# Collection and Management of Satellite Data for Hydrological Models


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A thesis submitted to University of London for the fulfillment of the requirement of a Ph.D. Degree


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May 1990.

بسم الله الرحمن الرحيم

أولم ير الذين كفروا أن السماوات والارض كانتا رتقا
ففتقناهما وجعلنا من الماء كل شيء حي أفلايؤمنون

صدق الله العظيم

A translation

Do not the Unbelievers see that the
heaven and the earth were joined
together (as one unit of creation),
before We clove them asunder?
We made from water every living thing.
Will they not then believe.

The Holy Qur'an.
Sura XXI (Anbiyaa)
The Prophets Verse 30

**For my mother**

and

**in memory of my father.**

# Abstract

This thesis reports on the development of a system for the acquisition of AVHRR data, the processing of this data into hydrological parameters then the organisation and management of this data.

The derivation of hydrological parameters through the use of remote sensing data has been well reported in the literature. The integration of the different derived estimates into a uniform and integrated set of data for use in Hydrological models have been lacking. The aim of the this project is the presentation of a system that solves and presents the problems faced in the development of such a system.

This thesis is concerned with the integration of a set of methods, each concerned with a hydrological parameter, into a compatible system for the remote sensing estimation of hydrological parameters. The information produced by remote sensing methods are populous in space. A system is needed to manage this significant body of generated data. A database was selected and used for this task.

The proposed system is a prototype system concerned primarily with an investigation of the different processes involved in the integration of the different methods into a compatible package. The system evolved, with the introduction of the database in the system, to become an embryonic Hydrology and Remote Sensing Information System acronymed as HyRSIS.

Programs used in this project comprise of two kinds, those written

'in house' and 'acquired' from different researchers. Compatibility of programs and data files was solved and then used as building blocks of HyRSIS.

A main program was used as driver for the interaction with the different programs. A design criterion was established for future development of such a system. The system provided solutions for two the problems of the big size of the data and the non suitability of remote sensing data for hydrological modelling. The use of the database provided the housing and the managing tool for the bulk of the data. A protocol for the retrieval of data from the database was established.

For the first time the hydrological model used, in this project and probably for any hydrological model, was run using several parameters derived from remote sensing sources and supplemented by conventional data. The same model was also run using conventional data, as a prime source, and supplemented with remote sensing data.

# Acknowledgment

The realisation of this thesis is endowed to the contribution of many. The author wishes to thank and offer gratitude to all those who helped and made it happen.

Dr I J Dowman for his continuous guidance throughout the research, concern for my acquisition and understanding the knowledge in this field of science, and critical assessment of this thesis.

Dr E. C. Barrett, Dr. A. R. Harrison, Dr. J. DeSousa, Mr. R. Lucas and Mr. T. Richards of the Remote Sensing Unit in the Department of Geography in Bristol University, For allowing me to use their methods and software, the PERMIT technique for precipitation estimates and the multispectral technique for snow mapping, and for general discussion and interest.

Mr. A. Rango for allowing me to use SRM in my work and for sending me a copy of it.

Dr. Seguin for his correspondence allowing me to use his method and for sending me a related paper.

Yorkshire Water Authority for supplying the basin data free of charge.

Mr Blackie and Mr. Blyth, from the Institute of Hydrology, for discussions on the selection of the Aire basin.

Mr. J. Pearson for general help on the Vax system.

Mr. P. Schooling for advice on VAX FORTRAN and general help with the facilities of the Department of Geography. Dr. A. Ried for help on the $I^2S$ system.

Mr. O Akif of the Dept. of Photogrammetry and Surveying and Dr. D. G. Davis of Management Information Study Unit for their help with the ORACLE database system.

Mr. P. Eales and Mr. O. Akif for help on the Lites2 software.

Mr A. Hamid, Mr. A. Newton, and Dr. M. J. Zemerly for helping in printing the images for this thesis.

I am deeply indebted to the HARIRI Foundation for the financial support endowed for three and a half years for the completion of this study. This work would not have been possible without this support.

Elefteris, Giotis, Julia, Sophie, Igor, Valerie, Veronique, Nada, Amal, Inayah, Najib, and Sahar, friends for whom without their interesting and joyful company life in cold London would have been very dull. Also all my friends who are scattered around the world for their understanding of my neglect in writing to them because of my occupation with this work.

Last but not least, my family, starting with my lovely wife Ashraf who read and commented on my thesis and for her general support and encouragement, Betty for allowing me to marry her daughter and being kind to me. Ending with my family in Lebanon and all over the world who supported me and whose confidence in me never waivered, especially my Mother who endured my neglect by staying away for so long. This work would not have been if it was not for her.

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# List of Abbreviations

AgRISTARS Agriculture and Resource Inventory Surveys Through Aerospace Remote Sensing.

ANSI American National Standards Institute.

AVHRR Advanced Very High Resolution Radiometer.

BNSC British National Space Centre.

BU Bristol University.

CCT Computer Compatible Tape.

DBA DataBase Administrator.

DBMS DataBase Management Systems.

DCL Data Control Language statements are used by the DBA

DCL Digital Command Language.

DDL Data Definition Language

DEM Digital Elevation Model.

DML Data Manipulation Language

DMSP Defence Meteorological Satellite Program.

ERL Environmental Research Laboratory.

ERTS-1 Earth Resources Technology Satellite.

ESA European Space Agency project.

GIST Geographic Information System Toolkit

GMS Geostationary Meteorological Satellite.

GOES Global Operational Environmental Satellite.

HRV High-Resolution-Visible.

HyRSIS Hydrology and Remote Sensing Information System.

$I^2S$ International Imaging System.

IFF Internal Feature Format

IFFA Interactive Flash Flood Analyser.

IFOV Instantaneous Field Of View.

mOD metre Over Datum.

| | |
|---|---|
| MRSE | Spacelab Microwave Remote-Sensing Experiment. |
| MSB | Most Significant Bytes. |
| MSS | Multi Spectral Scanner. |
| NOAA | National Oceanic and Atmospheric Administration. |
| ODL | Oracle Data Loader |
| PERMIT | Polar-orbiter Effective Rainfall Monitoring Integrative Technique. |
| PRT | Platinum Resistance Thermometers. |
| RBV | Return Beam Vidicon. |
| SAR | Synthetic Aperture Radar. |
| SIR | Shuttle Imaging Radar. |
| SLAR | Side Looking Airborne Radar. |
| SMMR | Scanning Multi-channel |
| SMS | Synchronous Meteorological Satellite. |
| SPOT | Systeme pour l'Observation de la Terre. |
| SQL | Structured Query Language. |
| SRM | Snow Runoff Model. |
| TAE | Transportable Application Executive. |
| Tiros-N | Prototype series numbered NOAA 6 *et seq* |
| TM | Thematic Mapper. |
| UCL | University College London. |
| VISSR | Visible and Infrared Spin-Scan Radiometer. |
| WMO | World Meteorological Office. |

# Chapter One

## Introduction.

### 1.1 Introduction.

With the rare exception of some amoeba sized organisms, water is the basis of existence for all familiar forms of life on this planet. Life, according to modern science, has originated in water. Water has assumed special importance in the life of man and beast. The early settlements of man were around water holes and springs. The provision of a constant supply of fresh water was a marker sign of most civilisations. Early monuments of human effort to harness and manage their water resources are seen in the remains of earth dams like El-Kaffara, in Egypt, around 3000 B.C., and the Márib dam around 1000 to 700? B.C., in the Yemen. [Biswas A. K. 1970]. Their attempts continued throughout the ages. Evidence of human endeavours to efficiently employ water resources are scattered throughout the world. This is illustrated by the remains of public baths of Roman cities or in the complex irrigation systems of Andalucia (Moorish Spain).

Moving on to the twentieth century, man has endeavoured after the harnessing and exploitation of the Earth's resources in general, and water in particular. Water is a basic ingredient of many industrial processes. Today, water dams provide a significant proportion of the global electricity supply. It is imperative to mention the importance of water for the production of food. Especially with the constant reminder of the drastic consequences of water shortages, seen in the African Horn in this decade, and the African Sahel in the Seventies.

## 1.2 Hydrology and remote sensing.

The 'science' concerned with the study of the water cycle is called Hydrology. The historical origins of this science started with the Nilometer (3000 B.C.) gauge, for measuring the Nile flood level, and the first set of rain gauges in India (300 B.C.), both were introduced for the purposes of taxation. The foundation of the modern science of hydrology were laid down in the early thirties of this century.

Hydrologists always relied on gauges to provide them with information to assess the qualitative existence of water in the environment. However, a major change to the science of hydrology and the earth resources science was introduced with the advent of the space age.

The introduction of earth imaging satellites presented an entirely new way of observing the physical status of both clouds and earth surface at discrete points in time. The methods utilising sensors to collect data about a distance object are called remote sensing.

Remote sensing provided a new window for the hydrologists to gauge the natural phenomena. Subsequently, many methods were introduced for the study and estimation of the different hydrological parameters from remote sensing platforms.

As with every branch of science, the continued research into an ever increasing degree of accuracy, and the quest after the foundation of new methods for measuring the different parameters have resulted in a plethora of methods concerned with 'isolated' aspects of the hydrological cycle. However, the hydrological phenomena are concerned with a collection of the different parameters interacting together.

## 1.3 Research definition.

This thesis is concerned with the integration of a set of methods, each concerned with a parameter, into a compatible system for the remote sensing estimation of hydrological parameters. The information produced by remote sensing methods are populous in space. A system is needed to manage this significant body of generated data. A database was selected and used for this task. This process is discussed and dealt with in this thesis.

The proposed system was envisaged as a prototype system concerned primarily with an investigation of the different processes involved in the integration of the different methods into a compatible package. The system evolved, with the introduction of the database in the system, to become an embryonic Hydrology and Remote Sensing Information System acronymed as HyRSIS.

At the onset of this research, the issue of accuracy estimates of the different methods was considered of little importance, with the primary concern being the mechanism and the integration of the different building blocks of the system. However, the data presented in this Thesis demonstrates that good results were achieved on that front as well.

