Digital Analysis of Selected Glaciers of Afghanistan and Pakistan

Mohammad Saqib Khan
University of Nebraska at Omaha

Follow this and additional works at: https://digitalcommons.unomaha.edu/studentwork

Recommended Citation
https://digitalcommons.unomaha.edu/studentwork/2041

This Thesis is brought to you for free and open access by
DigitalCommons@UNO. It has been accepted for inclusion in Student
Work by an authorized administrator of DigitalCommons@UNO. For
more information, please contact unodigitalcommons@unomaha.edu.
DIGITAL ANALYSIS OF SELECTED GLACIERS OF AFGHANISTAN AND PAKISTAN

A Thesis
Presented to the
Department of Geography/Geology
and the
Faculty of the Graduate College
University of Nebraska

In Partial Fulfillment
of the Requirements for the Degree

Master of Arts

University of Nebraska at Omaha

By

Mohammad Saqib Khan
December, 1989
THESIS ACCEPTANCE

Accepted for the faculty of the Graduate College, University of Nebraska, in partial fulfillment of the requirements for the degree of Master of Arts, University of Nebraska at Omaha

Committee

<table>
<thead>
<tr>
<th>Name</th>
<th>Department</th>
</tr>
</thead>
<tbody>
<tr>
<td>John F. Shroder, Jr.</td>
<td>John F. Shroder, Jr. Ph. D</td>
</tr>
<tr>
<td>Michael P. Peterson, Ph. D</td>
<td></td>
</tr>
<tr>
<td>Charles R. Gildersleeve, Ph.D</td>
<td></td>
</tr>
<tr>
<td>Ramond A. Güenther, Ph. D</td>
<td></td>
</tr>
</tbody>
</table>

John F. Shroder, Jr.
CHAIRMAN

29 November, 1989
Date:


**Abstract**

**CHAPTER ONE:**
**Introduction**

Past history and previous work

Study area

Afghanistan, the land and geomorphic zones.

Geomorphology of the area

Climatic condition of Afghanistan during 1970-76 period

Data Sources and ground truth

Purpose of this study

**CHAPTER TWO:**
**Methodology**

Multispectral Classification of the Images

**CHAPTER THREE:**
**Analysis and Results**

**WAKHAN GLACIERS**

Unsupervised and Supervised Classification for 1972 Wakhan Image.

Cluster Classification

Parallelepiped Classifier

Maximum Likelihood Classifier

Unsupervised and Supervised Classification for 1976 Wakhan Image

Cluster Classification

Parallelepiped Classifier

Maximum Likelihood Classifier

Difference Image
Principal Component Analysis 38
Classification Comparison 38

SAKHI VALLEY GLACIERS 41
Unsupervised and Supervised Classification for 1972 Sakhi Image 41
Cluster Classifier 41
Minimum Distance to Means (MIND) Classifier 42
Maximum Likelihood Classifier 44
Unsupervised and Supervised Classification for 1976 Sakhi Image 44
Cluster Classifier 44
Minimum Distance to Means Classifier 46
Maximum Likelihood Classifier 46
Difference Image 46
Principal Component Analysis 50
Classification Comparison 50

KESHNIKHAN AND TIRICH MIR GLACIERS 55
Unsupervised (Cluster) Classification 55
Supervised Classification 58
Minimum Distance to Means Classifier 58
Maximum Likelihood Classifier 58

MIRSAMIR GLACIER 62
Unsupervised (Cluster) Classification 62
Supervised Classification 63
Maximum Likelihood Classifier 63
Minimum Distance to Means Classifier 65
Classification Comparison 65

CLASSIFICATION ACCURACY 65

SUMMARY 69

CHAPTER FOUR:
CONCLUSION 70

REFERENCES CITED 73
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table #</th>
<th>Description</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Precipitation data during 1972</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>Precipitation data during 1976</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>LANDSAT data source for the study area</td>
<td>13</td>
</tr>
<tr>
<td>4</td>
<td>List of the topographic maps and ground photos</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>Results from discriminant analysis for 1972 image</td>
<td>23</td>
</tr>
<tr>
<td>6</td>
<td>Results from discriminant analysis for 1976 image</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>Principal Component Analysis on Wakhan Glacier 1972</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Principal Component Analysis on Wakhan Glacier 1976</td>
<td>26</td>
</tr>
<tr>
<td>9</td>
<td>Clustering Statistics for Wakhan 1972</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>Clustering Statistics for Wakhan 1976</td>
<td>33</td>
</tr>
<tr>
<td>11</td>
<td>Clustering Statistics for Sakhi Glacier 1972</td>
<td>42</td>
</tr>
<tr>
<td>12</td>
<td>Clustering Statistics for Sakhi Glacier 1976</td>
<td>47</td>
</tr>
<tr>
<td>13</td>
<td>Principal Component analysis on Sakhi Glacier 1972</td>
<td>51</td>
</tr>
<tr>
<td>14</td>
<td>Principal Component analysis on Sakhi Glacier 1976</td>
<td>52</td>
</tr>
<tr>
<td>15</td>
<td>Clustering Statistics for Keshnikhan, Tirich Glacier</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>Statistics of Minimum Distance to Means for Keshnikhan, Tirich Glaciers</td>
<td>59</td>
</tr>
<tr>
<td>17</td>
<td>Statistics of Maximum Likelihood Classification for Keshnikhan, Tirich Glaciers</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>Clustering Statistics for Mirsamir Glacier</td>
<td>63</td>
</tr>
<tr>
<td>19</td>
<td>Statistics of Maximum Likelihood Classifier for Mirsamir Glacier</td>
<td>66</td>
</tr>
<tr>
<td>20</td>
<td>Statistics of Minimum Distance to Means Classifier for Mirsamir Glacier</td>
<td>67</td>
</tr>
<tr>
<td>PLATE #</td>
<td>Photograph Description</td>
<td>PAGE#</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>1</td>
<td>Color Composite Image for Wakhan 1972 Glacier</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>Results of Cluster Classification for Wakhan 1972 Glacier</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Results of Parallelepiped Classification (Wakhan 1972) Glacier</td>
<td>31</td>
</tr>
<tr>
<td>4</td>
<td>Results of Maximum Likelihood Classifier (Wakhan 1976) Glacier</td>
<td>31</td>
</tr>
<tr>
<td>5</td>
<td>Color Composite Image (Wakhan 1976) Glacier</td>
<td>34</td>
</tr>
<tr>
<td>6</td>
<td>Results of Cluster Classification for Wakhan 1976 Glacier</td>
<td>34</td>
</tr>
<tr>
<td>7</td>
<td>Results of Parallelepiped Classification (Wakhan 1976) Glacier</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>Results of Maximum Likelihood Classifier (Wakhan 1976) Glacier</td>
<td>36</td>
</tr>
<tr>
<td>9</td>
<td>Difference Image map for Wakhan Glaciers</td>
<td>37</td>
</tr>
<tr>
<td>10</td>
<td>Color Composite Image for Wakhan 1972 using Principal Component bands</td>
<td>37</td>
</tr>
<tr>
<td>11</td>
<td>Color Composite Image for Wakhan 1976 using Principal Component bands</td>
<td>39</td>
</tr>
<tr>
<td>12</td>
<td>Results of Cluster classification for Wakhan 1972 (PC 1) band</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>Results of Cluster Classification for Wakhan 1976 (PC 1) band</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>Color Composite image for Sakhi 1972 Glacier</td>
<td>43</td>
</tr>
<tr>
<td>15</td>
<td>Color Composite image for Sakhi 1976 Glacier</td>
<td>43</td>
</tr>
<tr>
<td>16</td>
<td>Results of Minimum Distance to Means Classifier for Sakhi 1972 Glacier</td>
<td>45</td>
</tr>
<tr>
<td>17</td>
<td>Results of Maximum Likelihood Classifier for Sakhi 1972</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>Color Composite image for Sakhi 1976 Glacier</td>
<td>48</td>
</tr>
<tr>
<td>19</td>
<td>Results of Cluster Classification for Sakhi 1976 Glacier</td>
<td>48</td>
</tr>
<tr>
<td>20</td>
<td>Results of Minimum Distance to Means for Sakhi 1976 image</td>
<td>49</td>
</tr>
<tr>
<td>21</td>
<td>Results of Maximum Likelihood Classifier for Sakhi 1976 image</td>
<td>49</td>
</tr>
<tr>
<td>22</td>
<td>Difference Image Map for Sakhi Glacier</td>
<td>53</td>
</tr>
<tr>
<td>23</td>
<td>Color Composite Image for Sakhi 1972 using (PC bands)</td>
<td>53</td>
</tr>
<tr>
<td>24</td>
<td>Color Composite Image for Sakhi 1976 using (PC bands)</td>
<td>54</td>
</tr>
<tr>
<td>25</td>
<td>Color Composite image for Keshnikhan Tirich Glaciers</td>
<td>57</td>
</tr>
<tr>
<td>26</td>
<td>Results of Cluster Classification for Keshnikhan, Tirich Glaciers</td>
<td>57</td>
</tr>
<tr>
<td>27</td>
<td>Results of Minimum Distance to Means Classifier for Keshnikhan, Tirich Glaciers</td>
<td>61</td>
</tr>
<tr>
<td>PLATE #</td>
<td>PAGE #</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Results of Maximum Likelihood Classifier for Keshnikhan, Tirich Glaciers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Color Composite for Mirsamir Glaciers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Results of Cluster Classification for Mirsamir Glaciers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Results of Maximum Likelihood Classifier for Mirsamir Glaciers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Results of Minimum Distance to Means Classifier for Mirsamir Glaciers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE #</th>
<th>PAGE #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
</tr>
</tbody>
</table>

1. Map of the study area
2. Map showing the geographic zones of Afghanistan
3. Flow diagram showing steps to classify images
4. Flow chart showing methodology for the comparison of two images
5. Map of Wakhan area showing different glacier features
ABSTRACT

The present study represents an attempt to classify and compare features of selected glaciers and their surroundings in Afghanistan and Pakistan for two different time periods. The classification utilizes digital data imaged by the MSS (multispectral scanner) carried by the LANDSAT satellite. This digital data permits fairly reliable measurements of the many different features including glacial ice, snow, moraine, water, vegetation and different rocktypes in the adjacent valleys. The LANDSAT digital data were evaluated using both supervised classification and unsupervised classification algorithms. The supervised classifications include Parallelepiped, Minimum Distance to Means and Maximum Likelihood classifications; the unsupervised classification incorporated was a CLUSTER algorithm. The study indicates that the LANDSAT multispectral scanner data are still very useful and contain more information about the larger features than maps. In many cases the snow and ice boundaries can be clearly identified. A comparison of images from two different dates showed significant variations. Overall the classification is about 50 to 80 percent accurate.
ACKNOWLEDGEMENTS

