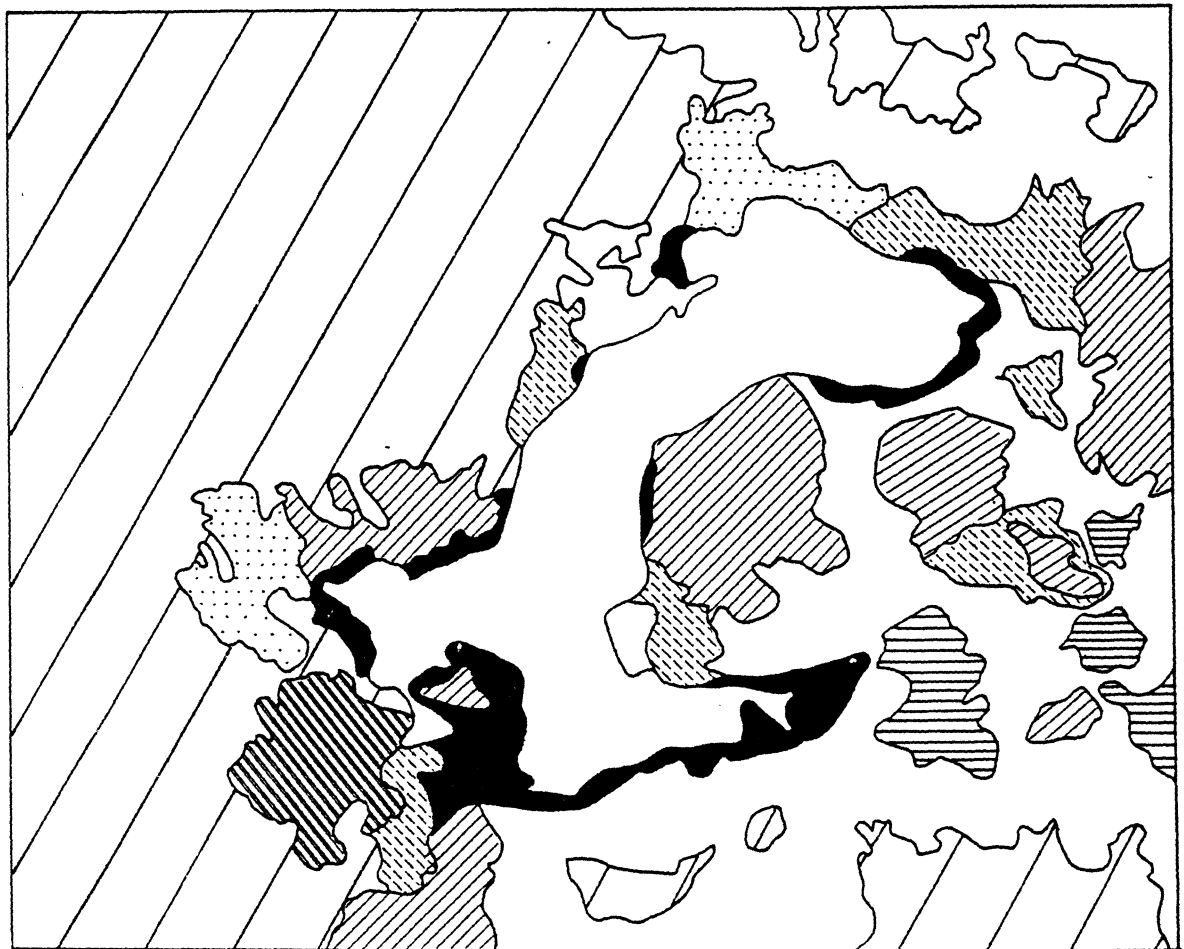
A variety of soil types are found in the areas surrounding the lake itself. In order of importance these are gleysols, cambisols, vertisols and phaeozems representing approximately 3.22%, 2.04%, 1.85% and 1.75% of the soils in the drainage basin

Physical and Chemical Parameters of the Major Soil types in the Basin of Patzcuaro