## 1.4 Aims and accomplishments of the project .

The incorporation of remote sensing estimates of hydrological parameters has always been done for individual parameters. An integrated study of the interaction of the different parameters, remotely sensed, with each other and with hydrological models was lacking. The failure to use remote sensing derived data in an integrated way for the purpose of advancing our understanding of the hydrological phenomenon is a twofold problem. The first being the fact that remote sensing sources provide voluminous data which presents a handling problem. The second being that traditionally the design of hydrological models has been based on conventional data sources and are not adequate to make full use of remote sensing data sources. The present research is concerned with providing a prototype study on how to approach an integrative study like this, and deal with the problems emanating from this approach. In order to limit the work load to a manageable size this project has concentrated its effort on the integration of the following parameters: precipitation, temperature, snow and evaporation. In order to achieve this, a system dealing with the processing of remote sensing data from raw imagery to the delivery to a hydrological model was devised. The mechanism, the interaction, features, and characteristics of the different methods were defined, solved and integrated in one system. This was done in the following manner:

1- All programs, both imported and written in house, were upgraded to fit the use of this project. Each were then used as building blocks of the HyRSIS.

2- The input files, of image data, were unified for the various methods thus providing compatibility of input data.

3- The output image data transformed to numeric data files and then loaded to a database in a customised fashion.

4- A main program was used as driver for the interaction with the different programs. This program organises the interaction of the user with the different methods. Each set of programs, dealing with a particular parameter or function, are housed together according to their logical usage progression.

5- A design criterion was established for future development of such a system.

6- The system provided solutions for two of the problems mentioned above, the big size of the data and the non-suitability of remote sensing data for hydrological modelling. The use of the database provided the housing and the managing tool for the bulk of the data. A criterion was established for the retrieval of data in a format compatible with the hydrological model. This could be done for any hydrological model desired, until the time of remote sensing based hydrological models comes.

7- For the first time, the hydrological model used in this project and probably for any hydrological model, was run using several parameters derived from remote sensing sources and supplemented by conventional data. The same model was also run using conventional data, as a prime source, and supplemented with remote sensing data. The results of the two cases were compared.

8- One source of remote sensing information was used. This source has a relatively low resolution reducing the amount of details. However, the resultant data is still bulky. It is felt that before rushing to use satellite platforms providing an ever increasing amount of detail, the scientific and commercial community should learn how to manage and efficiently use data originating from low resolution sensors.

## 1.5 Contents of thesis.

This thesis is composed of nine chapters, starting with an introduction chapter. This is followed with Chapter Two which starts with a survey of different remote sensing platforms. Also included in this chapter is a comprehensive literature review of the subject. It also provides an insight into the different methods used for the estimation of the different parameters.

Chapter Three proposes the structure of the system and the aims of this thesis research together with the reasons for the selection of the sensor used in this project. Furthermore the selection of a method for every parameter for the estimation of the different parameters is discussed. In addition, a detailed description of the sensor and the theories behind the different selected methods are presented.

Chapter four examines in depth the details of the different methods for the processing the remote sensing image information into hydrological estimates. An issue of this chapter is the geometric correction of the satellite image. A section is provided for explaining the different processes executed to extract the pixel data of the study area selected for the project.

The description of the study case and the study area is incorporated in Chapter Five. The circumstances and details of the stages of defining the place and the duration of the case study are also presented in this chapter.

Chapter Six is the Database chapter. It presents the historical evolution and background of different types of databases. The criterions for selecting a database are presented. The use of the database in this project is presented coupled with a description of the operation use of the used database.

Chapter Seven describes the system HyRSIS. The different modules along with the different operating levels along side the available features of the system are discussed.

Chapter Eight describes the results achieved in the processing of the different modules. It discusses and examines the accuracy of these results and compares them with conventional data.

Chapter Nine comprises of the conclusion and discusses operational use of the system. Recommendations for the future expansion and development of HyRSIS are presented.

### 1.6 Presentation of the different subjects of the thesis.

Two methods were used for the presentation of the different subjects in this thesis. The first method is issue oriented. Briefly, this means that different subjects are discussed in a chapter with the discussion concentrating on one aspect of the different subject, for example, such as the theory behind the subject. The second method is the treating of all aspects of an individual subject in one chapter. The discussion of this subject will be covered in relation to its use in this thesis.

The first method was used for Chapters Two, Three and Four, while Chapter Five is devoted to describe the theory and the implementation of database.

# Chapter Two

## Remote Sensing of Water Resources.

### 2.1 Introduction.

Hydrology is the science of the water cycle. Hydrological modelling is the branch of this science that deals with the simulation of the behaviour of this cycle. Water appears in nature in three forms liquid, solid and gas. Hence, for modelling purposes it is necessary to identify and quantify the existence of water in its three stages as precipitation, snow, and evaporation. Temperature is the influencing factor that initiates the changes in the physical state of water. Accordingly its registration is of immediate concern to hydrologists.

This project is concerned with the establishment and the application of an integrated study of remotely sensed hydrological parameters. This chapter will introduce the idea of remote sensing of water parameters. The different sensors in orbit around the earth, collecting images though varied spectral responses, are reviewed. The data and information yielded by satellites are used to estimate hydrological parameters such as precipitation, evaporation, snow. The different methods for estimating these parameters, precipitation, snow fall and evaporation. from satellite data are reviewed. The details of the project will be presented in the following chapter.

A large number of papers and reports exist reported in the literature, concerning the remote sensing of the different hydrological parameters. Work on these projects is done by university researchers and organisations that have interests in the field of water resources. Some of these projects are reported here. The criteria for selecting the methods reviewed reviewed here are

1 - They should present as wide an idea as possible on the subject without going through all the available studies.

2 - They should present the methods that are of relevance and interest to the line of work in this thesis.

A method is selected, for each of the parameters, in order to use as a generator of estimates for a remote sensing integrated approach towards hydrological studies.

## 2.2 Conventional ways of collecting data for Hydrological Models.

The science of hydrology has relied on gauges for collecting data such as the amount and intensity of precipitation, evaporation estimates, snow characteristics and extent, and temperature. The type of gauges differ according to the parameter being measured. The intensity of gauge distribution varies throughout the world from one country to another and even from one region to another in a country [Barrett 1977].

Registering data using gauges is not without difficulties. The physical conditions surrounding the gauge influence the efficiency of the registration. These conditions vary from wind direction and the orientation of the gauge to the place of its installation. It has been shown that up to 20% differences might occur between gauges separated by 20 feet [Viessman, 1977]. Thus the distribution of gauges produces a direct effect on the collected data and on the representation of the gauged parameter.

In an ideal world, the distribution of gauges would be uniform all over the planet Earth, but this is not the case. Vast amounts of the Earth's surface are not covered with gauges. The areas that have gauges lack enough numbers to go around except for a few areas that are adequately covered. Add to this the growing evidence that the population of these gauges is in decline [Barrett 1977]. This can lead to poor coverage and misrepresentation of the hydrological parameters being gauged. In order to overcome this problem and get an areal representation of water, hydrologists use statistical methods to interpolate and generate the distribution of parameters between gauges. The availability of a technique that reinforces and helps establish a better description of this distribution is welcome.

## 2.3 The use of Remote Sensing for the determination of Hydrological Parameters.

Conventionally, gauges provide information of the hydrological parameters being quantified by merit of being '*in situ* sensors'. In contrast to this satellites are able of providing estimates of these parameters from remote distances.

Qualitative measurement of water from such huge distances might seem as an awkward idea, but water stands out clearly in remotely sensed images. The plethora of sensors orbiting the earth provide a variety of platforms that cover a wide range of methods of assessing the existence of water. The multiple ways of remotely sensing water will be expanded on later in this chapter when talking about individual parameters. Remote sensing was introduced to this field of science because of the distinct advantages of remote sensing over *in situ* sensors. Those being:

- Remote sensing platforms provide data with high density in space (i.e. continuous areal coverage) instead of point measurements .

- Remote sensing data can be obtained for areas where conventional measurements do not exist (extensive areas of the earth's surface).

Schultz [1986] stated that remote sensing data can be most helpful for the design and operation of hydrological models, especially if combined with ground truth.

The drawbacks of remote sensing are mainly to do with the fact that this technology is fairly complicated, uses high technology and generally is not available to the under developed countries of the world, those countries who are in need and under pressure to identify and manage their water resources; precisely those who could most benefit form this technology. This situation is compounded, on two levels, with the under-investment in in-situ sensors and the general absence of networks of gauges. These are needed to establish ground truth with reference to satellite parameter estimates as well as for their own use as measuring devices for the existence of the different hydrological parameters.

Remote sensing provides an extra tool for the hydrologist in the study of the water cycle. In-situ sensors provide ground truth for the investigator using remotely sensed images. Gauge data are integrated in many methods developed for the study of these images. Therefore, it should be clear that, for the foreseeable future, satellite platforms will not replace gauges but are here to complement and expand our knowledge of the world we live in.

| Type of satellite. | Range in the electromagnetic spectrum. | |
|---|---|---|
| Multispectral | Visible | 0.36 - 0.7 μm |
| | InfraRed | 0.7μm-1mm($10^3$μm) |
| | Near InfraRed | 0.7 - 1.3 μm |
| | Mid Infrared | 1.3 - 3.0μm |
| | Far InfraRed | 3.0 - 1000 μm |
| Microwave | 1 mm($10^3$μm) - 1 m ($10^6$ μm) | |

Table 2.1 Regions of Electromagnetic Spectrum covered by Imaging Satellites

## 2.4 Review of Remote Sensing Sensors.

### 2.4.1 Classification of Imaging Satellite.

#### 2.4.1.1 Introduction.

Remote sensing sensors are varied and numerous. Each platform provides a different perspective for looking at our globe. Different sensors are sensitive in different regions of the electromagnetic spectrum. Thus providing different windows from which one can look at the earth. The classification of the different types of satellites depend on the criteria of classification. A way of classifying satellites is according to the range of electromagnetic bands they utilise. Satellites covering the Visible and InfraRed region and in more than one channel are called multispectral sensors. Satellites covering the microwave region are simply called Microwave sensors. Refer to Table 2.1 for wavelength values of the different regions. A further classification could be achieved for each type of sensors which will be discussed later on in this section.

#### 2.4.1.2 Multispectral sensors.

Multispectral sensors can be classified into two kinds of sensors. Earth observation and Meteorological. This classification is basically dependent on the initial intended task of the satellite at launch time. The fundamental differentiating features between the two types is the spatial and temporal resolution of the sensor. The spatial resolution of the earth resources type is at a maximum of 120 metres while meteorological satellites spatial resolution usually start at 1.1 kilometre. The return cycle of earth resources is usually in the order of several days while meteorological satellites provide repeat image coverage of the earth in hours, twice a day, or even minutes, every 30 minutes.