It is impossible to acknowledge individually each of the many authors and teachers from whom I have learned; yet I would like to recognize the contributions of those who agreed to serve on my thesis committee, Dr. John F. Shroder, Jr., Dr. Michael Peterson, Dr. Charles R. Gildersleeve of the Geography and Geology Department, and Dr. Ramond A. Guenther, of the Physics Department, University of Nebraska at Omaha. As my graduate advisor, Dr. John F. Shroder, Jr. patiently guided me and encouraged me to explore a range of opportunities associated with this topic. His hours of hard work and encouragement are greatly appreciated. Credit must be given to Dr. Michael Peterson for initially guiding and helping me in the fascinating world of remote sensing. My recognition to Dr. Charles Gildersleeve for his enthusiastic reading and suggestions of the thesis. I want to give special recognition to Dr. Ramond A. Guenther for the many hours he devoted to this thesis as outside reader. I would also like to thank Dr. Jeffrey S. Peake for his interest in the thesis and his valuable suggestions. I also appreciate the help of Roger M. Hubbard, the manager of the Remote Sensing Application Laboratory and Andrew P. Dinville of the Geography and Geology Department, who provided unlimited computing time. Finally, I would like to thank to Dr. Donald Rundquist, director, CALMIT, University of Nebraska-Lincoln for his guidance and encouragement.
INTRODUCTION:

Scholars of the world are vitally concerned with monitoring the environment. A valuable tool for assessing the environment is the tool of remote sensing. Most of the effort in remote sensing has been toward the data acquisition, interpretation and analysis of different features. Remote sensing, particularly from a satellite, is potential, effective and economic means of information gathering about natural resources.

Remote sensing has played a fundamental role in geologic and geographical exploration. It is the most practical method of measuring many pertinent physical properties of large, generally inaccessible areas. LANDSAT has become an invaluable remote-sensing tool for the scientific community. With the help of LANDSAT satellites, large geographic areas may be imaged in multiple bands using the multispectral scanner (MSS). For many parts of the world, these images are repeated several times. These successful LANDSAT missions have provided the scientific community with vast quantities of new data about the earth. For the scientist, the synoptic view provided by satellite imagery has proved especially useful, particularly the multispectral information obtained for each scene by the multispectral scanner. One LANDSAT scene, about 32,000 km², is acquired in the four spectral bands by the MSS. Each scene contains over $3 \times 10^7$ bits of information, representing the reflected brightness values of each pixel in each wavelength band (Siegal 1976). The study of glaciers has been one of the many applications of LANDSAT multi-spectral scanner data.

The Hindu Kush, Karakoram and Himalayan mountain ranges in Afghanistan and Pakistan host some of the largest mountain glaciers in the world. Because many of these glaciers exist in isolated and inaccessible regions, only very limited field work can be accomplished in these areas (Braslau, et al., 1978). Access
difficulties, mainly due to remoteness of the terrain, limited finances, logistics and particularly the current political uncertainty in Afghanistan necessitate the remote sensing of the glaciers of the region (Shroder, 1980).

Glacial studies contribute a vast amount of information which can be used for regional and worldwide climatic modelling, monitoring a large proportion of the earth's stored fresh water supply (especially for countries like Afghanistan and Pakistan), and a better understanding of mountain environments (Shroder, in press). With the advances in computer technology, it is now possible to obtain high quality classification of glacier components and concomitant analysis of such highly inaccessible areas.

Currently, glaciers and ice caps store about three quarters of the world's supply of fresh water or an equivalent of 60 years of global precipitation. Melt-water from glaciers provides much needed moisture in dry areas of the world such as in Afghanistan (Rundquist, et al., 1979). Therefore, the knowledge of yearly accumulation of snow and ice plus the runoff expectation can be very useful in planning water-related activities in arid regions. In countries such as Pakistan, where 99 percent of the electric power is generated from rivers which are totally dependant upon glacial meltwater, these studies can help in planning to avoid future energy problems (Rundquist et al., 1980).

The glaciers of Afghanistan and Pakistan exhibit a unique set of properties found in very few localities. Among these are the glacial surges and resultant ice-dammed lakes, these dams have a tendency to burst, producing the catastrophic floods called jökulhlaups (Mayewski & Jeschke, 1979). Thus, remote sensing of glaciers helps monitor glacial history. The present study is an attempt to classify, compare and evaluate selected glaciers of Hindu Kush and Karakoram mountain ranges in Afghanistan and Pakistan.

It is felt that such an evaluation will answer to several questions about the region and help assess the water resources:
1. Can the older satellite imagery be used successfully to assess various parameters of glaciers in the Hindu Kush and western Himalaya?

2. Can the imagery be used to detect any changes in glaciers or associated landforms?

PAST HISTORY AND PREVIOUS WORK:

The ability to observe significant snow and ice features with satellites was first demonstrated when television cameras were mounted on the TIROS-2 weather satellite in 1961. The LANDSAT (ERTS) program was started in the late 1960's. LANDSAT-1, launched in 1972, was capable of recording observations of cartographic quality in 4 separate bands. These four spectral bands are: 0.5-0.6 microns (band 4), 0.6-0.7 microns (band 5), 0.7-0.8 microns (band 6), and 0.8-1.1 microns (band 7), with a resolution element (pixel) size of 79 x 79 meters. The convergence of its sun-synchronous orbit at high latitudes makes it possible to monitor individual ice flows, cracks and leads. LANDSAT-1 data have been found to be particularly useful for the monitoring and study of glaciers and their attendant surface features, to determine the character of medial and terminal moraines and the extent of snow cover debris and movement (Gloersen et al., 1975). Particularly interesting is the ability to locate and monitor surging glaciers.

A considerable amount of work has been done on glaciers using remote sensing. Several workers have used LANDSAT multispectral scanner computer compatible tapes (CCT) in their studies to monitor and evaluate glaciers. Krimmel and Meier (1975) used LANDSAT 1 MSS imagery to evaluate glacier movement, surface and bedrock features, terminus changes, snow lines and glacial surges. Ostrem (1975) used MSS imagery for the studies of glaciers in Norway. He used band 4 and band 7 to delineate snow from ice, with band 7 producing the best result. Gloersen and Salomonson (1975) discussed the use of bands 4, 5, and 7 while working on South Cascade Glacier.
in Washington state. Rundquist et al., (1980), after examining and working on several glaciers, contended that the maps produced from LANDSAT digital techniques are adequate as far as several types of geological investigations are concerned. Their maps approached a scale of 1:24,000 but their resolution was still 79 meters. Rundquist and Samson (1980), while working on Khumbu Glacier in Nepal, found that band 5 is most useful for identifying glacial features. They also noted that bands 5 and 7 together produced better results than all four bands combined together.

STUDY AREA

Five different glaciers have been examined in this study in order to classify and provide the similarities and noticeable differences. The areas are Koh-i-Wakhan, Sakhi Valley, Tirich Mir, Koh-i-Keshnikhan and Mirsamir. The above mentioned glacierized areas are generally located in the Hindu Kush mountain ranges. Most of them lie near the Afghanistan-Pakistan border (Fig. 1). Several glaciers in the Karakoram Himalaya were also investigated (Batura, Chantar) but the results are not included here (Shroder et. al., 1984).

AFGHANISTAN, THE LAND AND GEOGRAPHIC ZONES:

Afghanistan or the "Land of Afghans" sits land locked half way around the world from the United States. It is a harsh, but beautiful land dominated by the disembodied mountainous core of the Hindu Kush. The Hindu Kush is the western most extension of the Karakoram and the Himalayas. It extends from the Pamir Knot into central Afghanistan in a general northeast-south westerly trend to within one hundred miles of the Iranian border.

Many passes cut through the central Hindu Kush mountains and these are the main routes between north and south for centuries. Located north of the Hindu Kush are the Turkestan Plains, rolling semi deserts with elevation between 270 and 370 meters. The flood plains of the Amu Darya (classical Oxus in the extreme north, which
forms the boundary between Afghanistan and Russian Turkestan) and its tributaries are relatively level and in some places marshy. The dry western and south western sections are mainly the extensions of the Iranian Plateau rising gradually in altitude from west to east (Dupree, 1973).

Fig. 1: Map of the study area showing location of different glaciers.
Afghanistan has been divided into eleven geographic zones (Fig. 2). The first six among these are Wakhan Corridor-Pamir Knot, Badakhshan, Central Mountains, Eastern Mountains, Northern Mountains and foothills, Southern Mountains and foothills. These are related to the Hindu Kush Mountain system. The remaining five zones are Turkestan Plains, Harat-Farah Lowlands Seistan (Sistan) Basin-Helmand (Hilmand) Valley, Western Stony Deserts and the Southwestern Sandy Desert.

The unique area of Wakhan belongs geographically to the greater Pamir Mountain system but it is a separate geographic entity and it leads directly into the Pamir. Relatively flat valleys exist in Wakhan, Ishkashim and Qala Panja. The Ishkashim valley is about 3 Km across to 4 Km long while the Qala Panja is about a kilometer in all directions.

**GEOMORPHOLOGY OF THE AREA:**

The Hindu Kush, Karakoram and Himalayas are the largest and highest mountain ranges in the world and trend roughly east-west. The Hindu Kush on its west end can be considered to originate at the head of the Taghdumbash Pamir, where two ranges, the Mustagh and the Sarikol join at a point between the Wakhjir (4,923 m) and Kilik (4,755 m) passes in Afghanistan. From here, the Hindu Kush forms the watershed between the Oxus and Indus basins and trends in a direction of northeast to southwest, running approximately 1,300 km to northeastern Afghanistan with about 800 km forming the border between Pakistan and Afghanistan (Chwascinski 1966; Wissmann 1959). The highest peak is Tirich Mir (7,700 m) which is close to the Afghanistan-Pakistan border. The general elevation of the Hindu Kush is approximately 5,000 meters. The highest point in central Afghanistan is Koh-i-Bandaka and is second in the whole country to Tirich Mir.
Fig. 2: Maps showing the Geographic Zones of Afghanistan (After Dupree, 1973).
The glaciers of the Himalayas have been classified into the following four types (Visser 1938; Washburn 1939):

(1) 'BASIN RESERVOIR' or ALPINE TYPE:

These are longitudinal glaciers that come out of one or several cirques or basins and have only one outlet. The nourishment is generally by avalanche and thus the ice fronts are extensively debris covered (Shroder, In press).

(2) 'PLATEAU RESERVOIR' or SCANDINAVIAN TYPE:

These are generally characterized by plateau snow fields that serve as a source area.

(3) 'INCISED RESERVOIR' or MUZTAGH TYPE:

These lie deeply in dissected topography with no basin or plateau source area. Snow avalanches provide most of the nourishment.