| SOIL TYPE     | STRUCTURE | TEXTURE | COLOUR    | PROFILE DEPTH (CM) | % SAND | % SILT | % CLAY | pH  | Ca-PPM | Mg PPM | K PPM | P PPM |
|---------------|-----------|---------|-----------|--------------------|--------|--------|--------|-----|--------|--------|-------|-------|
| Humic Andosol | A         | Blocky  | 10YR4/4   | 0-27               | 6      | 22     | 72     | 6.2 | 4.1    | 1.1    | 0.4   | 6.9   |
|               | B         | Blocky  | 7.5YR3/4  | 27-69              | 2      | 48     | 50     | 6.4 | 3.8    | 0.6    | 0.1   | 4.1   |
| Acrisol       | A         | Blocky  | 5YR3/3    | 0-10               | 22     | 38     | 40     | 6.0 | 3.1    | 2.9    | 0.8   | 6.1   |
|               | B         | Massive | 5YR3/5    | 10-45              | 60     | 18     | 20     | 6.1 | 2.1    | 0.3    | 0.1   | 5.8   |
| Luvisols      | A         | Blocky  | 5YR3/3    | 0.23               | 30     | 34     | 36     | 6.3 | 6.6    | 3.0    | 1.0   | 6.4   |
|               | B         | Blocky  | 5YR3/3    | 25-58              | 38     | 34     | 28     | 6.3 | 6.6    | 2.9    | 0.4   | 7.4   |
| Cambisol      | A         | Blocky  | 7.5YR3/2  | 0.12               | 20     | 40     | 40     | 6.5 | 12.5   | 2.6    | 0.8   | 4.9   |
|               | B         | Blocky  | 7.5YR3/4  | 12-45              | 22     | 34     | 44     | 6.8 | 10.5   | 5.6    | 0.5   | 4.3   |
| Vertisols     | A         | Blocky  | 7.5YR3/1' | 0-30               | 48     | 26     | 26     | 6.4 | 10.7   | 4.7    | 0.5   | 82.2* |
|               | B         | N/A     | 10YR3/1   | 30-60              | 48     | 22     | 30     | 6.9 | 11.9   | 7.2    | 0.5   | 35.2* |
| Phaeozem      | A         | Blocky  | 7.5YR2/2  | 0.26               | 32     | 38     | 30     | 6.0 | 8.9    | 3.9    | 1.0   | 18.9  |
|               | B         | Blocky  | 5YR2/2    | 26-82              | 38     | 30     | 32     | 6.5 | 8.9    | 2.7    | 0.1   | 7.9   |
| Gleysols      | NO DATA   |         | NO DATA   |                    |        |        |        |     |        |        |       |       |

\* Agricultural land. High P values possibly reflect use of fertilizers  
Source - Bassols, 1986.

Table 2.3



0 km 2

Figure 2.5 The distribution of the major soil types in the Basin of Pátzcuaro.

respectively (CRAC, 1981).

In the low-lying area to the west of Tzurumutaro (Fig. 2.2) referred to locally as '*La Ciénaga de Chapultepec*', the soils are dominated by vertisols. These soils have developed on almost flat surfaces and in general have a soil profile less than 1 m in depth. Small areas of soils designated cambisols are located in the western part of the basin in the vicinity of Erongarícuaro.

Bordering much of the lake, in particular the southern part, are gleysols, which remain inundated for long periods of the year: mollic gleysols predominate. Gleysols have developed on recently deposited colluvial sediments which have been washed down from the upper slopes of the basin (Barrera, 1986).

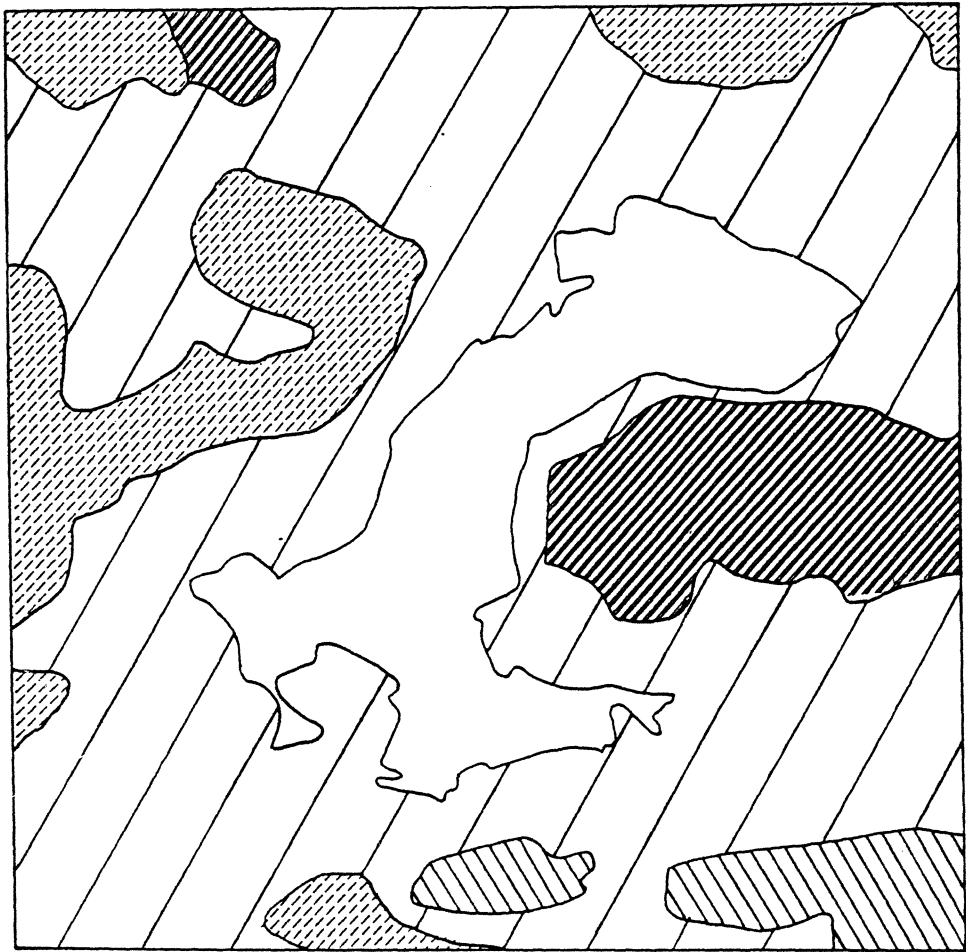
Haplic phaeozems have been mapped in a number of restricted locations in the areas around Ihuatzio, San Pedro Cucuchuchu and Quiroga (Fig. 2.5). It is noticeable that those areas where phaeozems are found correspond to those parts of the basin that are most severely eroded. It is possible that these soils are not correctly classified and in fact represent soils that have developed on freshly exposed bedrock.