#### 2.4.1.3 Microwave Sensors.

The sensors can also be classified into two kinds: active and passive microwave. Passive microwave sensors collect the emitted and reflected electromagnetic waves of different bodies. The active microwave sensors have an on board source of electromagnetic waves. These waves are emitted towards the target body and the reflected waves are collected by the sensor.

Table 2.2 show a selection of imaging satellites and their corresponding classification. A selection of sensors, Landsat, SPOT, NOAA-AVHRR, GOES, SMMR and SAR, will be reviewed in this section.

| Imaging Satellites. | | | |
|---|---|---|---|
| Multispectral | | Microwave | |
| Earth Resources | Meteorological | Passive | Active |
| Landsat1-5 | Tiros/N Series | Nimbus 7/SMMR | Seasat/SAR |
| SPOT-1,-2 | NOAA/AVHRR | | ERS-1 |
| | GOES | | Nimbus/7 (SAR) |
| | Meteosat | | |
| | DMSP | | |

Table 2.2 Classification of a selection of satellites.

### 2.4.2 Earth Resources Satellites.

#### 2.4.2.1 Introduction.

Earth resources satellites are, as their name imply, intended for the study of the earth's surface and any other surface indications of the subsurface strata that can be deduced through careful study. These satellites have high spatial resolution but at the same time low temporal resolution.

#### 2.4.2.2 Landsat.

The first Earth resources sensor to be introduced was Landsat. It initial name was the Earth Resources Technology Satellite ERTS-1. The name was changed from ERTS to Landsat before the launch of the ERTS-2 platform (to distinguish it from the planned Seasat oceanographic satellite) [Lillesand and Kiefer 1987]. ERTS-1 retroactively named Landsat-1 was first launched in the year

1972. Landsat is the name of a series of satellites that has been launched into space since that time which are providing continuous coverage of the earth. Five satellites have been launched up till now, Landsat-1, -2, -3, -4, and -5. A further two are intended for future launch Landsat-6 and -7.

Landsat-1, -2, and -3 were similar. Landsat-1 and -2 were identical. Each of these satellites carried on board two instruments. Namely the Return Beam Vidicon (RBV) and the Multi Spectral Scanner (MSS).

The RBV registers a scene instantaneously, in camera fashion. This fact combined with a reseau grid in the image plane facilitate meticulous geometric correction. RBV had three spectral channels green, red, and near infrared.

MSS scan each line from west to east while the satellite is moving along its orbit. This combination results in a progression of scan lines. An image is a composite of these scan lines. Each MSS scene is framed into 185 X 185 km. MSS had four channels green, red, and two InfraRed channels.

RBV became a secondary source of information in comparison with the MSS system. It was discarded from use in Landsat-4 and -5 despite its high photogrammetric qualities. The replacement system was the Thematic Mapper (TM). MSS was continued on these two satellites for the purpose of continuity.

TM, essentially, is a blown up MSS system. It is an improvement on MSS on three levels, spectral, radiometers and geometric. It has seven bands, increased sensitivity in each channel and design changes which were incorporated to improve geodetic positioning.

| Sensor | Mission | Sensitivity (μm) | Nominal Spectral location | Resolution |
|---|---|---|---|---|
| RBV | 1 2 | 0.475-0.575 | Green | 80 |
| | | 0.580-0.680 | Red | 80 |
| | | 0.690-0.830 | Near-IR | 80 |
| | 3 | 0.505-0.750 | Green to Near-IR | 30 |
| MSS | 1-5 | 0.5-0.6 | Green | 79/82[a] |
| | | 0.6-0.7 | Red | 79/82 |
| | | 0.7-0.8 | Near-IR | 79/82 |
| | | 0.8-1.1 | Near-IR | 79/82 |
| | 3 | 10.4-12.6[b] | Thermal - IR | 240 |
| TM | 4-5 | 0.45-0.52 | Blue | 30 |
| | | 0.52-0.6 | Green | 30 |
| | | 0.63-0.69 | Red | 30 |
| | | 0.76-0.90 | Near-IR | 30 |
| | | 1.55-1.75 | Mid-IR | 30 |
| | | 10.4-12.5 | Thermal-IR | 120 |
| | | 2.08-2.35 | Mid-IR | 30 |

[a] 79 m Landsat-1 to-3 and 82 m for Landsat-4 and -5.
[b] Failed shortly after launch (band 8 of Landsat-3)

Table 2.3 Sensor, sensitivity and resolution, Used on Landsat-1 to -5 Missions.

Source [Lillesand T.M. and Kiefer R.W. 1987]

The number of spectral bands was raised from four to seven by the introduction of three new bands, one in the visible (blue), and two in the thermal infrared. Table 2.3 lists the spectral bands and resolution of each band for all the sensors launched in the Landsat series. The experience gained from the MSS system allowed the fine tuning of the different bands to improve the spectral differentiation of earth surface features.

The radiometric response is registered in a range between 0 and 256, in comparison with 0 to 64 used by MSS. Thus, smaller changes can be observed also allowing for greater sensitivity for the relationships between bands.

TM resolution of 30 metres (except the thermal infrared band 120 m) coupled with some design improvement allowing for better geodetic positioning presented an improvement on the MSS system.

### 2.4.2.3 SPOT.

SPOT, *Systeme pour l'Observation de la Terre*, is a new earth observation system that was introduced in 1986 by France in corroboration with Sweden and Belgium. The payload of SPOT consists of two identical imaging systems *High-Resolution-Visible* (HRV). Each HRV instrument can operate in one of two modes panchromatic (black and white, 10 m resolution) and multispectral (three bands green, red, and near InfraRed, 20 m resolution).

SPOT has also the capability of side viewing providing

1- a relatively low repeat visit time.

The ability to side viewing provide the chance to image a particular scene for successive days. The satellite can image the same area as it passes the same latitude.

2- stereoscopic imaging of scenes

Images collected from different tracks, i.e. on different, for the same area compose a stereoscopic pair. These pairs could be used to build a stereo model from which height information are then extracted.

SPOT is also intended to provide continuity of coverage. SPOT-2 was launched on 22nd of January 1990 it is identical to SPOT-1. SPOT-3 and -4 are proposed to incorporate some design changes. Some of these changes are the introduction of an extra channel in the near infrared and the replacement of one of the HRV instruments by a five band instrument with ground resolution of 1 km to 4 km.

### 2.3.2.4. Applications of Earth Observation Satellites.

The usage of these satellites spans a wide spectrum of applications. These application has been mainly concentrated on vegetation changes because of the vegetation specific spectral bands. Mapping applications has also been extensive especially with the introduction of SPOT. It's capability of side viewing facilitating stereographic mapping provides a breakthrough and the beginning of a new era for satellite mapping.

The spectral capabilities of MSS, TM, and SPOT, has resulted in numerous land and sea applications. These application are categorised and summarised briefly in the following:

- The marine environment: physical chemical, biological, geological Oceanography. Coastal pollution and water quality management.

- Water resources: Surface water, soil moisture and evapotranspiration, snow and ice mapping lakes and rivers studies.

- Land use: urban and suburban land use, land mapping, change of land use, energy conservation monitoring.

- Geological application: mapping, economic geology, engineering geology, hazards and land morphology.

- Engineering applications: Terrain analysis, site investigation, water resources engineering, landslides hazards and transport studies.

_ Agriculture: resource mapping, production management, crop classification.

- Forest monitoring: inventory, damage assessment, and forest management.

The wide use of Earth Resources Satellites can be realised from the above list of applications. The improved resolutions of these satellites bring the chance of observing the earth in great detail. This could be of dual, positive or negative, effect for the usage of these imagery. The positive effect is the greater detail available from these images resulting in a better understanding of the physical conditions and for monitoring changes in the environment. On the other hand too much detail could result in the inundation of the user with information that is not really needed resulting in a possible camouflaging or obscuring of the desired features. For example geological faults are more recognisable on the lower resolution of MSS images than on those of TM.

### 2.4.3 Meteorological satellites.

#### 2.4.3.1 Introduction.

Meteorological satellites were initially introduced for the monitoring of weather systems. They are usually characterised with coarse spatial resolution especially if compared with the land observation systems. On the other hand these systems provide global coverage on regular and frequent basis. Many countries have various types of these satellites. Table 2.4 includes a survey of the important atmospheric satellites.

Meteorological satellites are divided into two kinds, polar orbiter and geostationary satellites. As indicated by their names these satellites are classified according to the method they orbit Earth.

The polar obiter kind provide coverage of the earths by orbiting the earth in a near polar orbit passing over the north pole and the south pole in each orbit. The geostationary satellites orbit the earth around the equator with a repeat cycle equalling that of earth thus remaining in a stationary relative position to a point on the earth's surface. A representative of the two types will be briefly discussed, NOAA and GOES. Although the two satellites carry on board various meteorological sensors the ones reviewed are those that have been extensively used for land applications, the AVHRR instrument of the NOAA satellite and VISSR of GOES.

| Family name | Country of origin | Number launched | Approx. period covered | Special remarks |
|---|---|---|---|---|
| Vangaurd | USA | 1* | Feb-Mar 1959 | Early experimental satellites with primitive Visible and infrared |
| Explorer | USA | 2* | Aug 1959-Aug 1961 | imaging system |
| Television and Infrared Observation Satellite Tiros | USA | 10 | Apr 1960-Jul 1966 | First purpose-built weather satellites |
| Cosmos | USSR | 22* | Apr-1963-Dec 1970 | Some Weather satellites in this large cosmopolitan Russian satellite series |
| Nimbus | USA | 7 | Aug 1964-present | Principal American R and D Weather satellite |
| Environmental Survey Satellite (Essa) | USA | 9 | Feb 1966-Jan 1972 | First American operational weather satellite |
| Molnia | USSR | 8 | Apr 1966-May 1971 | Dual purpose communication/ weather observation satellite |
| Application Technology satellite(ATS) | USA | 4* | Dec 1966-June 1981 | First meteorological Geostationary satellite to test SMS concepts |
| Meteor | USSR | 20 | Mar 1969-present | Current Russian operational weather satellite series |
| Improved Tiros observational satellite(Itos) | USA | 1 | Jan 1970-June 1971 | NOAA prototype |
| National Oceanic and Atmospheric Administration Satellite(NOAA) | USA | 5 | Dec 1970-Dec 1979 | Second generation American operational weather satellite series |
| Defence Meteorological Satellite program(DMSP) | USA | 10 | Feb 1973-present | Military weather satellites |
| Synchronous Meteorological Satellite(SMS) | USA | 2 | May 1974-Dec 1975 | Testbeds for operational geostationary weather satellite systems |
| Global Operational Environmental Satellite(GOES) | USA | 4 | Oct 1975-present | First operational geostationary weather satellites |
| Geostationary Meteorological Satellite(GMS) | Japan | 2 | July 1977-present | First geostationary weather satellite cover of E. Asia/Pacific |
| Meteosat | Western Europe (ESA) | 2 | Nov 1977-Nov 1979 | First Geostationary weather satellites covering Africa/Europe |
| Tiros-N (Prototype series numbered NOAA 6 *et seq* | USA | 4 | May 1979-present | |

*denotes families which have included satellites designed for non-meteorological purpose also; numbers of weather satellites only listed here

Table 2.4 A summary of important atmospheric satellite families, 1959-1981 [Source Barrett and Curtis 1982].