(4) 'AVALANCHE or TURKISTAN TYPE:

These are related to Plateau type but lack tributary reservoirs. The first two types show seasonal snow lines or firn limits while the same may not be applicable the last two types. This information will be used in assessing characteristics of the glaciers in this study.

CLIMATIC CONDITIONS OF AFGHANISTAN DURING 1970-1976 PERIOD:

Climate in general:

The climate is arid due to the fact that the area is largely too far north to be affected by oceanic rain-bearing winds. Monsoon influences (which sweep over India from June to September) generally cease in the vicinity of the Chitral area of Pakistan, 200 miles east of the Munjan (Scott et al., 1967). According to Sivall (1977), the Monsoon occasionally influences the area in the mountains north and west of Kabul. This arid climate affects the
vegetation and therefore the human response to the mountain environment. The mountain sides tend to be bare, boulder strewn slopes with jutting crags and deep defiles carved into them. This contrasts amazingly with the sparkling glaciers and snow fields above 4600 m. The only vegetation seen is in the valleys and on the terrace of gentle slopes of the valleys (Scott et al., 1967).

Much of the country's precipitation is in the form of winter snow with a small but important contribution from spring rain. From November to March, snow blankets the mountains. Peaks over 5,500 meters are permanently snow-covered and several sizable glaciers exist in northeastern Afghanistan. Snow begins to melt in March causing the rivers to rise. Seasonal fluctuations occur simultaneously because most rivers get their waters from these glaciers. Most rivers have maximum flow in the spring and minimum in summer with the major exception in the Wakhan area where maximum snow melting is in late August (Dupree, 1973). This rather arid climate has affected the vegetation as well as the people.

The climatic conditions during the four year period were not exceptional except for the droughts of 1970 and 1971 that caused crop failures and loss of livestock in some regions. These were followed by the wet years of 1972 and the first half of 1973 (Rathjens, 1975). Tables 1 and 2 show the annual precipitation of 1972 and 1976 respectively. These tables indicate a wet year for 1972 and a relatively dry year for 1976. The data recorded from 40 stations in 1972 for the northern areas show about 372 mm of precipitation. On the other hand the data collected from 60 stations in 1976 show only about 244 mm precipitation. The precipitation was mostly in the form of snowfall. Therefore we can conclude that the 1972 and first half of 1973 were quite wet, while 1976 was a dry year.
DATA SOURCES AND GROUND TRUTH:

The LANDSAT data source for the study areas are given in table 3. Besides the LANDSAT scenes, the maps and the ground photographs available are described in table 4.

PURPOSE OF THIS STUDY:

The overall objective of this study is to analyze the glacial characteristics and associated features of selected Hindu Kush glaciers. The glaciers of the Hindu Kush exhibit a unique set of properties not very common elsewhere in the world. These include extensive moraine cover, extreme high altitude, widespread snow cover and snow fields, strong shadows due to steep gradients and high relief in protected north facing cirques, high activity ratio and the lack of extensive ground truth. All these factors contribute to the inability to carry out an accurate digital analysis and evaluation of glacial components in this region. However, the rapid development of computer assisted remote sensing techniques over the past several years has increased the ability to work with these data.

Digital image processing techniques can be used to analyze clean ice, rock-mantled ice, firn, various moraine types, outwash plains and water.

Two repetitive LANDSAT coverages for Wakhan and Sakhi Glaciers were available. An attempt is made to determine the significant changes in these glaciers. However, the response time of glaciers, that is, the time between snowfall changes at the glacier's nourishment area and the change in the glacier terminus is centuries to thousands of years for glaciers of the size of those in the Wakhan. While it is not possible to detect changes in the terminus of a glacier using satellite imagery, it may be possible to identify changes, if any, in the terminus and firn/ice boundaries (ELA or snow-lines) Only the changes greater or larger than 79 meters can be identified as the pixel resolution is 79 meters.
The overall objectives of the study are to:

1) Assess the feasibility of using the older satellite imagery to assess the larger features of glaciers.
2) Measure the areas of such glacier features as zones of accumulation and ablation.
3) Compare major and minor features of two different classified computer maps of the same area.
4) Find out whether seasonal snowfall changes on glaciers in the Hindu Kush affect the glaciers in a sufficiently short time and to detect these changes on the available imagery which is only four years apart.
5) Investigate seasonal or other changes of landforms associated with the glaciers.
6) Compare different classified images of the same area by subtracting one from the other to see whether or not valid differences can be detected.
7) Test the accuracy of supervised versus unsupervised classification of the imagery.

In the absence of ground survey, LANDSAT CCTs are used as the primary data source and ground truth is provided by geologic maps of various scales, ground photographs and some written descriptions.
### MONTHLY TOTAL PRECIPITATION FOR 1972.

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of Stations</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JANUARY</td>
<td>40 Stations</td>
<td>81.08 mm</td>
</tr>
<tr>
<td>FEBRURY</td>
<td>40 Stations</td>
<td>57.09 mm</td>
</tr>
<tr>
<td>MARCH</td>
<td>41 Stations</td>
<td>97.60 mm</td>
</tr>
<tr>
<td>APRIL</td>
<td>42 Stations</td>
<td>63.14 mm</td>
</tr>
<tr>
<td>MAY</td>
<td>42 Stations</td>
<td>58.69 mm</td>
</tr>
<tr>
<td>JUNE</td>
<td>41 Stations</td>
<td>11.60 mm</td>
</tr>
<tr>
<td>JULY</td>
<td>42 Stations</td>
<td>01.80 mm</td>
</tr>
<tr>
<td>AUGUST</td>
<td>40 Stations</td>
<td>00.09 mm</td>
</tr>
</tbody>
</table>

Table 1: Precipitation data from 40 stations in Afghanistan during 1972.

### MONTHLY PRECIPITATION DATA FOR 1976

<table>
<thead>
<tr>
<th>Month</th>
<th>No. of Stations</th>
<th>Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>JANUARY</td>
<td>61 Stations</td>
<td>37.74 mm</td>
</tr>
<tr>
<td>FEBRURY</td>
<td>24 Stations</td>
<td>91.00 mm</td>
</tr>
<tr>
<td>MARCH</td>
<td>62 Stations</td>
<td>89.53 mm</td>
</tr>
<tr>
<td>APRIL</td>
<td>63 Stations</td>
<td>53.54 mm</td>
</tr>
<tr>
<td>MAY</td>
<td>62 Stations</td>
<td>15.89 mm</td>
</tr>
<tr>
<td>JUNE</td>
<td>63 Stations</td>
<td>02.69 mm</td>
</tr>
<tr>
<td>JULY</td>
<td>66 Stations</td>
<td>04.18 mm</td>
</tr>
<tr>
<td>AUGUST</td>
<td>64 Stations</td>
<td>03.00 mm</td>
</tr>
</tbody>
</table>

Table 2: Precipitation data from 60 stations in Afghanistan during 1976.
### DATA SOURCE

<table>
<thead>
<tr>
<th>LANDSAT SCENE.</th>
<th>PATH/ROW.</th>
<th>DATE.</th>
<th>AREA.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. E-2566-5041</td>
<td>163/35</td>
<td>10 August 1976</td>
<td>Sakhi Glacier</td>
</tr>
<tr>
<td>2. E-2566-5041</td>
<td>163/35</td>
<td>10 August 1976</td>
<td>Tirich Mir</td>
</tr>
<tr>
<td>3. E-2566-5041</td>
<td>163/35</td>
<td>28 August 1976</td>
<td>Koh-i-Kesnikhan</td>
</tr>
<tr>
<td>4. E-2566-5041</td>
<td>163/35</td>
<td>28 August 1976</td>
<td>Mirsamir</td>
</tr>
<tr>
<td>5. E-1047-5171</td>
<td>162/34</td>
<td>08 Sept 1972</td>
<td>Koh-i-Wakhan</td>
</tr>
</tbody>
</table>

Table 3: LANDSAT data source for the study areas.
## GROUND TRUTH

<table>
<thead>
<tr>
<th><strong>AREA</strong></th>
<th><strong>MAPS (scale)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sakhi glacier</td>
<td>1. (1:100,000) topographic</td>
</tr>
<tr>
<td>&quot;</td>
<td>2. (1:100,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>3. (1:250,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>4. (1:100,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>5. Ground Photographs</td>
</tr>
<tr>
<td>Tirich Mir</td>
<td>6. (1:250,000) topographic</td>
</tr>
<tr>
<td>&quot;</td>
<td>7. Ground Photographs</td>
</tr>
<tr>
<td>Koh-i-Keshnikhan</td>
<td>8. (1:25,000)</td>
</tr>
<tr>
<td>&quot;</td>
<td>9. Ground Photographs</td>
</tr>
<tr>
<td>&quot;</td>
<td>10. (1:50,000) topographic</td>
</tr>
<tr>
<td>&quot;</td>
<td>11. Ground Photographs</td>
</tr>
<tr>
<td>Mirsamir</td>
<td>12. (1:250,000) topographic</td>
</tr>
<tr>
<td>Koh-i-Wakhan</td>
<td>13. (1:10,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>14. (1:25,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>15. (1:50,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>16. (1:50,000) &quot;</td>
</tr>
<tr>
<td>&quot;</td>
<td>21. Ground Photographs</td>
</tr>
</tbody>
</table>

**TABLE 4: List of the topographic and ground photos.**
Chapter Two

Methodology

Three different software were used for this study. These include EYE-COM (UNORSAL), ELAS and ERDAS packages. Most of the processing work was accomplished at Remote Sensing Application Laboratories (RSAL), University of Nebraska at Omaha. However, some of the work on ELAS software was completed at CALMIT, University of Nebraska, Lincoln.

The following procedure was adapted for each of the study areas.

1. A 512 * 512 pixel image of each band of the four was extracted from the LANDSAT CCT scene of each area using ERDAS software and then converted into ELAS format using the programs called TEMP and ETOE.

2. A Discriminate Analysis Program was applied to these bands in order to test them statistically. This program showed which band contained more information on different glacial features. The Principal Component Transformation was applied to different bands the results of which were used in the analysis. All the bands were then enhanced by using FILTER, EGAL and other related algorithms in order to identify different features on the image and compare them to the maps and photographs.

3. Three out of the four bands selected from those available were combined to obtain a color composite image using the best selection of bands for classification. The combination was usually Blue, Green and Red in picture plane 1, 2 and 3 respectively (on the EYE-COM).

4. Each color composite image was then enhanced to eliminate the unnecessary noise and get a better picture of the glacier using the program ZOOM (which enables the operator to focus closely in on a section of an image) as well as GAMMA.
6. These color composite images were taken individually and various classification programs were performed on these images (scenes). This procedure determined and showed which of these programs and what band combinations produce better results based on visual inspection (Fig 3).