## 2.6 VEGETATION

The long history of human disturbance has produced a mosaic of vegetation communities in the Basin of Pátzcuaro. A simplified diagram of the main vegetation assemblages is shown in Figure 2.6. Although it is difficult to determine what the "natural vegetation" was, Watts and Bradbury (1982) believe that a pine/oak assemblage dominated the lower slopes of the basin with stands of fir above 2,500 m a.s.l. Barrera (1986) recognised a number of present-day vegetation types which roughly corresponded to different elevations within the basin.

In the high altitude areas (2,900 to 3,300 m a.s.l.) the vegetation is dominated by fir with some pine. Only the highest peaks in the region fall into this category. The most important species found in this association are *Abies religiosa* and *Pinus pseudostrobus*.

Pine is the most important species represented in the Basin of Pátzcuaro. Pine-



0 km 2

Figure 2.6 Simplified diagram of the main vegetation assemblages in the Basin of Pátzcuaro.

dominated forests are still found situated between 2,100 and 3,000 m a.s.l. Various species have been recognised, the most common being *Pinus teocote*, *P. lawsonii*, *P. leyophylla*, *P. michoacana*, *P. montezuma* and *P. pseudostrobus* (Barrera, 1986).

Oak communities are characteristic of the mountain areas of México and together with pine constitute a large percentage of the vegetation cover in areas with sub-humid temperate climates (Rzedowski, 1978). Oak and pine share certain ecological characteristics and are frequently found in association with one another. In the Basin of Pátzcuaro pine/oak assemblages are found between 2,100 and 2,800 m a.s.l.; oak assemblages are dominated by *Quercus rugosa*, *Q. ostusta*, *Q. castanea*, *Q. candicaris*, and *Q. laurina*.

Barrera (1986) reported that two types of *matorral* are characteristic of this region: *Matorral de Baccharis* and *Matorral Xerófilo*. *Matorral de Baccharis* is believed to recolonize areas of pine/oak forest which have been overgrazed and are subject to frequent burning (Rzedowski and McVaugh, 1966). In the Basin of Pátzcuaro this vegetation type tends to be found between 2,500 and 3,000 m a.s.l., and develops on nearly all the soil types found in the area, especially andosols, luvisols and acrisols (Barrera, 1986); the principal components are *Baccharis concerta*, *B. ramulosa*, *P. leyophylla*, *P. lasonii*, *Mimosa bucifera* and *Yuca filifera*.

*Matorral Xerófilo* is found on the lower slopes of the basin between 2,037 and 2,300 m a.s.l. The main species of this vegetation assemblage are *Euphorbia calyculata*, *Opuntia* spp. and *Verbesina* spp. These species are frequently found in areas that are severely degraded and are considered to represent a sub-climax vegetation that is the result of human disturbance (Caballero et al., 1981)

## 2.7 PRESENT DAY LAND USE

Apart from the steepest slopes, the majority of the land in the basin is used for agriculture. The more gently-sloping areas which border the lake are the most intensively

cultivated. A number of large irrigation schemes are currently in operation, the most important in the areas of La Ciénaga de Chapultepec, Erongarícuaro and Quiroga are administered by the Secretaria de Agricultura y Recursos Hidraulicos (SARH). Elsewhere, local farmers have cut channels from the lake to bring water to irrigate their fields. Although traditional farming techniques continue to flourish, there has been an increase in the amount of machinery used in agriculture. This has resulted in a significant change in the method and nature of agriculture within the basin in recent years (CREFAL, 1979).