### 2.4.3.2 National Oceanic and Atmospheric Administration (NOAA) satellites.

The first of the NOAA series was launched in December 1970, of relevance to our study is the TIROS/N series, first launched 1979, numbered NOAA-6 *et seq* that housed the Advanced Very High Resolution Radiometer AVHRR instrument. Table 2.5 contains the characteristics of the NOAA-6 through to NOAA-12.

| Parameter | NOAA-6 -8 and -10 | NOAA -7 -9 |
|---|---|---|
| Launch | 6/27/79 3/28/83 9/17/86 | 6/23/81 12/12/84 |
| Altitude(km) | 833 | 833 |
| Period of orbit(min) | 102 | 102 |
| Orbit inclination | $98.9^0$ | $98.9^0$ |
| Orbits per day | 14.1 | 14.1 |
| Distance between orbits | $25.5^0$ | $25.5^0$ |
| Day-to day orbit shift [a] | $5.5^0$E | $3.0^0$E |
| Orbit repeat period(days)[b] | 4-5 | 8-9 |
| Scan angle from nadir | $\pm 55.4^0$ | $\pm 55.4^0$ |
| Optical field of view (mr) | 1.3 | 1.3 |
| IFOV at nadir(km) | 1.1 | 1.1 |
| IFOV off-nadir maximum(km) | | |
| Along track | 2.4 | 2.4 |
| Across track | 6.9 | 6.9 |
| Swath width | 2400 km | 2400 km |
| Coverage | Every 12 hr | Every 12 hr |
| Northbound equatorial crossing time (pm) | 7:30 | 2:30 |
| Southbound equatorial crossing time (am) | 7:30 | 2:30 |
| AVHRR spectral Channels (μm) | | |
| 1 | 0.58-0.68 | 0.58-0.68 |
| 2 | 0.72-1.10 | 0.72-1.10 |
| 3 | 3.55-3.93 | 3.55-3.93 |
| 4 | 10.5-11.50 | 10.3-11.30 |
| 5 | Channel 4 repeat | 11.5-12.50 |

[a] Satellite differences due to differing orbital alignment.
[b] Caused by orbits per day not being integer.

Table 2.5 Characteristics of NOAA-6 through NOAA-10.[Source Lillesand & Kiefer 1987]

This instrument has five spectral channels covering the visible in band one, the near infrared in band two and bands three four and five in the thermal infrared. AVHRR provides global coverage with its 2400 km swath width. This is facilitated by the wide scanning angle of AVHRR 55.4$^{o}$. The ground resolution is 1.1 km at nadir. This resolution deteriorates as the off-nadir viewing angle increases. This is compounded with the effect of the earth's curvature. The maximum values deteriorated pixel size are 2.4 km along track and 6.9 across tack. See Section 3.3 for more details on AVHRR.

Despite the fact that AVHRR has been used primarily for atmospheric studies it has been used for numerous applications. A quick browse through the applications of AVHRR leads to the following list

- Snow Studies,
- Flood Monitoring,
- Soil Moisture Analysis,
- Monitoring Vegetation Progress,
- Fire Fuels Monitoring,
- Fire detection,
- Urbanisation effects,
- Dust and Sand Storm Monitoring ,
- Geological Applications.

[Source: Hydrologic and Land Science Applications of NOAA Polar-Orbiting Satellite Data.]

#### 2.4.3.3 GOES Satellites.

These satellites are part of the civilian meteorological satellite programs in the U.S.A. NOAA and NASA cooperated on this system, the Synchronous Meteorological Satellites (SMS), also known as the Geostationary Operational Environmental Satellite GOES. This type of satellite is placed over the equator with an orbit period that equals the earth's rotation period. Thus staying in a fixed position relative to a location on the earth's surface, hence the name geostationary. The programme provide a network of satellites spaced at $70^0$ longitude around the globe. GOES-VISSR incorporate two Channels one visible band between 0.55 and 0.75 μm and another band in thermal InfraRed between 10.25 and 12.6 μm. VISSR stand for Visible and Infrared Spin-Scan Radiometer. The visible band operates during day light while the Thermal InfraRed is continuous. GOES scans an image of the whole disk of the globe every half an hour. Resolution at nadir is 1.1 km for visible and 8 km for InfraRed bands. The distortion of GOES images increases as we move towards the poles of Earth. Since the satellite is in a geostationary orbit around the earth the only limit on image acquisition is the the speed the earth disk is scanned and relayed, 30 minutes per image.

GOES applications has been mainly concentrated on weather forecasting and regional land cover studies such as snow mapping where the scale and details are not of great importance.

### 2.4.4 Microwave Satellites.

#### 2.4.4.1 Introduction.

These satellites register images of the earth in the microwave region of the electromagnetic spectrum. Two modes of microwave sensors exist , the active and the passive modes. Some satellites carry more than one system combining active and passive instruments on board.

A system exists for each mode SAR, Synthetic Aperture Radar an active sensor, and SMMR Scanning Multi-channel Microwave Radiometer a passive sensor. Both were flown on several satellites together or apart. Seasat had on board a SAR and an SMMR sensors alongside some other instruments. Different sensors collect data utilising different bands 'windows' in the microwave region. Figure 2.1 show the division of the Microwave region of the electromagnetic spectrum with their respective names.

| | P | L | S | C | X | Ku | K | Ka | |
|---|---|---|---|---|---|---|---|---|---|
| 0.3 | 1 | 2 | 4 | 8 | 12.5 | 18 | 26.5 | 40 | GHz. |
| 100 | 30 | 15 | 7.5 | 3.75 | 2.4 | 1.67 | 1.1 | 0.75 | cm. |

Figure 2.1 Frequency and respective wavelength of bands in the microwave region.

Instead of reviewing a specific satellite, in the following SAR and SMMR are presented as representative of active and passive microwave sensing. But first a general description of the advantages, disadvantages and the applications of microwave sensing.

Microwave sensors advantages are

- operational under all weather conditions with capabilities for sensing the Earth day and night.
- provide description of the surface roughness.
- in the case of the active sensors provide own source of illumination.
- vegetation and subsurface penetration capabilities.

The disadvantages are

- image distortions.
- extensive shadowing of areas characterised with relief.
- coarse resolution especially for passive applications.

Microwave sensors applications spans across

- geological information: joints, faults, shear zones, strata.
- soil mapping, vegetation cover, moisture content, depth of soil.
- snow pack mapping, types of snow, melting snow conditions.

### 2.4.4.2 SAR Systems.

SAR systems evolved from Side Looking Airborne Radar (SLAR) systems. SLAR systems beams microwave signals and collect the returning signals from the ground. The ground resolution, range & azimuth resolution, is controlled by two independent parameters, *pulse length* and *antenna beamwidth*. The pulse length determines the range resolution which in turn is determined by the duration of the pulse transmission. The azimuth resolution (Ra) is determined by the beam width (ß) and the range of the sensor (Rs).

$$Ra = Rs \cdot \beta \text{ Where } \beta = \lambda / AL,$$

$\lambda$ = the wave length, and AL = the Antenna Length.

Thus the resolution of SLAR for a predetermined wavelength is dependent on the length of the antenna. To avoid having a large antenna on board the sensor its length can be synthesized by processing the signal received back from a point over a period of time, hence the name synthetic. This is done in SAR systems through modified data recording and processing techniques of the returning signal.

SAR systems were flown on the following platforms

- Seasat SAR (L band)

- Shuttle Imaging Radar SIR (L band) SIR-A SIR-B
- Spacelab Microwave Remote-Sensing Experiment (MRSE) (X band). A malfunction prevented producing images.

These systems were experimental and short lived. Future planned systems include

- SIR-C (L- & C- bands by USA and X- band by Germany/Italy) & SIR-D
- ERS-1 SAR ( C band ) European Space Agency project (ESA) 30 m resolution.
- Radarsat SAR ( C band ) Canadian Project 25 m resolution.
- Japanese ERS-1 SAR ( L band) 25 m resolution.

**2.4.4.3. SMMR.**

SMMR systems have been flown on Seasat and Nimbus 7 both launched in 1978. SMMR operate five wavelengths 4.45, 2.8, 1.66, 1.36, & 0.81 cm. The sensor is dual polarised thus providing 10 channels. SMMR is a passive sensor registering the emitted microwave signatures by earth surface bodies. These emitted waves occur either naturally or are reflected radiations from other sources such as the sun. The resolution of SMMR varies from 30 to 159 Km, the resolution differs for the various channels, rendering the sensor as only useful for global applications. SMMR applications in water related studies has proven of good quality. It provided information on different aspect of water studies, such as water vapour profiles, sea surface temperature, cloud water content, snow cover mapping, snow cover water equivalent, sea ice and surface wind.

### 2.4.5 Discussion on the use and applications of the different sensors.

As can be seen from the last section the user of satellite systems is faced with a plethora of sensors with sensitivity varying across the electromagnetic spectrum and resolutions starting from 10 meters, SPOT panchromatic band, to 159 kilometre, SMMR 4.45 cm wavelength. For a start this discussion will start with a comparison of the use of different sensors. The comparison will be between like and like i.e. between comparable sensors such as Landsat and SPOT, AVHRR and VISSR, and SAR and SMMR. Afterwards a comment on the whole set of sensors will be presented.