7. Two repetitive coverages were available for Koh-i-Wakhan glacier and Sakhi Glacier. The Wakhan area coverage was taken on the 8th September 1972 and on the 9th of August, 1976. The coverages for Sakhi Glacier were taken on the 28th September 1972 and 10th August 1976. An attempt was made to determine the overall changes within the glacier, particularly the terminus changes within that time period. A variety of approaches were available to conduct this comparison. Two different methods were used.

A:– The visual interpretation method involved plotting the snow lines onto a base map or as an overlay. This is the most common way of analyzing imagery. In this way the changes in the snow-lines or the terminus were analyzed visually.

B:– The second approach to the problem was to analyze the glacier changes automatically. With this method, the two images were enhanced to get a better picture. At least 10 known control points were chosen from both the base map and the two classified images and their X, Y coordinates were determined. Both the images were registered by using image to image registration techniques. These registered images were compared using the DBASE Program (in ELAS) to get a difference image. This difference image indicated the changes that had occurred in that time frame, including the changes of the glacier and its surroundings. A flow chart is drawn to explain the method (Fig.4).

MULTISPECTRAL CLASSIFICATION OF THE IMAGES

Two different classification techniques were used. These are

1. Unsupervised Classifier
2. Supervised Classifier
An unsupervised classifier program (CLUSTER), which is available in EYE-COM, ELAS and ERDAS softwares, was also applied. This program performs an unsupervised classification on a composite image stored in three picture planes. This routine automatically calculates training areas for as many discreet classes as it can find (up to 32 classes), based on natural groupings present in the image file. Unsupervised classification requires only a minimal amount of initial input from the analyst. It is a process whereby numerical operations are performed that search for 'natural' groupings of the spectral properties of pixels. The user allows the computer to select the class means and covariance matrices to be used in the classification. After the classification, the user then converts these natural classes into 'information' classes of interest, based upon the field data and other related evidences (Jensen, 1986).

In supervised classification, on the other hand, the identity and location of some of the land cover-types, such as urban, agriculture, forest and rock-types etc., are known a priori through a combination of field work, analysis of aerial photography, maps and personal knowledge about the area. The analyst then attempts to locate specific sites (training sites) in the remotely sensed data that represent homogeneous examples of these known land-cover types. After this the multivariate parameters, such as mean, standard deviations, covariance matrices, correlation matrices, etc., are calculated for each training site. Each pixel within and outside the training area is then evaluated and assigned to the class of which it has highest likelihood of being a member. Several supervised classification schemes are used including Maximum Likelihood, Minimum Distance to Means and Parallelepiped classifications. The Maximum Likelihood classifier algorithm evaluates variance and correlation of an unknown pixel in relation to the established training sites. An assumption of Gaussian (normal) distribution for the training sites is made in order to describe the mean vector and covariance matrix.
FIG 3: Flow chart showing steps to classify images by applying 3 different classifiers.
From this statistical probability, an unknown pixel can be assigned to a particular class based on its value as it relates to these multidimensional class boundaries. (Lillesand and Kiefer, 1979).

The Minimum Distance to Means decision rule is computationally simple and commonly used. The classification accuracy is comparable to more computationally intensive algorithms, such as the Maximum Likelihood algorithm. It also requires the user to provide the mean vectors for each class in each band from the training data. It then performs a minimum distance classification in which it calculates the distance to each mean vector from each unknown pixel.

In the Parallelepiped classifier program (PARA), the highest and lowest training values are utilized. A range or rectangular decision region was established with this supervised classifier. Each unknown pixel is then compared to these decision regions and classified accordingly (Lillesand and Kiefer, 1979).

Digital assessment was performed on several different components of these glaciers, including clean ice, rock-mantled ice, firn, various moraine types, outwash plains and water. This assessment provided spectral signatures (the unique combination of reflectance values for a feature using the various LANDSAT bands) which allowed production of computer generated maps depicting the various glacial components.

The methodology that is adapted in this study is a slightly different approach to the problem. Some new ideas (described above) are applied to produce better possible results. The glaciers of the Hindu Kush vary greatly in terms of size, amount of precipitation and solar insolation, surrounding rock lithologies, exposure, and morphological type. The various classification programs applied to all these glaciers will produce classified images, in which different glacial features and various landforms will be associated.
FIG 4 : Flow chart showing the methodology for the comparison of two images.
CHAPTER THREE

ANALYSIS AND RESULTS

Image interpretation in the present context is the act of detecting, recognizing and classifying the Earth's surface and subsurface characteristics using remotely sensed data. For this purpose the following stages can be recognized

1. Selection of features
2. Extraction of features from images
3. Assigning parts of images to classes

The latter two procedures are generally recognized as classification. There are two distinct methodologies: The Supervised Classification and the Unsupervised Classification. Both methods are used in this study.

All the enhancement and classification methods were performed using the above techniques in order to produce the best quality image maps and attempt to extract maximum information possible.

WAKHAN GLACIERS:

The Wakhan area is the Afghan strip along the upper tributaries to the Amu Darya in the northeastern part of Afghanistan. Morphologically this mountainous area is divided into the deeply dissected western Wakhan which contains the highest peaks (up to 7,000 meters), a transitional middle section and the broad flatter eastern Wakhan. Geologically the mountain range is formed of granite, gneiss-and clay slate/quartzite series. The entire valley system shows traces of glaciation (Mirwald et al., 1967).
Climatically, the crest of the eastern Hindu Kush forms the dividing line between monsoonal and continental areas. The snow-line climbs from west to east from 4,900 to 5,300 meters. Tree growth is entirely limited to stream banks and ravines, which is not enough for forest formation (Mirwald et al., 1967).

Using the techniques and methods describe in chapter two, both the Wakhan images of September 1972 and August 1976 were extracted from their respective LANDSAT scenes. This discriminate analysis program was applied on both these Wakhan images (Table 5). As is clear from this table the Discriminate analysis of the 1972 image showed that the bands 4, 6 and 7 are most suitable for gathering snow related information. On the other hand, the 4, 5 and 7 band combination is appropriate for ice, rock types and alluvial fans. Therefore band 4, 5 and 7 were chosen for unsupervised classification (UNSUP) in ELAS.

The discriminate analysis for August 1976 Wakhan image (Table 6) produced a variety of band combinations for each training site. As a result of this, bands 5, 6 and 7 were used for the unsupervised classification.

The principal component transformation produces best results as 97 percent of the information was found in principal component band 1 (PC1) (Table 7). Small coefficient of variation and high correlation coefficient exists between and/or among the four bands. The same is true for the 1976 Wakhan Image (Table 8). On the basis of this, the PC1 for both Wakhan images was used in the classification.
### Table 5: Results from Discriminant Analysis for 1972 image.

<table>
<thead>
<tr>
<th>DISCRIMINANT FUNCTION</th>
<th>TRAINING AREA</th>
<th>CONSTANT</th>
<th>BAND 4</th>
<th>BAND 5</th>
<th>BAND 6</th>
<th>BAND 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SNOW</td>
<td>-80.80719</td>
<td>2.63452</td>
<td>-4.22981</td>
<td>0.83768</td>
<td>4.22923</td>
</tr>
<tr>
<td>2</td>
<td>ICE</td>
<td>-12.16937</td>
<td>1.02807</td>
<td>-0.79619</td>
<td>-0.03894</td>
<td>0.19385</td>
</tr>
<tr>
<td>3</td>
<td>ROCK TYPE</td>
<td>-5.11354</td>
<td>0.40901</td>
<td>-0.54583</td>
<td>0.11819</td>
<td>0.61932</td>
</tr>
<tr>
<td>4</td>
<td>ALLUVIAL FAN</td>
<td>-6.50099</td>
<td>1.02386</td>
<td>-1.13767</td>
<td>0.09865</td>
<td>0.64740</td>
</tr>
</tbody>
</table>

Table 5: Results from Discriminant Analysis for 1972 image.
### DISCRIMINANT ANALYSIS FOR WAKHAN AREA IMAGE (AUG. 1976)

<table>
<thead>
<tr>
<th>DISCRIMINANT FUNCTION</th>
<th>TRAINING AREA</th>
<th>CONSTANT</th>
<th>BAND 4</th>
<th>BAND 5</th>
<th>BAND 6</th>
<th>BAND 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SNOW</td>
<td>-86.88235</td>
<td>1.29731</td>
<td>-0.36145</td>
<td>1.38174</td>
<td>-2.58536</td>
</tr>
<tr>
<td>2</td>
<td>ICE</td>
<td>-19.23039</td>
<td>0.16552</td>
<td>0.94264</td>
<td>-0.11828</td>
<td>-1.16762</td>
</tr>
<tr>
<td>3</td>
<td>ROCK TYPE</td>
<td>-9.58608</td>
<td>-0.11778</td>
<td>0.41352</td>
<td>0.21963</td>
<td>-0.38340</td>
</tr>
<tr>
<td>4</td>
<td>ALLUVIAL FAN</td>
<td>-16.87614</td>
<td>-0.19950</td>
<td>0.48148</td>
<td>0.34522</td>
<td>-0.38399</td>
</tr>
</tbody>
</table>

Table 6: Results from Discriminant Analysis for 1976 image.
### Principal Component Analysis on Wakhan Glaciers 1972

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>MEAN(x)</th>
<th>SD(s)</th>
<th>COV(s/x)</th>
<th>CHANNEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>65.37</td>
<td>35.20</td>
<td>0.054</td>
<td>#2</td>
</tr>
<tr>
<td>#3</td>
<td>61.21</td>
<td>34.40</td>
<td>0.056</td>
<td>#4</td>
</tr>
</tbody>
</table>

### Correlation Matrix:

<table>
<thead>
<tr>
<th></th>
<th>1.00</th>
<th>0.99</th>
<th>0.98</th>
<th>0.91</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>0.97</td>
</tr>
<tr>
<td>0.99</td>
<td>1.00</td>
<td></td>
<td>0.90</td>
<td>0.97</td>
</tr>
<tr>
<td>0.98</td>
<td>1.00</td>
<td>0.90</td>
<td></td>
<td>0.97</td>
</tr>
<tr>
<td>0.91</td>
<td>0.97</td>
<td>0.97</td>
<td>0.97</td>
<td></td>
</tr>
</tbody>
</table>

### Eigen Values:

<table>
<thead>
<tr>
<th></th>
<th>3.88</th>
<th>0.10</th>
<th>0.01</th>
<th>0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.88</td>
<td></td>
<td>0.10</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>0.10</td>
<td>0.10</td>
<td></td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td></td>
</tr>
</tbody>
</table>

### Percent of Variance by Eigenvalue:

<table>
<thead>
<tr>
<th>Percent</th>
<th>97.105</th>
<th>2.551</th>
<th>0.225</th>
<th>0.119</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