Settlement within the basin is concentrated on the lower slope areas. The main population centres are located at Pátzcuaro and Quiroga. In recent years the rapid increase in the population has resulted in increased urbanization in the area. Pátzcuaro which was built 3 km from the lake now stretches down to the lake shore.

## 2.8 HYDROLOGY

The slopes surrounding Lake Pátzcuaro are incised by a dense network of gullies and arroyos (Fig. 2.7). Except in the most intense rain events many of these remain dry throughout the year. The most important are the Arroyos San Gregorio and Chapultepec which flow from the springs of La Alberca and Chapultepec, respectively, and discharge into the southern part of the lake. As these arroyos are fed by springs they tend to be perennial. In recent years, however, a considerable proportion of their discharge has been used for irrigation, resulting in a significant reduction in flow (Barrera, 1986). The Arroyo Santa Fé which enters the lake between the communities of Santa Fé and Quiroga (Fig. 2.2) is also an important source of inflow to the lake. However, like Chapultepec and San Gregorio, much of its discharge is now diverted to irrigate farm land. Two other arroyos of importance are the Guani and San Miguel which flow through the City of Pátzcuaro and Erongarícuaro respectively. Water from these streams is utilized by the towns and is finally discharged into the lake as sewage.

As mentioned above, the drainage density in the lake basin varies considerably

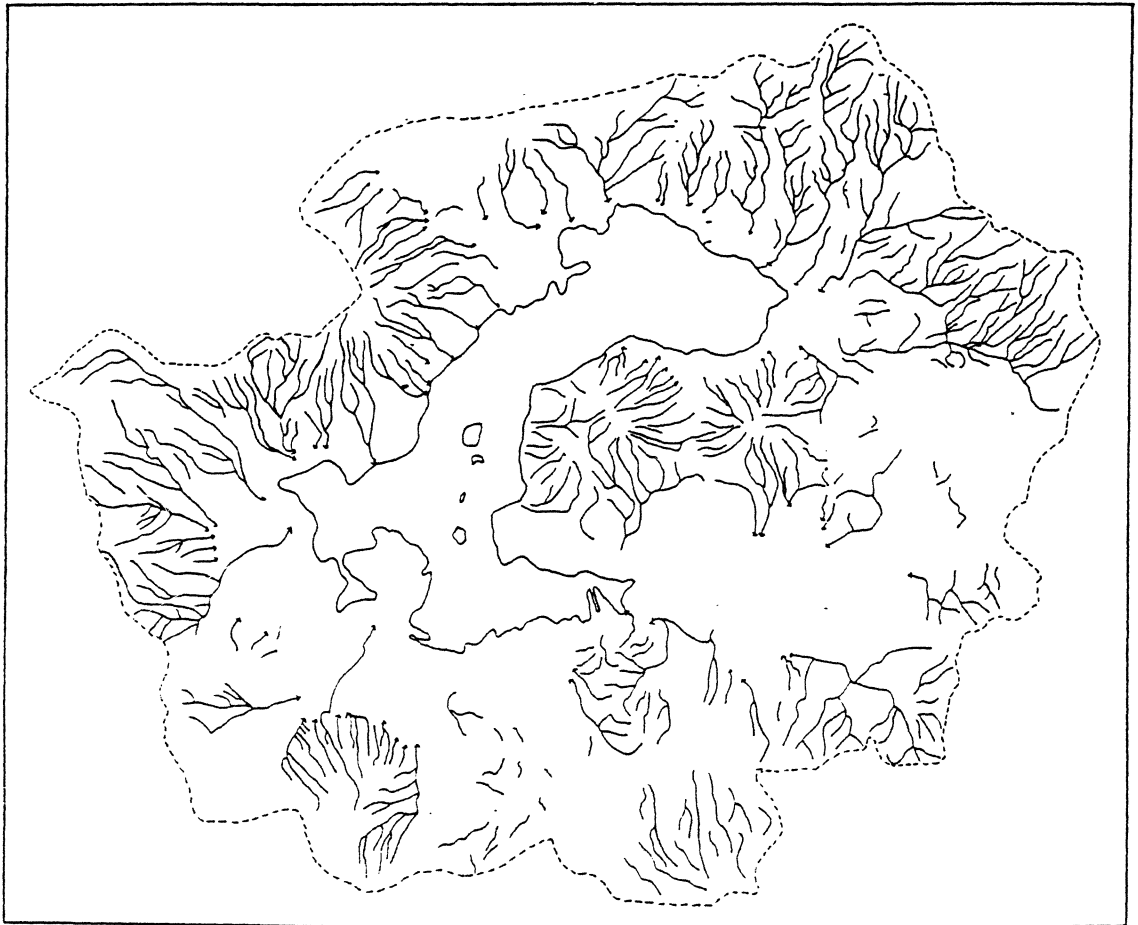


Figure 2.7 The drainage network in the Basin of Pátzcuaro.