*Landsat and SPOT*, these two sensors provide detailed coverage of land cover on sporadic basis because the detrimental effect of cloud cover, although their passes times are regular. Landsat provide a better capability for land cover mapping on the thematic scale. The seven bands of TM provide a wider coverage of the electromagnetic spectrum and greater sensitivity to changes of the physical conditions of the Earth's surface in comparison with the three band of SPOT. On the other hand SPOT provides a better repeat coverage of the earth because of the utilisation of its side viewing capability. This facility, side viewing, reinforced with land resolution of 10 metres present SPOT as a powerful instrument for photogrammetric applications especially those concerned with height. The off nadir imaging of the same area from different satellite tracks provide stereo pair images, which could be constructed into a photogrammetric model from which digital elevation information could be extracted.

*AVHRR & VISSR*, provide coverage on multiple images per day basis but with coarse resolutions relative to earth resources platforms. However, the resolutions provided by the two sensors reflect the initial intended use as meteorological sensors. The land applications of the two sensors provide a good device for observing the changing natural phenomenons where the changes are happening in hours and the resolution is of secondary importance. AVHRR provide better resolution and a geometric registration for areas away from the equator. While VISSR provides images as required thus providing constant supply of information on the natural phenomenon. The two sensors complement each other. AVHRR is useful for high latitudes where the geometric registration is important, while GOES is useful for cases of rapid changes in weather conditions such as cyclones or rain storms.

*SMMR & SAR*, these microwave sensors have a potential for the future. However, a big set back is the resolution of SMMR which render it only useful for global studies. SAR systems on the other hand have a high resolution but are not currently operational. The great potential of SAR systems could be seen from the great number of planned SAR systems. (See Section 2.4.4.2) Mätzler *et al* [1982] reported on the application of SAR systems for snow mapping concluding that "Back scattering from snow covered ground includes contributions from the snow surface, from the snow layer, and the underlying ground surface. Snow wetness has the greatest influence on radar return, other relevant parameters are snow surface roughness, stratigraphy, and grain size, and the roughness of the ground surface." The intensity of information carried by the returning signal is well stated in the above quotation.

The hydrologic applications of the above systems are varied. Each of the sensors provides unique information on the physical status of the natural phenomenon. An integrative use of these sensors will provide a detailed description of the status of water resources in the environment as the different sensors complement each other. AVHRR and VISSR provide information about the existence and quantification of precipitation, snow, temperature, and soil mapping. While the microwave sensors provide information about the physical characteristics of the natural occurrence of these parameters. The land resources sensors provide detailed mapping capabilities of the soil, and snow. The repeat rate of coverage is served well with the different sensors. While AVHRR provide a more detailed coverage of clouds, away from the equator, VISSR provide constant coverage for rain storms which AVHRR might miss. Cloud cover prevent the imaging capabilities of land conditions for multispectral satellites while they do not affect microwave sensors. Thus a constant and complementary coverage of the water resources will always be available if different sensors were employed. However, this approach poses great difficulties and demand on the resources of the user. The sensor used in this study is AVHRR, a discussion on the reasons behind its selection is presented in section 3.3.

## 2.5 Hydrological Models.

### 2.5.1 Introduction.

Hydrological Models are mathematical formulations which are trying to simulate the hydrologic phenomena, which are either changing with time or not. Models are used to increase our understanding of the behaviour of the hydrologic process in order to understand and reconstruct past performances and predict future behaviour.

Models are built on an understanding of the hydrological process under consideration and then tested on historical data. This, hopefully, will result in a model that is representative of the hydrologic phenomena. Thus enabling the prediction of future conditions. The effect of the different individual parameters incorporated in the model can be tested one by one to understand their influence on the model. This may lead to the understanding of the behaviour of the corresponding physical elements, of those parameters, in the real world.

The Hydrological Model defines the status of water in the basin. Understandably the main data input to the model is water in its three phases, namely, precipitation, snow and evaporation. Temperature is an equally important parameter because it defines the threshold for the change of the different forms of water.

### 2.5.2 Types of Hydrological Models.

#### 2.5.2.1 Introduction.

Hydrological models are divided into two main types *deterministic* and *stochastic models*. Deterministic models, the subject of this thesis, are models that try to simulate the hydrologic events. Stochastic models try to reproduce the statistical behaviour of a hydrologic time series without regard to an actual event.

#### 2.5.2.2 Types of Deterministic Models.

Deterministic models are also divided into several kinds. The variety of deterministic models were introduced because no one model can precisely imitate the processes of a hydrologic system. A quick survey of deterministic models and very brief description of them follows.

*Research models:* intended for research.

*Conceptual models*: Composed of a series of functions describing the hydrological processes of the catchment.

*Lumped models:* Treat the whole of the basin, or big portions of it, as if it was homogeneous and subject to a uniform external inputs.

*Distributed Models:* Divide the basin into a large number of smaller subareas, simulate each one separately and then combine them to produce a general response.

*Continuous models:* generate outflow over long periods.

*Event Models:* simulate single events such as a single storm.

*General Models:* can be used on any basin.

*Catchment specific models:* designed for a single catchment with basin characteristics built in. Each of these models relies on different philosophies, assumptions and equations in their attempt to describe the performance of a prototype system.

A model, the Snow Runoff Model (SRM), was selected for use in this project. The detailed description of this model will be provided in Section 3.4.6. However, some light will be thrown on the reasons for selecting this model. SRM is a model that could be categorised in many of the above types of deterministic hydrological models, thus enabling the use of the derived remote sensing parameters, for a variety of types using one model. SRM process snow, precipitation and temperature information, while evaporation could be incorporated. It can process precipitation information with or without snow input, this provides a surface runoff model especially where snow is not of constant occurrence as in the case of the British Isles.

The extensive use of SRM in the different hydrological applications mentioned above could be achieved through careful use. SRM was initially designed for snow runoff simulations in mountainous basins, however, it caters for other situations such as non-snow events, with runoff generated by rainfall and the natural yield of the basin. It also caters for situations where evaporation affects the amount of basin yield, however, this is not done in a direct way. The incorporation of evaporation in the hydrological model is achieved through sampling its effect in the runoff coefficients instead of providing a parameter which directly represents evaporation in the modelling formulae.

It can be seen from the above that SRM is basically designed for specific situations with the option of using it for other cases providing careful use is guaranteed. Thus, SRM provides a versatile hydrological model, that when stretched, can be used for varied hydrological applications regardless of its name which links it closely to snow-fall cases. This property of catering for different situations, through diligent use, is most desirable when trying to present an integrated system as it provides an insight into different cases while at the same time limiting the work undertaken for the project to a manageable size.

## 2.6 Precipitation studies.

### 2.6.1 Introduction.

Many methods exist for the estimation of precipitation from satellite imagery. Over 30 methods were surveyed by the World Meteorological Office WMO [1986] (Figure 2.2). The choice of methods is even more than that included in this survey, since some methods have variants not counted. These methods can be categorised into the following:

1 - Cloud indexing methods.
2 - Rainfall Climatology Methods.
3 - Life History Methods.
4 - Bispectral Methods.
5 - Cloud Model Methods.
6 - Passive Microwave Methods.*
7 - Active Microwave Methods.* [Barrett & Curtis 1982]

* Not included in Fig 3.2.

| Channels | | One | | Two |
|---|---|---|---|---|
| Predictors | | Visible | Infrared | Visible and Infrared |
| One | | Kilonsky-Ramage<br>Follansbee-Oliver | Arkin-Bristol | Lovejoy-Austin |
| Two or More | Linear | | DelBeato-Barrell<br>Whitney-Herman<br>Negri-Adler(CST)<br>Kruger et al<br>Stout et al<br>Fenner-Motell-Weare<br>Doneaud et al | Martin-Howland<br>Callis-LeComte<br>Creutin et al<br>(FAO) |
| | Non-Linear | | Tamsat Permit<br>Griffith-Woodley<br>Weiss Smith<br>Adjusted Griffith-Woodley | BIAS Heitkemper<br>Scofield-Oliver<br>Nail Wu et al<br>Lee et al<br>Tsonis-Isaac<br>Admit |

Figure 2.2 Classification Matrix of Visible/Infrared Techniques for the production of precipitation estimates. (After WMO, 1986)

They concluded that the cloud indexing type showed most flexibility and yielded most results in support of continuous operational rainfall monitoring programmes.

Five of the methods for studying precipitation are presented here. Three of these methods are included in one program sponsored by one organisation, the U.S. Department of Agriculture, but at the same time approaches the problem of rain-fall estimation using satellite data in different ways.

### 2.6.2.The AgRISTARS programme .

#### 2.6.2.1 Introduction.

The U.S. Department of Agriculture has a program for providing precipitation estimates of the major crop growing regions in the U.S.A, U.S.S.R and South America called the AgRISTARS programme. AgRISTARS stand for Agriculture and Resource Inventory Surveys Through Aerospace Remote Sensing. It has sponsored three state of the art techniques, The Bristol Method, The EarthSat Method and The Environmental Research Laboratory (ERL) method. [Moses and Barrett, 1986]

**2.6.2.2 The ERL Method.**

The Environmental Research Laboratory (ERL) method, also known as Griffith-Woodley, is based on empirical relationships, derived by Griffith et al. [1987] between calibrated Radar echo areas and geostationary-satellite observed cloud areas. A time/history relationship was obtained between echo area and cloud area by normalising echo with respect to the maximum cloud area achieved during its life time. These relationships were observed in Florida. The computer program needs modification for use of NOAA/AVHRR imagery. It could be run automatically or manually. This method is the most automated of the three techniques incorporated in the AgRISTARS programme. It has a cloud history method that is mainly used for convective situations.

**2.6.2.3 The EarthSat Method.**

The Earth Satellite corporation developed a cloud indexing method based on regression relationships between cloud temperature and rainfall. Regression models show high variability and weak correlation. In order to improve results, satellite data were used in combination with synoptic data.

This method can be used automatically to generate rainfall estimation in the case when special conditions are met, i.e. images every six hours, and satisfactory air vertical motion fields which are calculated by a numerical method. In practice the meteorologist has a significant role in this method.

**2.6.2.4. The Bristol Method.**

It is a cloud indexing method using empirical relationships between cloud type, mean monthly rainfall and periodic accumulated rain. The empirical relations were derived from a variety of studies for specific areas within tropical and mid latitude zones. These derived characteristics were built into the ''global regression'' charts for widespread application. In this method, Remote Sensing images are assigned indices relating to cloud cover and probability and intensity of associated rain.