### Cumulative Percentage:

<table>
<thead>
<tr>
<th>Percent</th>
<th>97.105</th>
<th>99.656</th>
<th>99.881</th>
<th>100.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 7**: Results of principal component analysis for Wakhan 1972 image. Note the high correlation between the four MSS bands.
**PRINCIPAL COMPONENT ANALYSIS ON WAKHAN GLACIERS 1976**

<table>
<thead>
<tr>
<th>CHANNEL #1</th>
<th>CHANNEL #2</th>
<th>CHANNEL #3</th>
<th>CHANNEL #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEAN(x)</td>
<td>43.61</td>
<td>53.72</td>
<td>52.82</td>
</tr>
<tr>
<td>SD(s):</td>
<td>34.94</td>
<td>38.71</td>
<td>37.57</td>
</tr>
<tr>
<td>COV(s/x):</td>
<td>00.80</td>
<td>00.72</td>
<td>00.71</td>
</tr>
</tbody>
</table>

**CORRELATION MATRIX:**

<table>
<thead>
<tr>
<th></th>
<th>1.00</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.98</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.98</td>
<td>0.99</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>0.94</td>
<td>0.95</td>
<td>0.97</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**EIGEN VALUES:**

|       | 3.88 | 0.10 | 0.01 | 0.00 |

**PERCENT OF VARIANCE BY EIGEN VALUE:**

|       | 97.769 | 1.623 | 0.529 | 0.078 |

**CUMULATIVE PERCENTAGE:**

|       | 97.769 | 99.392 | 99.922 | 100.00 |

**TABLE 8:** Results of principal component analysis for Wakhan 1976 image. Note the high correlation between the four MSS bands.
UNSUPERVISED AND SUPERVISED CLASSIFICATION FOR 1972 IMAGE:

Unsupervised (CLUSTER) Classification:

The unsupervised classification approach (CLUSTER) was used on the color composite image for 1972 (Plate 1), the results of which are shown (Plate 2). A total of 32 clusters were selected for this unsupervised classification in order to get the maximum number of classes for the different features in the image (Table 9). The separation of fresh snow from ice and moraine is distinct, and the glacier boundaries can be determined. The alluvial fans came out as two different classes. This is probably due to the different soil characteristics as the bigger alluvial fan (on the lower right hand side of the scene) contains soil, debris etc., transported by the Ptukh river. It contains mostly argillites (Fig 5) and is classified as a separate class compared to the rest of the alluvial fans, which may composed of granitic rock material. Many similar features are classified as different classes. This is due to the fact that the spectral response of some of the pixels are different though they could be representing the same feature. In other words the same features at two different locations within an image may have a different signature. There are many reasons for this pixel behavior including the sun angle, relief and terrain features and the characteristics of that object. Some of the clusters are meaningless because they represent mixed classes of earth surface materials.

Supervised Classification:

Parallelepiped Classification:

This classification was performed on bands 4, 5 and 7 on both the images separately. Five different training sites were selected based on the available ground truth. These include snow covered areas, ice, alluvial fans and rock-types. Plate 3 shows the classified map generated by computer. The margins of ice and snow are
PLATE 1: A color composite image for Wakhan 1972 area. Bands 5, 6 and 7 are placed in picture plane 1, 2 and 3. Notice the extension of snow over a larger area.

PLATE 2: The results of applying an unsupervised classification (CLUSTER) of Wakhan LANDSAT image for 1972. A total of 32 clusters were used. The categories include: dark blue areas = snow, yellow = glacier ice. Alluvial fans appear in two different clusters due to the different rock material. ELAS software is used.
## CLUSTERING STATISTICS FOR WAKHAN 1972

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Percent of Scene</th>
<th>Class description</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>04.66%</td>
<td>Water</td>
<td>Dark Blue</td>
</tr>
<tr>
<td>2</td>
<td>04.79%</td>
<td>Vegetation</td>
<td>Brown</td>
</tr>
<tr>
<td>3</td>
<td>20.49%</td>
<td>Snow</td>
<td>Blue</td>
</tr>
<tr>
<td>4</td>
<td>11.89%</td>
<td>Ice</td>
<td>Yellow</td>
</tr>
<tr>
<td>5</td>
<td>08.53%</td>
<td>Argillites</td>
<td>Navy Blue</td>
</tr>
<tr>
<td>6</td>
<td>10.89%</td>
<td>Granites</td>
<td>Light Blue</td>
</tr>
<tr>
<td>7</td>
<td>10.59%</td>
<td>Alluvial Fans</td>
<td>Dark Brown</td>
</tr>
<tr>
<td>8</td>
<td>10.56%</td>
<td>Shaded area</td>
<td>Dark green</td>
</tr>
</tbody>
</table>

Table 9: Results of LANDSAT bands 4, 6 and 7 of the Wakhan Valley glaciers for 1972
FIG. 5 Map of the area showing different glacial features.
FIG. 5 Map of Wakhan area showing different glacier features.
PLATE 3: This classified map is the result of applying a Parallelepiped Classification algorithm to the training data of Wakhan LANDSAT image. Bands 4,5 and 7 were used. The 5 different categories including snow (white), ice (blue), alluvial fans (yellow) two different rock-types, argillite (brown) and granite (yellow) can be seen.

PLATE 4: The results of applying a Maximum Likelihood Classifier on Wakhan area glaciers. The categories include: white = snow, blue = ice, brown = argillites, light brown = granite, yellow = alluvial fans. Bands 4,5 and 7 are used.
clearly distinguishable. Two different rock types i.e., argillites and granite are classified as separate classes. These are represented by brown and yellow colors respectively. The black areas are ice mixed with dirt and came out as a separate class. This classifier is simple yet very productive.

**Maximum Likelihood Classifier:**

A second classifier called Maximum Likelihood was also applied. In this case, similar training sites were selected for this classification. The results (Plate 4) are very interesting and a much clearer image map is obtained as a result of this classifier. Alluvial fans, both rock-types and snow and ice differences are very clear.

**UNSUPERVISED AND SUPERVISED CLASSIFICATION FOR 1976 IMAGE:**

**Unsupervised (CLUSTER) Classification:**

CLUSTER Classification was performed on the color composite image (Plate 5) using the ELAS software system, which is a little faster method compared to ERDAS. A total of 32 CLUSTERs were generated by the computer. This option was selected due to the reason that a maximum number of clusters are better than the fewer number. These 32 clusters were then grouped into 10 major classes (Table 10). The results (Plate 6) shows the map containing 32 clusters. All the major features are visible. There are, however, some meaningless clusters which are due to the mixed classes (pixels).
### CLUSTERING STATISTICS FOR WAKHAN 1976

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Percent of Scene</th>
<th>Class description</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>05.37%</td>
<td>Water</td>
<td>Dark Blue</td>
</tr>
<tr>
<td>2</td>
<td>09.81%</td>
<td>Dirty Ice</td>
<td>Yellow</td>
</tr>
<tr>
<td>3</td>
<td>07.54%</td>
<td>Large alluvial fan</td>
<td>Blue</td>
</tr>
<tr>
<td>4</td>
<td>16.47%</td>
<td>Snow</td>
<td>Dark green</td>
</tr>
<tr>
<td>5</td>
<td>08.59%</td>
<td>Small A.Fan</td>
<td>Navy Blue</td>
</tr>
<tr>
<td>6</td>
<td>13.73%</td>
<td>Granites</td>
<td>Light Blue</td>
</tr>
<tr>
<td>7</td>
<td>11.71%</td>
<td>Argillites</td>
<td>Dark Brown</td>
</tr>
<tr>
<td>8</td>
<td>14.41%</td>
<td>Ice</td>
<td>Dark green</td>
</tr>
<tr>
<td>9</td>
<td>05.03%</td>
<td>Shaded area</td>
<td>Orange</td>
</tr>
</tbody>
</table>

Table 10 Results of LANDSAT bands 4, 6 and 7 of the Wakhan Valley glaciers for 1976.
PLATE 5: A Color Composite Image for Wakhan image for 1976. Bands 4, 6 and 7 are used. Notice the glaciers extending deep into the canyons. Yellow color represents the vegetation in the main Wakhan Valley.

PLATE 6: The results of performing an unsupervised (cluster) classification of the Wakhan 1976 LANDSAT image. Thirty two clusters were extracted and relabeled accordingly. (ELAS software is used).
Supervised Classification

Parallelepiped Classification:

This classifier is simple yet is widely used. The training sites were carefully chosen in order to select the exact sites that were used for the 1972 image. The Plate 7 indicates the obvious differences in the snow cover of the two dates. As seen visually and proven by the climatic data for those years, there is a much smaller snow accumulation area in the 1976 image map.

Maximum Likelihood Classifier:

Similar training areas were chosen for this decision rule and the results are remarkably clear. A much clearer map (Plate 8) was obtained. The snow/ice boundary is clearly distinguishable. Both granite and argillites are clearly marked.

DIFFERENCE IMAGE:

From the comparison of the two classified images (Plate 9). It is evident that the snow occupies less area in the 1976 image compared to that in the 1972 image. The areas with no change over the four year time period are indicated in black. The most probable explanation of this difference is less precipitation. This is also evident from the Afghan meteorological data which states that over the four years there had been a gradual decrease in the overall precipitation in the Hindu Kush mountain region. This may lead to the possibility of a slight retreat in the Wakhan area glaciers but this possibility cannot be proved because ground data and field observations are lacking. Also the glaciers of the size of Wakhan sometimes take hundreds of years to show significant changes.
PLATE 7: This classified map is the result of applying a Parallelepiped Classifier to the training data of 1976 Wakhan image. The different classes are: white = snow, blue = ice, brown = argillites, yellow = granite, black = mixed classes.

PLATE 8: The results of applying a Maximum Likelihood Classifier to Wakhan 1976 LANDSAT image, using the same training sites. Notice the differences in alluvial fans and the reduced area of snow compared to 1972 classified map.
PLATE 9: The photograph shows a Difference Image map. The black area represents snow, and the area of no difference. All the other areas show some difference in the area for the four years time interval.

PLATE 10: The photograph shows the color composite image for Wakhan Valley for 1972. The color composite is made using the three Principal Component bands, i.e., PC 1, PC 2 and PC 3.
PRINCIPAL COMPONENT ANALYSIS:

Principal component analysis (PCA) has proven to be of significant value in the analysis of remotely sensed data. PCA is a technique of pinpointing the subtle information, variation and composition of soil and rock materials, but more important is the fact that for a single LANDSAT scene, there is considerable redundancy. The bands are usually highly correlated. PCA thus performs the function of reducing a large amount of data into 1, 2 or 3 PC bands, that can be analyzed to produce good quality results.