in the northern part of the basin (Fig. 2.4) where it ranges between 1.9 and 2.8 km km<sup>-2</sup> compared to between 1.3 to 2.2 km km<sup>-2</sup> in the southern part. With few exceptions these streams are ephemeral. The form of the drainage network also differs, being more dendritic in the north of the basin while in the south the gullies form smaller, unbranching and more intermittent networks. These variations probably reflect a number of factors, the most important being lithology and geology. In the northern part of the basin where the mountain ranges are steepest and the geology is dominated by older andesitic volcanics, little runoff is able to percolate into the soils; consequently there is a greater possibility of erosion and eventual channel development. Furthermore, the catchment area to the north of the lake is much greater than to the south, adding to the amount of runoff generated in each sub-catchment.

In the southern part of the basin large areas of lava flows are found, and as discussed above these are locally referred to as *zacapuhru* or 'badlands' because their extremely porous nature has made them unusable for agricultural purposes. Due to this, surface channels have not developed and any precipitation that falls on these areas percolates through and eventually reaches the lake as through-flow.

## 2.9 MORPHOMETRY AND BATHYMETRY OF THE LAKE

It was not until 1980 that the first detailed bathymetric map of Lake Pátzcuaro was produced (Tellez and Motte, 1980). Since then three separate investigations have produced new versions (SARH, unpubl.; PESCA, unpubl.; Chacón Torres, 1989). Of these, only that of Chacón Torres (1989) makes any attempt to analyse the morphometry of the lake; the following description is taken from his study.

Lake Pátzcuaro covers an area of 126.4 km<sup>2</sup> and has a perimeter of 114 km. The maximum length of the lake is 19.8 km and lies along a SSW-NNE trend following the direction of the main axis. The mean width is 6.4 km with a maximum of 10.9 km in the southern basin.

The distribution of shoreline gradients reflects the nature of the slopes

surrounding the lake (Fig. 2.8). In the southern part of the basin where the lake is bordered by gently-sloping deposits the shoreline slope is generally less than 2%. Slightly steeper slope angles, between 2 and 5%, are found on the western shore and in the area around Tzintzuntzan and Quiroga, while the slope angle of the northern shore tends to be much steeper, falling between 5 and 25%.

The shallowest areas are found in the southern part of the lake where depths rarely exceed 3-4 m (Fig. 2.9). Depths of water in the "neck" of the lake vary between 6 and 10 m while the greatest depth is observed in the northern basin which has a maximum depth of 12.2 m. The mean depth of the lake is 4.5 m.

## 2.10 THE WATER BUDGET

The water budget for any given lake depends on a number of factors that determine the inputs and outputs from the lake. Pátzcuaro, being a closed lake with no major inputs, will be sensitive to changes in such parameters as precipitation, evapotranspiration, runoff and groundwater seepage. To enable the water budget to be calculated, information on all these parameters is required. Unfortunately, such data from the Basin of Pátzcuaro are limited although Chacón Torres (1989) has attempted to reconstruct a simple water balance for the lake.

Annually, Lake Pátzcuaro receives 123.3 million  $m^3$  of water through direct precipitation inputs, while 186.2 million  $m^3$  is lost to evaporation. Thus, assuming that there are no other losses, 62.9 million  $m^3$  is transferred to the lake from the catchment annually. This amounts to 8% of the total input of precipitation into the watershed. Using these data Chacón Torres has shown that there is a very strong positive correlation ( $r=0.93$ ) between the observed and expected lake levels over the period 1970-1986 (Fig 2.10), and certainly annual fluctuations in the level of the lake closely reflect the wet and dry seasons. In view of this, it would appear that the actual amount of rainfall which falls directly into the lake is one of the most important factors influencing its level. As the lake appears to respond very quickly to changes in these parameters it is possible to classify