The method was modified and adapted to be used on image processing systems including VIRGS, VICOM and $I^2S$. This method is very dependent on human interpolation. The Bristol Method is composed of several techniques. The various techniques study precipitation with varying degrees of automation and precision.

### 2.6.3 Interactive Flash Flood Analyser - IFFA.

This method is an interactive computer system used by experienced meteorologists for the NOAA Flash Flood Program of the United States. The program produces short term satellite estimates of heavy precipitation. Clark & Morris [1986] reported this program. The IFFA is heavily dependent on the skills of the meteorologist who provides the analysis functions of the procedure while the computer is the tool.

Meteorologists select areas of excessive precipitation potential to perform precipitation estimates which are run on the system minicomputer. The analyst identifies and analyses important cloud signatures that are likely to be producing heavy precipitation.

After the meteorologist has identified an area that is likely to produce heavy rain, GOES half hourly images in the visible and infrared are collected and displayed on the monitor creating an animated image of the event. Three techniques were developed for estimates. Thunderstorms, winter storm-front rain and snow, and tropical cyclone for tropical storms and hurricanes. The estimates and estimated precipitation areas are interactively drawn by the meteorologist on the screen. Each half an hour, estimates can be summed up to the previous estimates in the event area, to produce precipitation totals per day.

### 2.6.4 Erik Liljas Method.

Erik Liljas [1984] of the Swedish Meteorological and Hydrological Institute devised a method using AVHRR data for the study of clouds and precipitation. His method employs an automatic method for :

1 - The classification of cloud types.

2 - Qualitative measure of precipitation.

3 - A reduction in the volume of data stored.

In this method the types of clouds and terrestrial surfaces can be discriminated in three or four dimensional intensity space. This is done using different thresholds to define different classes. A set of sixteen classes were defined for clouds and land.

The discriminatory thresholds feature differs for different sun elevations for different types of clouds. A set of ten classifications for varying sun elevation $20^0$ to $55^0$ were constructed.

The method classified clouds that produces precipitation to be of the nimbo-stratus and cumulo-nimbus types of clouds. An albedo of more than 60% and a cloud top temperature below $-15^0$ C were found to be the necessary requirements to produce rain i.e. light precipitation. A set of six classes of rain were defined. The heaviest precipitation being associated with the brightest and coolest tops (of clouds).

The method gives information of the distribution of the precipitation and the relative precipitation intensities for fronts and showers. The extent of the precipitation is found by comparison with either synoptic observations or few rain gauges for the production of intensity estimates. The areal extent must be compared with correct radar measurements.

One of the shortcomings of this methods is the fact that it indicates rain falling when in fact it has stopped.

This method was devised and checked for the Scandinavian summer from the end of May to the beginning of September. In order to use it in wider application it should be tested for winter months and for other parts of the globe.

### 2.6.5 Comparison of the different previewed methods for estimating precipitation .

The various previewed methods provide the major precipitation estimation methods using remote sensing images. Each of the methods has its advantages and disadvantages. The use of any of the above methods relies on the purpose of use, the available sources of data and the way the method fits in any particular application. An objective judgment on the performance of each of these methods is difficult to reach as the criteria upon which they are based are so wide and varied.

The different methods provide estimates of precipitation for various situations and conditions. The methods of the AgRISTARS program are unified in the sense they all provide estimates of precipitation on a day by day basis for monitoring purposes. While the IFFA provide estimates for extreme meteorological cases i.e. storms. Erik Liljas method on the other hand tries to identify relative precipitation intensities in an automatic fashion. This method however has only been used for a limited duration, its application has been confined to one place and one season.

The IFFA method is necessary to complement any method that provides estimates on day by day basis in order to complement and provide data for an important occurrence of precipitation that might be overlooked by the other methods.

The methods of the AgRISTAR programme were compared in a paper by two leading authorities in this field [Moses & Barrett, 1986]. A case study was performed on the three methods. A base line of precipitation estimates, compiled from non-satellite information, was established for three rain-fall categories; light, moderate, and heavy. Then the three methods were used and the results were compared. They concluded that a technique of the Bristol method, 'climate entry', was the best performer, by providing improved estimates over the base line, in the moderate rainfall category and followed the EarthSat closely in the heavy rainfall category. The ERL method did not provide any improvement over the base line for any of the categories.

A method was needed for the production of precipitation estimates for this project. The Bristol Method was selected on the basis of its performance as reviewed by Moses and Barrett [1986]. The total precipitation over a period of time over a certain period is composed of several kinds of precipitation intensity ranging from drizzle situations to flash floods. The efficient production of precipitation estimates for the different intensities requires the use of different methods for each situation. However, a method should be selected to be used in the construction of an integrated prototype system rather than an amalgamation of methods. The Bristol method provide a series of methods for the production of precipitation estimates. This series is composed of methods that varies in their complexity and their dedication to specific precipitation situations.The PERMIT method of the Bristol method was used as it is a fully automated technique. It does not produce estimates for particular situations but rather estimates that could be treated as general inventory for the occurring precipitation over a certain area. This in turn excludes the need to include several dedicated techniques for the production of the precipitation estimates.

The selection of the PERMIT method of the should be viewed in the light of it's pragmatic use. The inclusion of intensity specialised techniques should be approached with care as HyRSIS is elevated from a prototype system to a fully operational system.

## 2.7 Snow Studies.

### 2.7.1 Introduction.

Snow melt is a source of a large portion of stream flow generated in mountainous basins. Remote sensing provides a good tool for providing improved estimates of snow cover. The characteristics of the sensor employed in mapping the snow extent have direct repercussions on the effective use of the collected information hence in what follows, different types of sensors for snow mapping are mentioned and their properties are described. The methods of utilising the mapped snow data are also described.

Snow extent is affected by the prevailing physical conditions of the basin; the morphology of the basin, temperature, and wind, speed and direction, affect the variation in the depth of the snow pack. The characteristics of the falling snow varies from one day to the next as it is dependent on several factors, atmospheric temperature, wind cycle and type of the snow storm.

Gauging snow has proved a difficult task indeed as up and down wind disturb the correct measurements, in gauges, of the snow giving poor results [Weiss and Wilson, 1975]. The difficulty in establishing an extensive and a homogeneous mesh of snow gauges, add to it the uncertainty over the reliability of the data collected by these gauges, make remote sensing an excellent tool for mapping of the snow extent, snow cover is very easy to delineate. Areal representation of snow cover is hindered never the less by the following considerations:

1. Clouds.
2. Vegetation cover.
3. Bare rock.
4. Mountain shadow.
5. Discontinuous snow cover.
6. Image quality and illumination levels.

[Rango and Martinec, 1986]

As if these basically image interpretation problems are not enough to contend with other problems arises as for the acquisition of these images. The most important problems faced in this field are:

1 - Resolution of imaging satellites both in time and space.

2 - The availability of images for the areas of interest that is cloud free.

The physical characteristics of Imaging Satellites were previewed earlier in section 2.3. In this section, the snow mapping characteristics of these sensors will be discussed. The usefulness of some of the satellites in snow studies are commented on. A brief review of the use of different bands is also provided.

### 2.7.2 Acquiring the Imagery Using Multispectral Satellite Sensors for Snow Mapping.

The best multispectral satellite system for snow mapping is the one with the highest resolution and highest repetitive coverage of a basin. (Refer to Table 2.6)

| Platform | Nominal Res. | Minimum Basin size | Return period |
|---|---|---|---|
| Landsat(TM) | 28.5 m | 2.5 - 5 $Km^2$ | 16 days |
| NOAA(AVHRR) | 1.1 Km | 200 - 500 $Km^2$ | 6 hours |
| GOES(VISSR) | 1.1 Km | 200 - 500 $Km^2$ | 30 minutes |
| *SPOT(HRV)* | *10/20 m* | *?* | *4 days.* |

Table 2.6 Basin size relative to multispectral sensor's ground resolution.

The use of multispectral sensors is hindered by the cloud coverage of the basin area while images are recorded. The Landsat type is best for resolution but the repeat rate is very limited and the risk of error is increased by a missing Landsat image after a snow storm [Rango *et al.* 1983].

NOAA(AVHRR) provides two over flights every 24 hours, one in the day the other in the night. It's resolution of 1.1 km near nadir limits the utilisation of this sensor to basins of the magnitude of 200 - 500 Km2.

The GOES(VISSR) is used when data is required more than once daily. This geostationary satellite provides the opportunity of imaging scenes cloud free whenever possible. The draw back, is that the distortion of images grows bigger as the scene is further away from the equator, areas which are most likely to have snow cover.

The Defence Meteorological Satellite Program (DMSP) has a sensitive sensor allowing moon light mapping. This might add an estimated five additional images per month that are suitable for snow mapping. [Foster, 1983].

The use of a particular sensor for the purposes of snow mapping depends on the operational requirements of each study. These requirements vary from one study to another. If a basin is smaller than 200 $km^2$, earth resources satellites are needed for the purposes of snow mapping. Regardless of the usefulness of their small resolution earth resources sensors are hindered by their long return period and the problems of cloud cover reducing the chances of land imaging. AVHRR provides a good combination of return period and registration integrity rendering it an optimal system for snow mapping on regional scale. AVHRR snow mapping capabilities are described in details is Section 3.3.5.

### 2.7.3 Processing multi spectral imagery for mapping snow.

Snow has high reflectance properties which causes it stand out in remote sensing images. Clouds are other components of the natural environment which have this property of high reflectivity. Snow mapping researchers sped a good deal of effort and time to distinguish between the two.

Photo-interpretation of images were the first techniques to be used for mapping snow. In places were the snow line is not well delineated and the snow areal distribution is irregular, digital image analysis is needed. Early digital image analysis relied on pattern recognition [Barnes and Bowely, 1968]. Techniques relying on the spectral signature of snow utilise the different spectral bands. Some of these techniques used one band such as near-infrared, TM band 5, to discriminate between snow, ice and water clouds. [Dozier 1984] The use of more than one band improves the snow/cloud separation. Hunt et al. [1974] used a thresholding technique, for DMSP satellite imagery, first on the visible channel to separate land and snow then on the near-infrared band to separate snow from clouds and ice. A further development in the use of multiple bands was when Bailey et al. [1987] used the visible channel of AVHRR to manually locate clouds and construct a mask to separate clouds from the scene. The rest of the scene is then thresholded to identify snow areas. Harrison and Lucas [1989] introduced a method that combines three channels for the purpose of snow mapping. They identified snow discriminatory channels and arrived at a thresholding technique that utilise the visible and two thermal infrared channels to map snow and discriminate between snow and cloud pixels.