Therefore, the principal component images are then classified. Tables 7 and 8 show the statistics for the PC bands, according to which most of the information is contained in PC1 for 1972 and for PC1 for 1976 synthetic channels (Plates 10 & 11). The CLUSTER classification was performed on the PC 1 for 1972 and in 1976. The results of these classifications came out better than the previous ones. Most of the features like snow and ice/moraine boundaries can be seen clearly. Even using the principal component, the different alluvial fans came out as separate classes. The possible explanation is the different debris or soil on the alluvial fan.(Plate 12 & 13). Another explanation could be that the changes of the alluvial fans are man-made (human induced) because Issak village is situated here and the land is under cultivation (Fig 5).

Classification Comparison:

Both the images were compared by using different methods. The unsupervised classification provides quite useful information for snow and ice for both 1972 and 1976 image maps. By comparing the two images visually and overlapping them on a light table, it appears that the snow line in the later image map has been reduced during the four years time period. The same conclusion is drawn from various supervised classified image maps.
PLATE 11: The photograph shows the color composite image for Wakhan Valley for 1976. Again three Principal Component bands i.e., PC 1, PC 2 and PC 3. are used.

PLATE 12: The photograph shows the unsupervised (CLUSTER) classified map produced from Principal Component 1 for 1972 Wakhan image. Notice the alluvial fan (orange) in the lower right hand corner of the photograph.
The fact is that 1972 and part of 1973 were quite humid years and the satellite images taken on 8th September show mostly the fresh precipitation. This is also indicated from the data collected by Afghan Meteorological Institute for 1972 and 1976 as shown in tables (Table 1 and 2). Therefore, most of the 1972 Wakhan glaciers are covered by fresh snow. However, the glaciers can be observed clearly in the 1976 image map. A close observation of the alluvial fans show that small changes occurred over the four year time period. This is probably due to the increase in cultivated area or a slight change in the path of the Wakhan River.

PLATE 13: The photograph shows the unsupervised (CLUSTER) classified map produced from Principal Component 1 for 1976 Wakhan image. Notice the changes in the bigger alluvial fan (orange) in the lower right hand corner of the photograph.
SAKHI VALLEY GLACIERS:

The Sakhi valley lies on the northern sector of the main ridge of the Hindu Kush with Kohi Bandaka (Bandaka mountain) among the higher peaks in the massive off-shoots running north towards Russia. Kohi- Bandaka is approximately 6,818 meters high.

Various classification techniques including unsupervised and supervised classifications were performed in order to extract maximum information. The following are the results of the analysis.

UNSUPERVISED AND SUPERVISED CLASSIFICATION APPROACH FOR 1972 IMAGE:

CLUSTER Classification:

Unsupervised classification is another attempt to see and analyze the area in some basic detail. The CLUSTER classification approach was used on a color composite image containing band 4, 5 and 7 (Plate 14). In ELAS software this function is designed to operate faster than the other systems like ERDAS. CLUSTER classification is an unsupervised classification technique and requires only a minimal amount of initial input from the analyst. The clustering of several classes is performed by the computer. Once the data are classified, the analyst then attempts to assign these "natural" or spectral classes into the information classes of interest. In the clustering, the program reads through the data set and sequentially builds clusters or groups of points in spectral space. There is a mean vector associated with each cluster. A total of 32 clusters were extracted for this image. These were then grouped into 6 information classes or clusters (Table 11).
CLUSTERING STATISTICS FOR SAKHI GLACIER 1972

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Percent of scene</th>
<th>Class description</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>47.50%</td>
<td>Snow</td>
<td>Light blue</td>
</tr>
<tr>
<td>2</td>
<td>10.04%</td>
<td>Shaded area</td>
<td>Yellow</td>
</tr>
<tr>
<td>3</td>
<td>09.98%</td>
<td>Alluvial fan</td>
<td>Red</td>
</tr>
<tr>
<td>4</td>
<td>14.68%</td>
<td>Rock types</td>
<td>Green</td>
</tr>
<tr>
<td>5</td>
<td>06.27%</td>
<td>Ice</td>
<td>Brown</td>
</tr>
<tr>
<td>6</td>
<td>11.71%</td>
<td>Dark colored rocks</td>
<td>Dark green</td>
</tr>
</tbody>
</table>

Table 11: Results of clustering of LANDSAT Sakhi image for 1972.

The results of this classification scheme are shown (Plate 15). Most of the important features are classified as separate classes. For example, the snow covered area, moraine and glacial ice can be clearly seen. Different colors are assigned to different classes. The fresh snow, mostly covering the eastern portion of the image is represented in blue color. Alluvial fans are the red colored areas scattered all over the image. The rock-types are green in color. Some of these classes are meaningless because they represent mixed pixels of earth surface materials.

Minimum Distance to Means Classifier (MIND Classifier):

Another classification approach is the Minimum Distance to Means approach. This is a supervised classification approach. This decision rule simply calculates an average location or centroids. It asks the user to provide the mean vectors for each class in each band from the training sites. The algorithm then calculates the distance to
PLATE 14: The photograph shows a color composite image of Sakhi Valley glacier taken from LANDSAT 1972 image. Notice the extension of ice over a larger area. Bands 4, 5 and 7 are used.

PLATE 15: Photograph shows an Unsupervised (CLUSTER classified map using 32 clusters. The blue color represents snow covering most of the glaciers. Yellow color represents the shaded area. Alluvial fans are red in color.
each mean vector (mean spectral value for each class) from each unknown pixel. Bands 2, 3 and 4 were used. Five different training sites were selected including snow, ice (moraine), rocktypes, vegetation and alluvial fans or flood plains. The resultant classified image (Plate 16) shows all the classes except the vegetation. The reason probably was that not enough training data was available and the only location that was assigned as a training site showed the signatures of mixed pixels.

There are certain limitations for this algorithm, i.e., after computing the distance it assigns the unknown pixel to the closest class and is therefore insensitive to different degrees of variance in the spectral response data.

**Maximum Likelihood classifier (MAXL classifier):**

A third and final method of classification used is the Maximum Likelihood classification approach. In this case the classifier quantitatively evaluates both the variance and correlation of the category spectral response pattern when classifying an unknown pixel. The training sites were carefully chosen and an attempt was made to input the same areas as assigned in the earlier classification. The result (Plate 17) shows much similarity to the previous classification. However, different colors are assigned in this classification. The resemblance in the information classes reveals a close relationship between the visual interpretation and those done by the computer.

**UNSUPERVISED AND SUPERVISED CLASSIFICATION APPROACH FOR 1976 IMAGE:**

**CLUSTER Classification:**

Similar techniques were employed for the 1976 image for the Sakhi Valley glaciers. A band combination of 4, 5 and 7 was used (Plate 18). The CLUSTER classification was based on 32 classes,
PLATE 16: This photograph shows the map produced by using the Minimum Distance to Mean Classifier. Notice the extension of snow over most of the picture. The shaded areas are red in color. The five classes are snow, ice, alluvial fans or flood plains, vegetation and rock-types.

PLATE 17: The photograph shows Maximum Likelihood Classifier used on Sakhi Valley glaciers. The deep yellow color represents the snow. Notice the similarities between this map and the previous one.
the maximum number of classes that the program had offered. The principal reason for these many classes is to distinguish as many different as possible spectral signatures. These classes are then grouped into 6 major classes (Table 12). The resultant image shows a clear snow boundary separating the freshly covered areas from the rest of the field. Moraine and clear ice are classified as separate classes. Other distinguished classes are vegetation and alluvial fans. There are, however, some of the scattered very small features that are not distinguishable and probably are the mixed pixels (Plate 19).

Minimum Distance to Means Classifier:

In this classification attempt, the same 5 distinctive areas were selected. These include vegetation, snow covered area, moraine and ice, alluvial fans and rock-types. An interesting classified image map is obtained based on these five training sites. The classified study area is shown in Plate 20. The snow covered areas, moraine, vegetation and ice are all clearly visible.

Maximum Likelihood Classifier:

A third and final approach is the MAXL classifier. Again similar sites were chosen for the 5 different training areas. The snow and ice are the clearly marked features. The classified image is very much similar to the previous one except that certain features like glaciers and moraine are slightly larger than that in the previous classified image map (Plate 21).

Difference Image:

Two different date images were available for the same area with approximately four years time interval. A similar approach, as described earlier was used in order to extract the information regarding the differences in the glacier over the 4 years. The two images were registered to each other so that the same pixel in
CLUSTERING STATISTICS FOR SAKHI GLACIER 1976

<table>
<thead>
<tr>
<th>Cluster</th>
<th>Percent of scene</th>
<th>Class description</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.65%</td>
<td>Snow</td>
<td>Red</td>
</tr>
<tr>
<td>2</td>
<td>35.90%</td>
<td>Shaded area</td>
<td>Light blue</td>
</tr>
<tr>
<td>3</td>
<td>14.68%</td>
<td>Rock type</td>
<td>Dark blue</td>
</tr>
<tr>
<td>4</td>
<td>06.27%</td>
<td>Ice</td>
<td>Medium green</td>
</tr>
<tr>
<td>5</td>
<td>09.34%</td>
<td>Moraine</td>
<td>Light green</td>
</tr>
<tr>
<td>6</td>
<td>05.23%</td>
<td>Vegetation</td>
<td>Dark yellow</td>
</tr>
</tbody>
</table>

Table 12: Results of clustering of LANDSAT Sakhi image for 1976.

Each band (of each image) should be at the same place during the overlapping process when the difference image was extracted.

The two images with a four year time difference were then subtracted from each other and a final difference image was extracted (Plate 22). Various interesting features can be seen:

1. A clear difference is observed in the fresh snow (from 1976 image) compared to the larger snow covered area (yellow) of 1972. Upon comparison of the two classified images it was found that the 1972 image contains snow extending over a larger area compared to the 1976 image. This is evident from the meteorological data that shows a rather wet season during 1972. On the other hand the 1976 data do not show much precipitation, particularly heavy snowfall.

PLATE 19: Photograph showing Cluster Classification approach on Sakhi 1976 image. Notice the smaller snow covered area (red). Ice is represented by light green color.
PLATE 20: Minimum Distance to Mean Classifier is used here. The photograph shows the classified map. Five different training sites were snow, ice, vegetation, alluvial fans and rock-types.

PLATE 21: Photograph showing the Maximum Likelihood Classifier approach for Sakhi Valley Glaciers. Similar training sites were chosen for this approach. A similarity can be seen between the two maps.
2. The black color represents the area of no difference. This includes some of the glacial moraine and dirty ice.

3. The resultant image shows some obvious changes that can be detected by visual inspection of the color composite images. However, no glacier advancement or retreat can be seen, mainly due to extensive snow cover in the 1972 image.