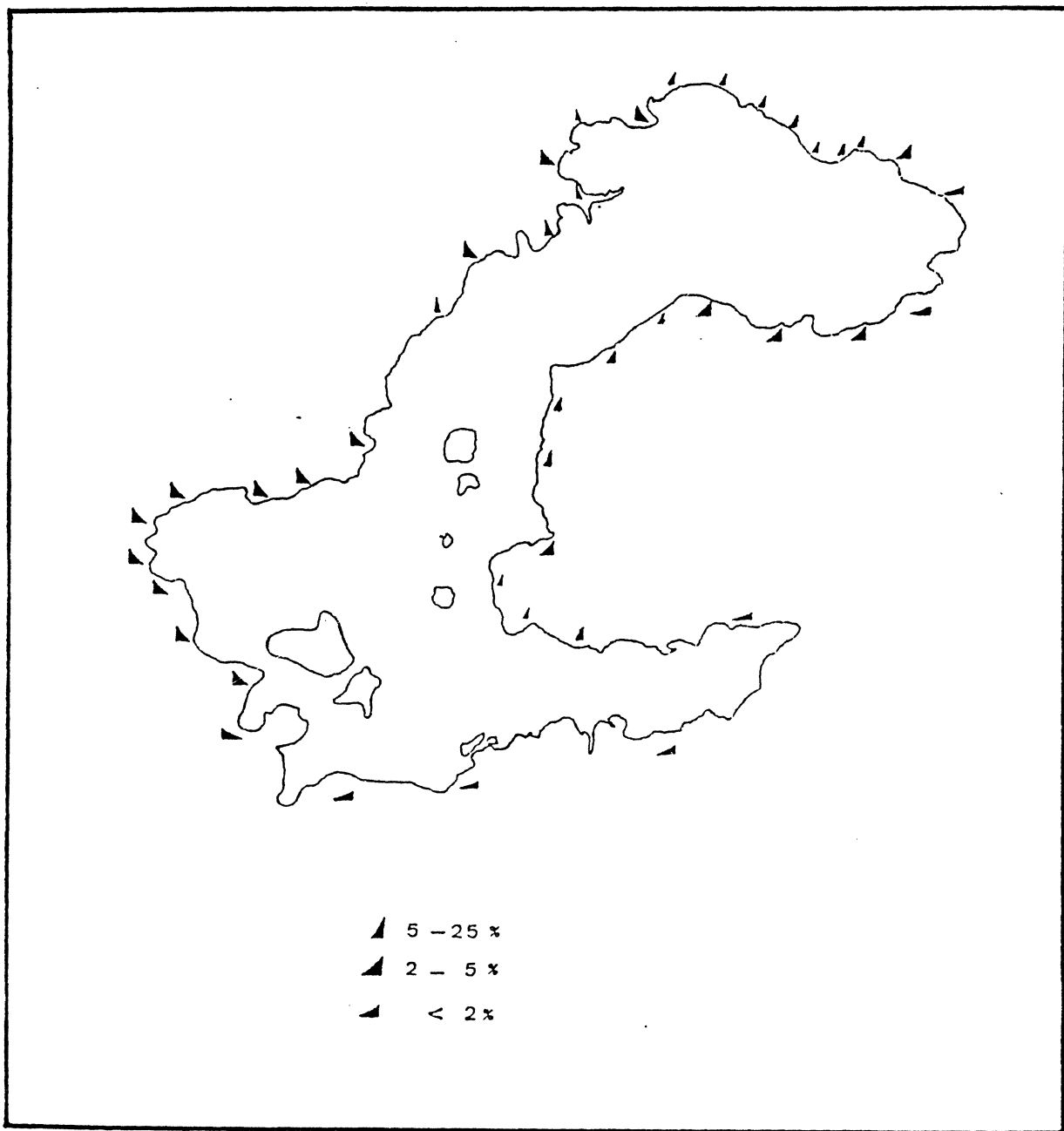


Figure 2.8 Variations in the shoreline gradients of Lake Pátzcuaro.



Figure 2.9 Bathymetric map of Lake Pátzcuaro.