The succession of the different methods mentioned above present an illustration of the process which multispectral techniques have matured over the years. The method of Harrison and Lucas presents the last phase of this process. It is the most sophisticated and utilises multiple bands of the remote sensing information. The method is also the most computerised one. In contrast with the other methods it utilises three spectral bands while the other methods use one or two bands only. This method was used in this project for the mapping of snow as it is the state of art for multispectral snow mapping techniques.

### 2.7.4 Microwave Satellites Snow Mapping Capabilities.

Microwave sensors enable snow mapping through clouds and are capable of providing information on important snow properties such as snow depth, water equivalent and melting conditions. [Rott 1986]. Several active and passive microwave sensor's have been on board remote sensing platforms. Microwave sensors extensive snow mapping capabilities stems from the fact that the sensor-received radiation from a body is influenced by the characteristics of the body such as:

1- Electrical and thermal properties of that object.

2- Surface roughness and size of the body.

3- Temperature variation in the material.

These properties vary significantly and in some cases uniquely according to the status of snow. Thus, the identification of various classes of snow each reflecting a different stage in the accumulating or melting process is facilitated.

So far only the L band on the SAR system, an active microwave sensor, has been used. This band was found in an airborne experiment to be not suitable for snow mapping [Rott 1986]. However, these airborne experiments showed a great potential and suitability using X-band and C-band. The X-band gave maximum contrast between snow covered and snow free areas, while the C-band will be of interest for mapping wet snow. The X-, L-, and C- bands will be flown on SIR-C while C-band will be flown on ERS-1 in 1990, which was scheduled for 1989, and

Radarsat.(See Section 2.3.4.2). In the digitally processed; SAR scene, bare rock appears bright, due to it's high backscattering characteristics, while surfaces of low backscattering properties appear grey and snow surface appear as smooth grey.

Passive Microwave sensor, the Scanning Multispectral Microwave Radiometer SMMR (resolution 20 - 159 Km) on Nimbus-7, used up till now proved to have better capabilities for snow mapping than active sensors. A major drawback of this system is the limited spatial resolution. For snow mapping the 18 GHz (of resolution 60 x 60 $Km^2$) and the 36 GHz (30 x 30 $Km^2$) channels were utilised after yielding the best results [Künzi 1982]. These channel resolutions are adequate for large scale snow mapping, i.e for basins whose areas are greater or equal to $10^5$ $Km^2$. The mapping of the snow is done through the calculation of the brightness temperatures gradient, GT, of the scene. A threshold value of GT is then applied to decide the existence of snow.

Although microwave mapping of snow has great potential and is not hindered by cloud cover, thus providing continuous coverage, it is not available operationally. This is attributed to two factors

1- Sensors has been flown for short periods.

2- Low resolution of Passive microwave sensors.

Sensors scheduled and planned for launch in the future will provide great opportunity for hydrologists on the snow mapping front. Meanwhile snow mapping has to rely on the use of Multispectral sensors.

### 2.7.5 Utilisation of Snow Cover Mapping in Hydrology Problems.

Remote sensing snow mapping provides an areal description of the snow extent over a certain basin. Remote sensing provides more information about the properties of the mapped snow. Microwave sensors provide information about the status of snow. Whether the snow pack is wet, dry and in some instances provide some information on depth. One of the methods described in Section 3.3.5 for AVHRR snow mapping is capable of producing more than one class of mapped snow. A better understanding of the hydrological processes and higher definition of snow impact on the water cycle of a basin will be achieved when these properties of snow are correlated with other hydrological information

The impact of snow on the global weather system makes the need for snow mapping at any scale imperative. Thus, SMMR mapping capabilities are appreciated for weather studies and for general inventory of rivers that are dependent on snow melt input.

As the snow cover data becomes available, and judged satisfactorily reliable and regular in real time, it will encourage snow melt runoff models [Rango & Martinec 1985]. This is part of the trend towards the use of areal hydrological information.

## 2.8 Evaporation.

Two predominant approaches are available for the estimation of evaporation. The methodological approach and the simplified approach.

The methodological approach incorporates the analysis of the thermal energy of the surface, climatic variations (temperature and humidity of air, wind speed, and solar rays), and the temperature and position of the surface layer. If this approach is to be used by remote sensing techniques it has some serious limitations.

1- The equations of mass transfer require a few minutes of measurement every hour. This is not available by remote sensing.

2- This method also requires the identification of too many parameters. This is also not obtainable by remote sensing.

3- This method is of localised characteristics which has little compatibility with remote sensing. [Vauclin 1983] As a consequece this approach is complex.

The simplified approach involves the lumping of the parameters describing the earth-atmosphere exchange and those of evaporation.

As in the case of temperature, the estimation of evaporation from space borne platforms is dependent on the the use of the thermal infrared data. Evaporation estimates depend on may factors ranging from the type of soil, air humidity, air pressure, net radiation and air and soil temperatures. Regardless of this fact ,recent studies [Vidal et al, 1987; Lacaze 1987; Seguin & Itier, 1982] have shown that evaporation could be estimated employing a simplified equation incorporating air temperature, net radiation and satellite estimate of land temperature. One scene per day was found to be enough to carry on the exercise.

Seguin and Itier [1982] reported that according to their practical experience sophisticated models, although useful for understanding basic processes, cannot be used for real estimation of evaporation.

A simplified procedure was proposed by Jackson *et al.* [1977] in which one instantaneous measurement is used to estimate the daily evaporation.

They suggested the following formula.

$$ET_d = Rn_d - B( Ts - Ta )_i$$

Where

$ET_d$ = Daily evaporation. $Rn_d$ = Daily net radiation.

Ts = Surface temperature. Ta = Air temperature.

B = A parameter.

Seguin and Itier [1982] conducted a theoretical and experimental study on the parameter B. It was related to wind velocity, the thermal stratification and surface roughness. Simplified procedures for practical use of the equation were devised. More details of this study are provided in Chapter 3.

The above equation has been universally agreed for use in the production of evaporation estimates. The difference between the different researchers in the estimation of the parameter **B** and its correlation to the characteristics of the study area.

## 2.9 Summary and conclusion.

This chapter has introduced the concept of remote sensing of the components of water bodies in the natural environment. It is useful to summarise the methods selected for incorporation in this project, to serve as a reminder, before they are detailed and expanded in the next chapter.

The different satellites providing remote sensing imagery of the earth have been reviewed and compared. In the light of this revision a sensor was selected for use in this project. AVHRR was selected on the basis of the good repeat rate of imaging and the provision of the required spectral images of the different methods used for estimating the various hydrological parameters.

The Bristol method was selected for the provision of precipitation estimates. This method provides estimates on inventory basis for periods of rainfall situations. It does not provide estimates for extreme cases of precipitation intensity such as flood cases. It can deliver precipitation estimates for the rain periods in a completely automated fashion while at the same time it is not a very complicated method.

The selected method for the mapping of snow is the Lucas-Harrison method. This method is the state of the art in snow mapping for multispectral sensors.

For evaporation the method selected is the universally agreed simplified method for the estimation of evaporation from a single infrared image during mid day. Seguin and Itier recommendations were taken into consideration as they were able to relate the parameters used in the simplified equation to the physical properties of the terrain.

The different techniques above have the common feature of being able to use AVHRR imagery as input for the production of the different hydrological parameters. This ensures the compatibility of the produced estimates as the different parameters are derived for each of the pixels.

The AVHRR sensor imagery, alongside these different methods, provide the core of the HyRSIS. The remainder of the methods and techniques used in this project are built on this foundation. The next Chapter will detail the concept and use of HyRSIS as well as reviewing in detail the chosen techniques and sensor.

# Chapter Three

## Outline of Project & Choice of Methods.

### 3.1 Introduction.

Chapter Two introduced briefly the subject of hydrology. It discussed traditional methods of collecting data for hydrological purposes. Remote sensing methods of collecting these data were also introduced. The subject of this thesis is the interaction and incorporation of remotely sensed data into hydrological studies. This section will introduce the background to the project and the outline of the work to be done. The methods selected for use in this project will discussed. The theory of each method will be provided. The criteria for selecting the methods and on what basis the different method are to be integrated will be discussed.

### 3.2 Outline of Project.

#### 3.2.1 Introduction.

The definition of a project and its execution is always controlled by physical factors of man-power, financial considerations, time and the desired results of the project. This section reflects on the background of the need for such a project, the structuring of the model and the task that has been set to be achieved in this project. An ideal global proposal for a project is discussed here, the above mentioned limitations exert the inevitable restriction on the amount of work that could be achieved, hence a definite proposal is put forward. It should be noted that most of the ideal global proposal is included in the undertaken project presented here. The extension of this work to achieve the objectives of the global proposal will be a straight forward exercise as the system and the methods of the project have already been laid down and are well defined in relation to the wider application of remote sensing methods to the subject of water resources.

### 3.2.2 Background to the Project.

Hydrology is an established branch of science that every remote sensing study on the national and international level has to consider, especially with the realisation of the importance of water for sustaining human life.

The British National Space Centre [BNSC 1986] prepared a study for the United Kingdom Utilisation Study of the COLUMBUS/SPACE STATION. A specialist panel on Land Science and Application prepared a report on their subject. In this report under the section on Hydrology/Land Surface Climatology it was suggested the development of a hydrological model for large drainage basins in the humid mid-latitude regions should be undertaken. Such a model should be designed to make use of data from remote sensing. This will provide estimates for five components namely rainfall, snow melt, evaporation, temperature, and infiltration rates estimates.

The aim of the BNSC study is to demonstrate the usefulness of satellite remote sensing techniques as a data source and to develop an operational method for the use of these data for hydrological purposes.

A study of such a model its structure and characteristics was prepared by Fortin et al. [1986] in a Canadian sponsored project. They suggested a model of a modular structure for which the initial version is to be comprised of nine modules Physiography, Precipitation, Hydrology, Input, Output, Forecast, Evapotranspiration, Optimisation and Main.

The aim of this Canadian study was to produce a whole package that has as an input the digital images of the basin (different types of sensors) with an end product of any requested information about the basin, to use in the planning and day to day management of an aquifer.

The Input module deals with the original digital imagery to produce hydrological information. The module also deals with conventional meteorological and hydrological data provided by *in situ* sensors and radar stations.