**PRINCIPAL COMPONENT ANALYSIS:**

The color composite image was subjected to principal component analysis approach. As previously mentioned this transformation method is utilized to compress a large number of data into smaller number of bands. It extracts the information from many bands and condenses them into small number of bands usually 1 to 3. The PC results showed that the Sakhi image, like the previous Wakhan image, is highly correlated (Table 13 and 14) and therefore one PC can also be utilized as well as the all four bands. The PC transformation are shown in Plate 23 & 24

**Classification Comparison:**

The results of both these images were then studied using light table and visual methods. The unsupervised classifier provides quite useful information for snow and ice covered areas for both the images. Again the snow in the 1972 image is wide spread compared to the snow in the 1976 image. Vegetation is not observed in the 1972 color composite as well as in classified maps. The reason probably is snow coverage. However, the vegetation is apparent in the 1976 image and also as a separate class in classified maps for 1976.
TABLE 13 Results of principal component analysis for Sakhi 1972 image. Note the high correlation between the four MSS bands.
TABLE 14: Results of principal component analysis for Sakhi 1976 image. Note the high correlation between the four MSS bands.
PLATE 22: Photograph showing the map of the Differences between the two years, i.e., 1972 and 1976. The black areas are the areas of no difference. Areas in green represents the snow for 1976, while the yellow indicates 1972 snow covered areas.

PLATE 23: This photograph shows the color composite image for the 1972 Sakhi Valley glaciers using the Principal Component transformation. PC 1,2 and 3 are placed in picture plane 1,2 and 3.
PLATE 24: The photograph shows the color composite using Principal Component transformation for 1976 image.
KESHNIKHAN AND TIRICH MIR GLACIERS:

The huge range of the Hindu Kush extends across the entire Afghanistan. It is nearly 1300 km long. The old traditional division introduced by British geographers and mountaineers in the 19th century divided the Hindu Kush into the eastern and western Hindu Kush.

The Keshnikhan glacier lies in the Wakhan corridor in the eastern Hindu Kush and is the most extensively studied region. A detailed (1:2500) map is available and is used as primary ground truth for the present study.

Tirich Mir lies on the southern ridge in Pakistani Chitral. The Tirich Mir peak (7,700 m) is the highest of the entire Hindu Kush and give rise to several streams of glaciers around it.

A 512 by 512 image was extracted for analysis from the LANDSAT tape of 10 August 1976. This study area encompassed the Keshnikhan Glacier, Tirich Mir Glacier as well as portions of Chintar Glacier in the southern half of the image. After experimentation with different band combination procedures, it was determined that the best color composite was obtained by combining bands 4, 5 and 7 (Plate 25). This color composite image was then subjected to various classifiers, including both unsupervised and supervised classifier. The ERDAS software at RSAL was used.

UNSUPERVISED (CLUSTER CLASSIFICATION):

The unsupervised classification algorithm adopted here is called Clustering. Fifteen clusters were selected. The classified map developed from this image shows many interesting features. These 15 classes were then analyzed using and algorithm called COLORMOD which gives the values in numbers for different colors assigned to different classes. Most of the time there are more than one different classes for the same feature on the ground which can than be combined to form a single information class on the basis of ground
evidence. The 15 different clusters are condensed into 8 information classes as shown in Table 15.

CLUSTERING STATISTICS FOR KESHNIKHAN, TIRICH GLACIERS:

<table>
<thead>
<tr>
<th>No.</th>
<th>Class Description</th>
<th>Clusters</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Snow covered area:</td>
<td>2 clusters</td>
<td>white</td>
</tr>
<tr>
<td>2</td>
<td>Ice</td>
<td>5 clusters</td>
<td>blue</td>
</tr>
<tr>
<td>3</td>
<td>Rock-types</td>
<td>1 cluster</td>
<td>light gray</td>
</tr>
<tr>
<td>4</td>
<td>Shaded areas</td>
<td>1 cluster</td>
<td>dark gray</td>
</tr>
<tr>
<td>5</td>
<td>Moraine</td>
<td>2 clusters</td>
<td>brown</td>
</tr>
<tr>
<td>6</td>
<td>Vegetation</td>
<td>1 cluster</td>
<td>red</td>
</tr>
<tr>
<td>7</td>
<td>Alluvial fan</td>
<td>2 clusters</td>
<td>light brown</td>
</tr>
<tr>
<td>8</td>
<td>mixed pixels</td>
<td>1 cluster</td>
<td>black</td>
</tr>
</tbody>
</table>

Table 15: Results of clustering on LANDSAT Keshnikhan, Tirich Mir image. The bands used are 4, 5 and 7.

The similar clusters were then given the same color and thus a classified map is obtained. Plate 26 shows the classified map generated by the computer. This photograph reveals a number of interesting features like snow and ice boundaries, lateral and medial moraine of the Tirich Mir glacier can be seen easily. The vegetation in the upper left hand corner is associated with the villages of Wark and Keshnikhan situated along the main Wakhan valley.
PLATE 25: A Color composite image for Keshnikhan, Tirich mir glaciers. Bands 4, 5 and 7 are used for picture plane 1, 2 and 3 respectively (Photograph from P.I.X.A.R).

PLATE 26: The results of performing an unsupervised (Cluster) classification of the Keshnikhan, Tirich glaciers LANDSAT image using bands 4, 5 and 7. 15 clusters were extracted and relabeled (Photograph from P.I.X.A.R).
SUPERVISED CLASSIFICATION:

Minimum Distance to Means Classifier:

This classifier was used to find out the differences, if any, there were when an image is classified both by unsupervised and supervised classification method. The training areas were carefully selected and care was taken in order to choose homogeneous sites. Interesting results have been observed. The list (Table 16) provides the total number of classes used, total number of pixels and their percentage. In this classification bands 4, 5 and 7 were chosen for classification.

The above mentioned chart summarizes the seven classes generated by the computer based on the original training sites. The Plate 27 shows the classified image map. The white color represents snow cover, mostly the snow in the accumulation zones. The light blue color represents the area of ice adjacent to the snow covered areas Most of it is clear from debris. The brown color indicates the moraine. The red color in the map is the vegetated area, mostly the villages along the main Wakhan river valley.

Maximum Likelihood Classifier:

Another supervised classifier was also used. As mentioned earlier this is a complicated method. It consumes a lot of computer memory and time, yet it is better because it quantitatively evaluates both the variance and correlation of the category's spectral response pattern when classifying an unknown pixel. Again exactly the same areas were selected for the training sites. The table (Table 17) shows the number of classes, number of pixels in each class and their percentage.

An interesting feature found here is the area which is originally the rocky terrain (ground truth), but this algorithm classifies it as a separate class because of its different spectral reflectance (Plate 28).
STATISTICS OF MINIMUM DISTANCE TO MEAN CLASSIFIER FOR KESHNIKHAN AND TIRICH GLACIER:

<table>
<thead>
<tr>
<th>Value</th>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.74%</td>
<td>Vegetation</td>
</tr>
<tr>
<td>2</td>
<td>9.00%</td>
<td>Snow</td>
</tr>
<tr>
<td>3</td>
<td>8.38%</td>
<td>Blue ice</td>
</tr>
<tr>
<td>4</td>
<td>6.93%</td>
<td>Moraine</td>
</tr>
<tr>
<td>5</td>
<td>15.49%</td>
<td>Barren rock</td>
</tr>
<tr>
<td>6</td>
<td>43.19%</td>
<td>Shadow area</td>
</tr>
<tr>
<td>7</td>
<td>12.70%</td>
<td>Loose rock</td>
</tr>
</tbody>
</table>

Table 16: Shows the total number of classes used, total number of pixels and their percentage. Bands 4, 5 and 7 are used.
STATISTICS OF MAXIMUM LIKELIHOOD CLASSIFIER FOR KESHNIKHAN, TIRICH GLACIERS:

<table>
<thead>
<tr>
<th>Value</th>
<th>Pixels</th>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00418</td>
<td>00.17%</td>
<td>Vegetation</td>
</tr>
<tr>
<td>2</td>
<td>20723</td>
<td>07.91%</td>
<td>Snow</td>
</tr>
<tr>
<td>3</td>
<td>13737</td>
<td>05.24%</td>
<td>Blue ice</td>
</tr>
<tr>
<td>4</td>
<td>31080</td>
<td>11.87%</td>
<td>Moraine</td>
</tr>
<tr>
<td>5</td>
<td>98794</td>
<td>37.69%</td>
<td>Barren rock</td>
</tr>
<tr>
<td>6</td>
<td>84712</td>
<td>32.32%</td>
<td>Shaded area</td>
</tr>
<tr>
<td>7</td>
<td>12673</td>
<td>04.83%</td>
<td>Mixed Pixels?</td>
</tr>
</tbody>
</table>

Table 17: Results of Maximum Likelihood Classifier. The total number of classes used, total number of pixels and their percentage are shown. Bands 4, 5 and 7 are used.
PLATE 27: The results of applying a Minimum Distance to Means classification algorithm to the training data Bands 4, 5 and 7 were used (Photograph from P.L.X.A.R).

PLATE 28: The results of applying a Maximum Likelihood classification algorithm to the training data summarized on page 29 (text). Bands 4, 5 and 7 are used. The Supervised classification categories are: white = snow, blue = ice, brown = moraine/rock debris on glacier, gray = rock-types and red = vegetation.
MIRSAimir Glacier:

Mirsamir (Lord of the Samir) peak is 5,809 m high and rises at the intersection of two ridges, the longer one of which trends west-south-west to east-north-east. Mirsamir is highest mountain in Samir Valley which is a branch of the Panjshir valley, north-east of Kabul. The general trend of the main mountain ridges is south-west to north-east. In each of the quadrants so formed, snow accumulation is sufficient to produce a glacier only on the north-facing slopes. The largest is known as East glacier and the one on the north-west is known as West Glacier (Gilbert, et. al. 1969).

The rock varies from slightly metamorphosed sediments found along the west flank of the Samir Valley to hard gneisses and schists which are dominant elsewhere. These rocks have well marked joint planes that weather into deep fissures and give rise to extensive block screes.

Similar classifiers discussed earlier in this chapter were applied on the Mirsamir Glacier:

UNSUPERVISED (CLUSTER) CLASSIFICATION:

Three (4, 5 and 7) out of 4 bands were selected (Plate 29). Fifteen clusters were selected. These clusters are listed in Table 18. The table provides 15 clusters in total. The cluster labeling is then performed by assigning a different color to every cluster set one by one, in order to group all similar information classes. In this manner it is possible to identify their location and spatial association with other clusters. This interactive visual analysis in conjunction with the information from map/ground truth is used to group the clusters into information classes. The computer generated map is shown in (Plate 30).
CLUSTERING STATISTICS FOR MIRSAMIR GLACIER:

<table>
<thead>
<tr>
<th>No.</th>
<th>Class description</th>
<th>Cluster</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Snow covered areas</td>
<td>2 Clusters</td>
<td>white</td>
</tr>
<tr>
<td>2.</td>
<td>Ice</td>
<td>5 Clusters</td>
<td>blue</td>
</tr>
<tr>
<td>3.</td>
<td>Vegetation</td>
<td>1 Cluster</td>
<td>red</td>
</tr>
<tr>
<td>4.</td>
<td>Shaded area</td>
<td>1 Cluster</td>
<td>dark gray</td>
</tr>
<tr>
<td>5.</td>
<td>Light colored rocks</td>
<td>3 Clusters</td>
<td>light gray</td>
</tr>
<tr>
<td></td>
<td>(sediments)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Dark colored rocks</td>
<td>2 Clusters</td>
<td>gray</td>
</tr>
<tr>
<td>7.</td>
<td>Mixed Pixels</td>
<td>1 Cluster</td>
<td>black</td>
</tr>
</tbody>
</table>

Table 18: Results of clustering on LANDSAT Mirsamir glacier image. Bands used are 4, 5 and 7.