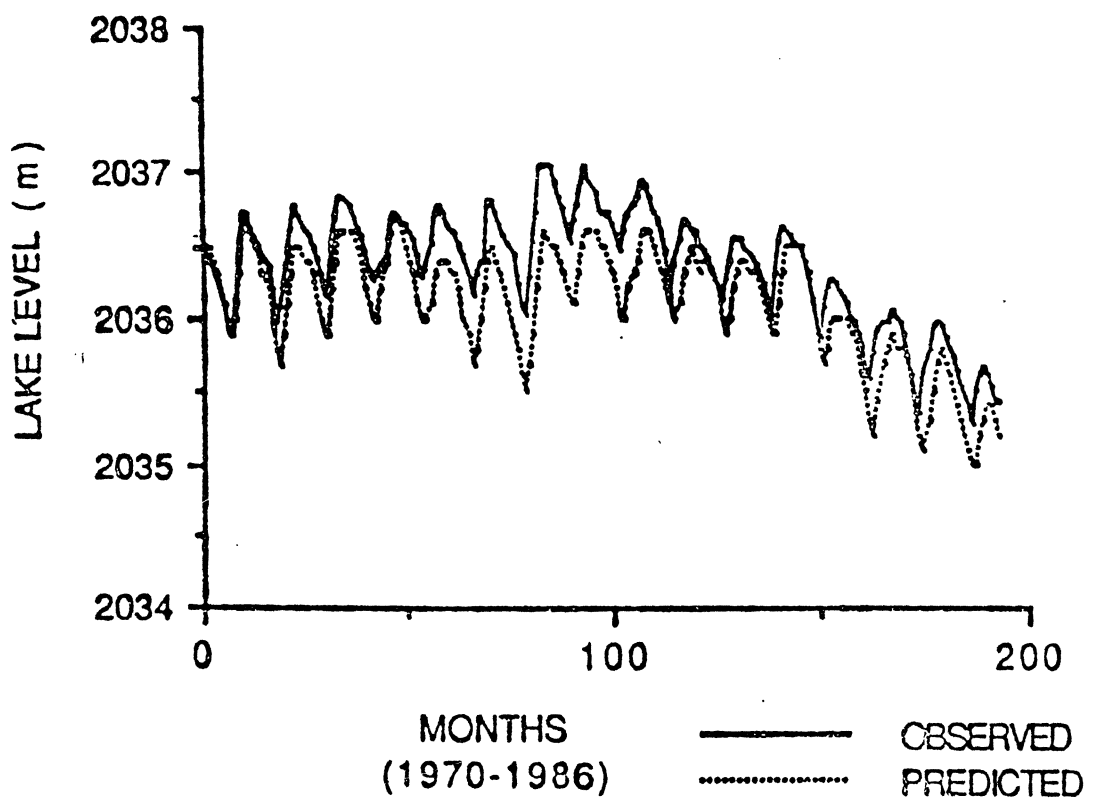


Figure 2.10 Observed and expected lake level variations for Lake Pátzcuaro, 1970-1986.

it as an amplifier lake as outlined by Street-Perrott and Harrison (1985).

## 2.11 MODERN LIMNOLOGY

A detailed analysis of the water quality of Lake Pátzcuaro has recently been completed by Chacón Torres (1989), based on data collected over a six-month period in 1986-1987. Chacón Torres (1989) noted that variations in the surface temperature of the lake varied between  $14.5^{\circ}\text{C}$  in January to approximately  $22^{\circ}\text{C}$  in June and July. The temperature of the bottom waters being about  $2^{\circ}\text{C}$  less than the upper waters. These results confirm those of earlier investigations by De Buen (1941) and Tellez and Motte (1980). De Buen (1944) classified Lake Pátzcuaro as a third order tropical lake as the surface temperature is never below  $4^{\circ}\text{C}$ , and the temperature of the bottom waters varies little from the recorded at the surface. The lake thus lacks thermal stratification and following Lewis' (1974) classification of lakes based on mixing, Lake Pátzcuaro can be described as a continuous warm polymictic type.

Observations on the surface currents have been made by Chacón Torres (1989). In a series of tests run over a three-month period between 1986-1987, he found that the surface current predominantly follows the direction of the wind, which for most of the year blows from the south west (Fig. 2.11).

Levels of dissolved oxygen recorded by Chacón Torres (1989) were similar to those reported by Yamashita (1939), De Buen (1941) and Tellez and Motte (1980). He concluded that the lake was saturated in respect to oxygen and no major horizontal or vertical differences in oxygen levels were detected.

Using secchi disks, Chacón Torres (1989) carried out readings in all parts of the lake to determine the degree of light penetration and recorded levels between 0.33 m and 0.48 m with a mean of 0.4 m. This is considerable less than the average secchi values of 5.75 m reported for Lake Zirahuén, one of the deeper lakes in the Central Mexican plateau, located to the south west of Pátzcuaro (Chacón Torres, 1989). Lake Pátzcuaro was found to be very turbid with maximum turbidity readings found in the

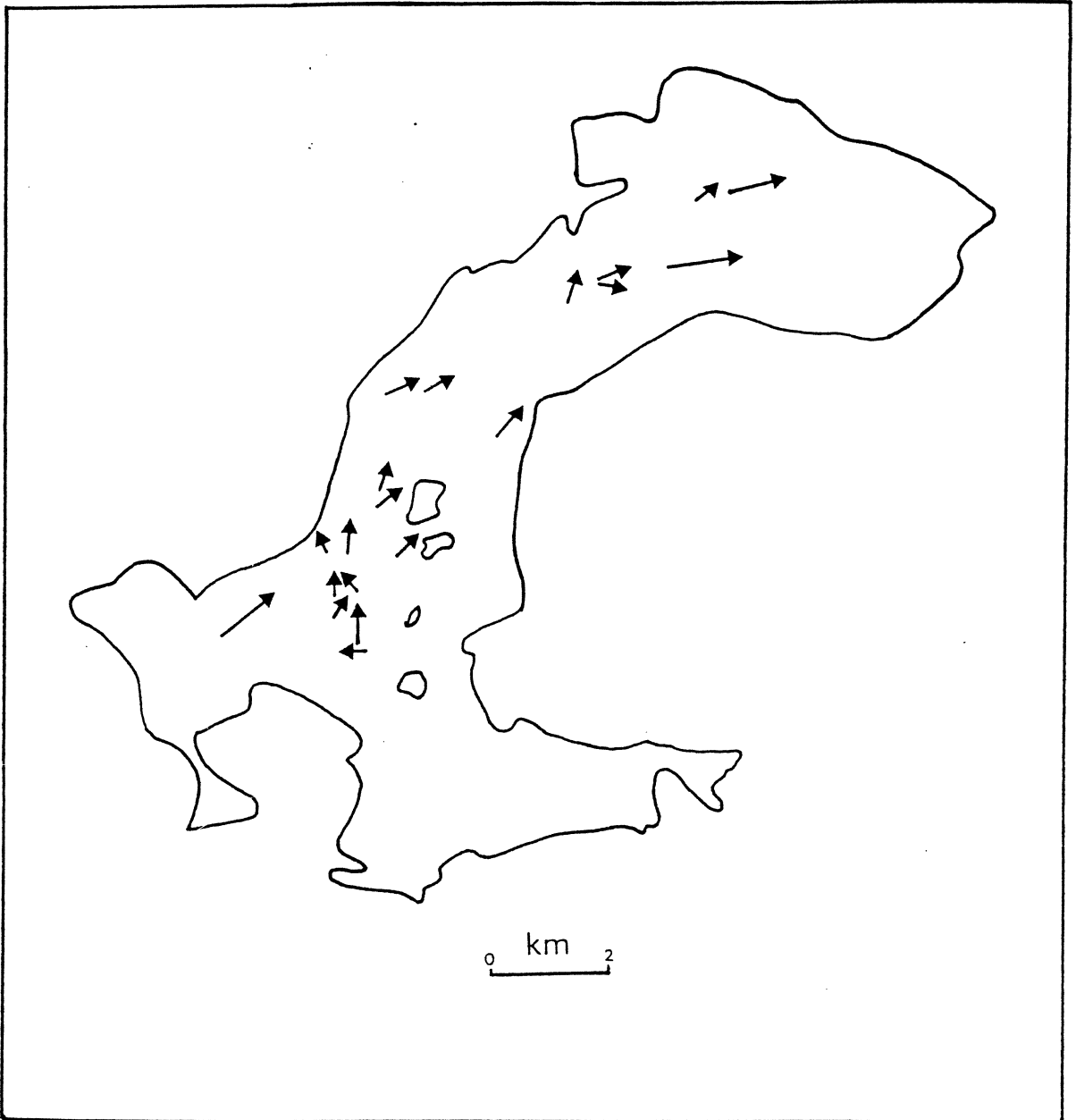


Figure 2.11 Main water currents of Lake Pátzcuaro.

northern part of the lake.

A comparison with previous investigations of light penetration in the lake carried out since 1938 clearly indicate that Lake Pátzcuaro has suffered a reduction in the transparency (Table 2.4). This has been most notable in recent years for which the majority of data are available. While this trend may reflect an increase in the input of sediment into the lake, it may also be a result of lower water levels and the effect of wind keeping sediment in suspension for longer periods of time or re-suspending sediment from the lake bottom.

Based on the water chemistry of the lake, Chacón Torres (1989) concluded that the lake is of Na-HCO<sub>3</sub>-CO<sub>3</sub> type which accords with the results obtained by the Tropical Palaeoenvironments Research Group (TPRG) in 1982 and 1985 (Fig. 2.12). An average value of electrical conductivity of 820  $\mu\text{s}/\text{cm}^{-1}$  was observed while the water was always alkaline with an average pH of 9.7.

The results from Chacón Torres water chemistry analysis have been re-analysed by Nick Barber (University of Oxford) using PCWATEQ (Truesdell and Jones, 1974) to determine what elements the lake water are saturated in. The results from this indicate that Lake Pátzcuaro is saturated in respect to haematite, magnetite, maghemite, geotherite, dolomite, calcite and aragonite, and undersaturated in respect to siderite, halite, and tronanite. Phosphorus, chlorophyll-a and suspended solids (Fig. 2.13) clearly showed horizontal variations across the lake, levels being low in the south and increasing to their highest levels in the northern basin. Mean total phosphorus concentrations for the lake over the period of study were high, 64.4  $\mu\text{g l}^{-1}$ . Goldman and Horne (1983) concluded that total phosphorus levels of this order are a clear manifestation of high inputs from erosion and/or municipal sewage.

Based on the results from his investigation, Chacón Torres (1989) concluded that the trophic status of the lake ranged from mesotrophic in the southern to eutrophic and hypereutrophic in the northern part of the lake (fig. 2.14). Thus the lake is considered to have high levels of fertilization and biological productivity.