The white color represents the snow covered area, the assumption being made that this is the accumulation zone. The red color represents the villages along the flank of the Samir Valley. Therefore six distinctive information classes are the result of combining fifteen different clusters together. The program used is called (RGB CLR) which assigns colors by values.

SUPERVISED CLASSIFICATION:

Maximum Likelihood Classifier:

The supervised classification called Maximum Likelihood is applied to the image. Seven different training sites were chosen. The program used for the selection of training sites is called TRAINING FIELD SELECTION. These training sites are shown in Table 19.

The resultant classified map is shown in photo 31 (appendix B). Upon comparison of the previous map which is produced by CLUSTER
PLATE 29: A color composite of Mirsamir Valley glaciers produced by placing band 4 in picture plane 1, band 5 in picture plane 2 and band 7 in picture plane 3.

PLATE 30: The results of performing an unsupervised (CLUSTER) classification of the Mirsamir Valley glaciers using bands 4, 5 and 7. Fifteen clusters were extracted and relabeled (P.I.X.A.R).
classifier, it can be seen that the vegetation is more clear in the main valley as well as in the other adjacent valleys. The alluvial fans are much brighter and distinct in this classified map.

**Minimum Distance to Means Classifier:**

This classifier is designed on a comparatively simple mathematical calculation. Again the similar areas were selected as Training sites in order to get maximum accuracy. Seven different training sites were selected (Table 20).

The classified map (Plate 32) shows all the major classes in detail. Snow covered area of the accumulation zone is classified neatly. The light blue color is the glacier ice mostly where the glacier is surging out into the deep valley.

**Classification Comparisons:**

From the analysis of these glaciers, i.e., by applying different classifiers on each of the band, it has been found out that many of the major features are classified in more or less similar manner. They maintain their outlining. However, the color of the smaller features or areas may change from one classification to another. The reason for this is the particular algorithm and the way it is written. The results of the Maximum Likelihood classified image are better because the mathematical analysis is more thorough than the other classifiers used in this study. However, it consumes much computer time and memory.

**CLASSIFICATION ACCURACY:**

Classification is a process of recognizing classes or groups whose members have certain characteristics in common. Ideally, the classes should be mutually exclusive and exhaustive; that is, there should be one and only one class to which an element is assigned, and all the elements in the domain of interest may be so assigned. In practical, however, these requirements are usually not achieved.
STATISTICS OF MAXIMUM LIKELIHOOD CLASSIFIER FOR MIRSAMIR GLACIER:

<table>
<thead>
<tr>
<th>Value</th>
<th>Pixels</th>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5028</td>
<td>01.92%</td>
<td>Snow covered area</td>
</tr>
<tr>
<td>2</td>
<td>3456</td>
<td>00.32%</td>
<td>Vegetation</td>
</tr>
<tr>
<td>3</td>
<td>11831</td>
<td>04.51%</td>
<td>Alluvial fans</td>
</tr>
<tr>
<td>4</td>
<td>53851</td>
<td>20.50%</td>
<td>ice fields</td>
</tr>
<tr>
<td>5</td>
<td>87029</td>
<td>33.20%</td>
<td>Light colored rocks</td>
</tr>
<tr>
<td>6</td>
<td>239</td>
<td>00.09%</td>
<td>Lake(water)</td>
</tr>
<tr>
<td>7</td>
<td>100710</td>
<td>38.42%</td>
<td>Shadowed area</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>262144</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 19: Results of Maximum Likelihood classifier. The table shows the total number of classes used, total number of pixels and their percentage. Bands 4, 5 and 7 are used.
STATISTICS OF MINIMUM DISTANCE TO MEANS CLASSIFIER
FOR MIRSAMIR GLACIER

<table>
<thead>
<tr>
<th>Value</th>
<th>Pixels</th>
<th>Percentage</th>
<th>Description</th>
<th>Color assigned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>008024</td>
<td>3.06%</td>
<td>Snow</td>
<td>White</td>
</tr>
<tr>
<td>2</td>
<td>001582</td>
<td>0.60%</td>
<td>Vegetation</td>
<td>Red</td>
</tr>
<tr>
<td>3</td>
<td>017584</td>
<td>6.69%</td>
<td>Alluvial fans</td>
<td>Ivory</td>
</tr>
<tr>
<td>4</td>
<td>012892</td>
<td>4.92%</td>
<td>Ice fields</td>
<td>Blue</td>
</tr>
<tr>
<td>5</td>
<td>120473</td>
<td>45.96%</td>
<td>Light colored rocks</td>
<td>Gray</td>
</tr>
<tr>
<td>6</td>
<td>000576</td>
<td>0.22%</td>
<td>Lake (water)</td>
<td>Blue</td>
</tr>
<tr>
<td>7</td>
<td>101049</td>
<td>38.55%</td>
<td>Shaded area</td>
<td>Black</td>
</tr>
</tbody>
</table>

Table 20: Results of Minimum Distance to Means classifier. The table shows the number of classes used, total number of pixels and their percentage. Bands 4, 5 and 7 are used.

The classes are based on properties possessed by the elements of a population, and classes are formed by grouping together those elements that are alike. An optimum classification will group elements together in classes which are separated from one another by discontinuities in the ranges of their observed properties. Classification can be either natural or artificial. A natural classification is an ideal classification (as describe above). On the other hand most classification schemes used for LANDSAT data are artificial. Analysts are concerned with classifying the LANDSAT data into features of specific interest. In terms of accuracy the supervised classification schemes are comparable as they correctly classified
PLATE 31: The results of applying a Maximum Likelihood classification algorithm to the training data. The categories of this classification are: red = vegetation, white = snow, blue = ice, light brown = alluvial fans, brown = rock-types and black = shaded areas.

PLATE 32: The results of applying a Minimum Distance to Means classification algorithm to the training sites. The categories of classification are: white = snow, light blue = ice/moraine, red = vegetation, dark blue = water lake, brown = rock-types, light brown/ off white = alluvial fans.
about 70-80 percent of the study area. The unsupervised algorithms correctly classify (generally about 50 to 60 percent of the study area). Identification of the other units, water and rock-types was not successful. There appear to be several reasons. It is possible that two different objects can reflect the same spectral signatures, or that the changes in the signatures are slight. In Wakhan area the alluvial outwash masking the bedrock, is significant factor in changing signature from one area to another. All these factors produce inhomogeneity in the spectral signatures of the training areas and reduce the overall accuracy of the classification. Being aware of these difficulties various methods (discussed above) were employed to improve the accuracy of the classified maps.

SUMMARY:

Chapter three presents details of the technical analysis of the selected glaciers. Two classification approaches, supervised and unsupervised were applied on the data. Emphasis is placed upon the classification of different glaciers and their comparison. Subtle similarities among different images of the same glaciated areas were also discussed and the computer generated maps were displayed.
CHAPTER FOUR

CONCLUSION:

In this study the ten year old LANDSAT MSS data were examined using the latest software technology. The difficulties such as the lack of ground data, the inaccessibility of the rugged terrain, the current political situation in Afghanistan and the lack of funds necessitate the use of the most sophisticated methods. In addition there were some hardware limitations.

The initial goals of the study were

(1) to analyze the glacial characteristics and features of these Hindu Kush glaciers,

(2) to classify the different glaciers and their comparison,

(3) to analyze the clean ice, the rock-mantled ice, firn, various moraine types, outwash plains and water, and

(4) to produce computer generated maps/pictures depicting the various glacial components.

The study also demonstrated the usefulness of the earlier LANDSAT MSS data. There were some difficulties in understanding the format of some of the magnetic tapes, specially when ELAS software was used. The reason for this is the various formats used by the EROS Data Center in early 70's. These tapes were deciphered using the UNIX operating system.

From the analysis and their results discussed in chapter 3, it is concluded that:

(1) The LANDSAT 1 images are still very useful and contain much information specially when dealing with larger features, i.e., features larger than 79 meters.
The methodology permits a reliable measurement of the desired area. Many different features like the zones of accumulation and ablation for snow on these glaciers can be easily detected from computer generated maps.

Various classification schemes were applied to these images and many different image maps were produced. The comparisons of the same area show similarities among many of the major and minor features in two different classified maps. This suggests that the LANDSAT data is self consistent and demonstrates that the LANDSAT data can still be used to extract new information.

Various methods to detect changes were used. Visual analysis of all the classified maps and of the overlapping images on a light table was performed. It is concluded that the larger snow field in the 1972 image is due to heavy snowfall for that year, but there is no change in the overall size of the glacier. The reason for this is that the seasonal response times for glaciers the size of Wakhan and Sakhi is of the order of hundreds of years.

It appears that some of the alluvial fans may contain fresh debris and they are classified as a separate class in the Wakhan 1976 image. Perhaps the changes in the alluvial fans for the Wakhan Valley are due to human activity, possibly the result of the agriculture development in the area. Another possibility is that the seasonal floods from the Patuk River and other adjacent streams, are significantly contributing debris to the these alluvial fans. The current study can be used to indicate such changes (larger than 79 meters).

The Difference Image obtained from subtracting one classified image from the other has provided significant results. It is found that the areas which show no differences (coded as black) are basically the snow covered areas in the Wakhan image. Also there is more snow in 1972 compared to 1976 because there was a greater amount of precipitation during the months of August and September.
in 1972. The difference image approach is very powerful and provides a map which reveals differences between images taken four years apart. Further work can be done to improve the quality and accuracy of the resultant maps. A great improvement in the difference maps would result if the pictures were taken at the same time of the year.

(7) In most cases, the supervised classification is more accurate compared to the unsupervised classification. The supervised classification is about 70-80 percent accurate. On the other hand the unsupervised classification is about 50 to 60 percent accurate.

Combining the results from both classifications yields good maps. It is shown that using the analytical tools of the 1980's on the LANDSAT can produce new and interesting information that can be useful in developing a historical perspective for the remote sensing of glacier zones in the remote areas of the world.
REFERENCES CITED