The data generated from Input module is provided to the Precipitation module and Evapotranspiration module.

The Main module is the link between the user and the different modules. The global structure of the model is programmed in this module. It provides the interactive phase.

The Hydrology module is split into two submodules, namely production and transport. These will calculate surface run off and its routing.

The Forecast module is for short term forecasting, the flood emergency cases.

### 3.2.3 Global Project.

#### 3.2.3.1 Introduction.

Different researchers have produced methods for producing hydrological estimates from remote sensing data. These procedures span through different sensors and different parameters not to mention the existence of the different procedures for the same parameter and the same sensor. What is noticeable is that these different procedures remain concerned with 'isolated' parameters of the hydrology process.

The work presented here is an attempt to produce an integrated and a coherent procedure to tackle a hydrology problem using remote sensing data as input, where this data is processed by different methods to produce the different hydrological parameters for the basin being studied. The parameters produced, namely precipitation, evaporation, temperature and snow cover will be stored in a database.

As seen, the emphasis is on the need to build a model for hydrology studies utilising remote sensing data sources. The work of this thesis covers the building of a procedure for tackling hydrological parameters, where the purpose is to identify and quantify their existence. After the acquisition of these data the aim is to store them, in a database, for the purpose of analysis and manipulation according to the requirements of the hydrologist concerned.

The project is to recommend the concept, structure, working mechanism, data management, and user machine interface of a

"Total Work Station" for hydrological studies. In the sense that all the hydrologist has to do in order to study the hydrology of a basin, is to sit in front of a terminal where the input data is mainly from remote sensing sources. This is not practical now, remote sensing is not sufficiently reliable and other sources of data should be considered as input. The mechanism of such a study is described in Figure 3.1.

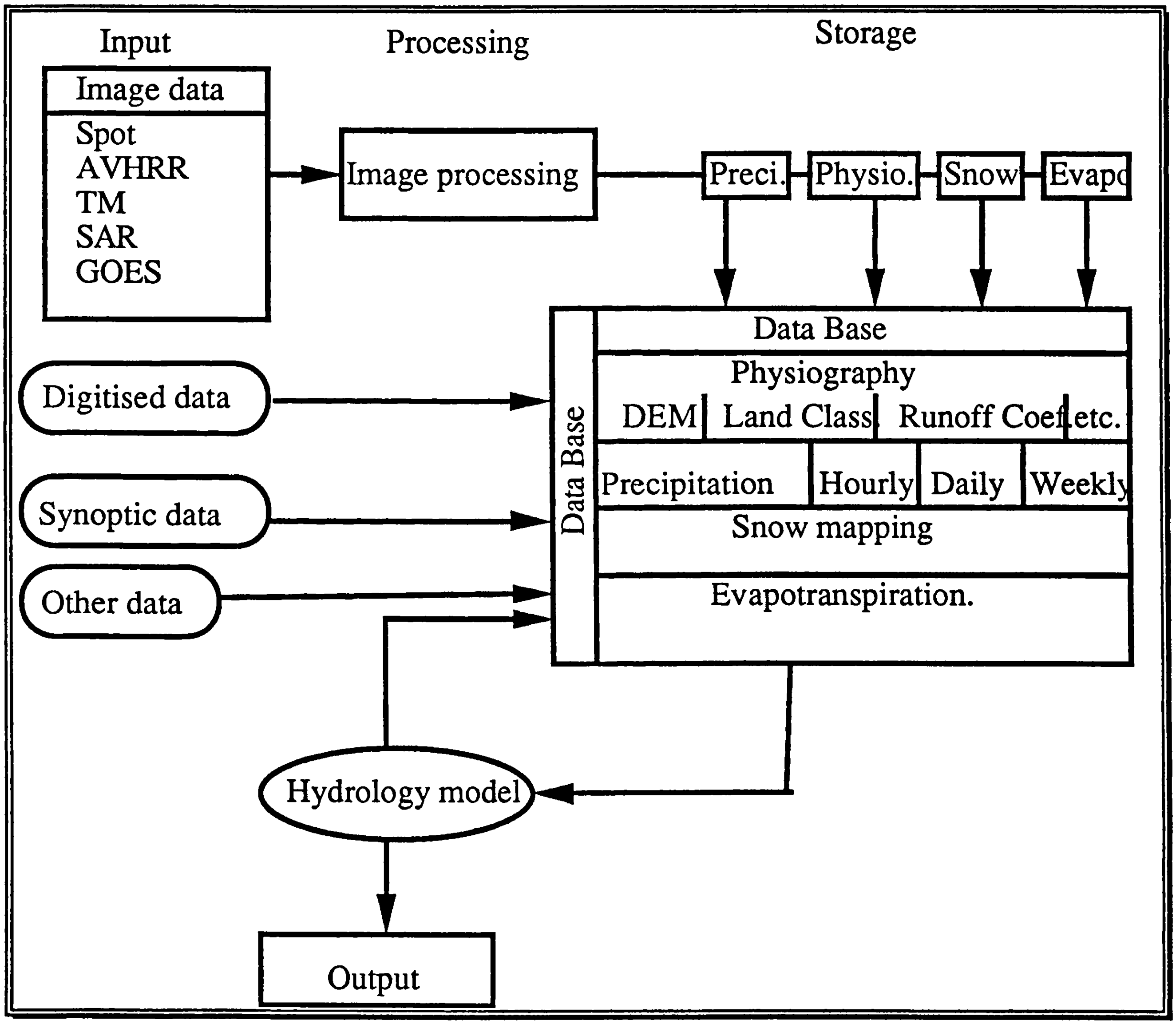



Figure 3.1 Different stages, Input, Processing and Storage of the project.

The figure illustrates the structure of the project, which is divided into three stages, Input, Processing, and Storage.

### 3.2.3.2 Input stage.

The Input stage comprises subprograms for the part dealing with remote sensing data from satellites for the estimation of the following:

1- precipitation.

2- snow mapping and description of the melting process.

3- evaporation and evapotranspiration.

4- physical properties of the basin.

For each of the above elements there exist many methods and procedures to extract hydrological data, for different sensor types, from the original satellite digital imagery. This work is involved with the selection of compatible methods, while the integration of some methods to improve estimates is also a concern. The input data comprises remote sensing data, of different sensor types, data from radar and conventional gauges. Remote sensing images are processed to produce the different hydrological estimates. The resulting processed data is then stored in a database. This database provides all the necessary input for the running of a hydrological model. The hydrological model processes this information which produces an output data, helping in the understanding of the behaviour of the basin and providing a quantitative analysis of the hydrological process. The data resulting from the hydrological modelling is used to update and provide estimates on the physical conditions of the basin to the database.

The interface stage (Figure 3.1) provides the analyst with the capability of selecting the type of hydrological problem that the user is interested in studying. This in turn decides the type of data needed which will be retrieved from the database. This stage also provides the image processing facility. The input data here is from remotely sensed images. The objective is to produce relevant hydrological data from the digital imagery provided. This is done using various subroutines. The third activity of this stage is the provision of an interface with the database. Other processes include activities such as digitising of maps as support input to the remote sensing data, and the use of synoptic data either for the purpose of using or for the purpose of comparison.

### 3.2.3.3 Image processing stage.

The image processing subroutines comprise computer programs that work on the remote sensing digital imagery of the scene to extract relevant data. These programs are:

1- Computer programs which calculate estimates of precipitation over the designated area. Various methods for such a program were discussed in Section 2.5.2. The choice between these methods for use here depends on the intended use of rain estimates.

2- Computer programs for mapping snow extent and the estimation of snow depth, and the estimates of other properties of snow that are anticipated to be feasible in the future such as water equivalent.

3- A program for the estimating from infrared images the amount of evapotranspiration occurring in the basin.

4- The Physiography module data are extracted from imagery through more than one computer program because of the diversity of data inputs of this module. These programs are

a- program for extracting digital elevation information of the basin.

b - program to classify land use, type, etc... .

c - program to estimate the degree of saturation of the land units.

Output of c and b will help in assigning runoff coefficients.

The product of the image processing phase and other sources of data are used to update the database.

### 3.2.3.4 Data storage and manipulation.

The database comprise several modules in which input data is stored. The data is stored in four different categories temporary, dynamic, permanent, and history cases.

*The temporary data:*; is used in the interactive case for the study of a rapidly changing situation, such as a flood. Some of these cases might have great relevance and are stored as case history, otherwise the data is stored for a while, then it is disposed of.

*The dynamic data;* is the data that describes the status of the changing water quantities in its three cases, liquid (precipitation) gas (evaporation) and solid (snow), in the basin. It is either entered as input data or as a result of the mathematical modelling of the hydrological problem of the basin. The dynamic data also contains the set of small time series that might be needed to perform the modelling. In addition to this, data that is changing over the period between simulations is also included in this category.

*The permanent data;* is the data that is to be used every time in the modelling without any significant change in it between simulations. This includes mainly the data stored in the physiography module.

*The case history data;* is the data that is not needed for the actual simulation of the basin. This data is a true description of the hydrological condition of the basin for a certain time. It is stored for further analysis in order to form better understanding of the hydrological problem.

#### 3.2.3.5 Database structure

The database is composed of several modules, the physiography module, precipitation module, snow module, and the evapotranspiration module.

<u>The physiography module.</u>

In this module the physical characteristics of the basin are incorporated. These are composed of a Digital Elevation Model (DEM) of the basin, land classification (run off coefficient), drainage systems, distribution of permeability coefficient and degree of saturation of soil strata (phereatic surface estimation). The data for this module should come mainly from remote sensing sources. Other sources of data may contribute to this module.

The data should be structured in such a way that is compatible with the hydrological model. The precipitation and snow modules have data structure that are dependent on the physiography module. The data in this module is of the permanent type. Changes in the data are not expected to occur in a short time space. A seasonal review should be sufficient except in the cases of known human work or a natural process (avalanches, erosion) occurring in the basin that is expected to make a significant change.

The precipitation module.

The spatial distribution of the precipitation values is defined. This is described over the module of the basin defined by the physiography module. There are three types of precipitation data. An hourly rain estimate, daily and weekly estimates. The hourly type of data is used for cases of flood forecast and are of temporary status because of the size of the storage facilities and in addition to this, the limited use of this data in other cases. The daily type of data is used in the simulation of the hydrological problems. While the weekly precipitation estimates are derived from the daily one and are used for routing of rivers, basin and run off.

The snow module

The snow module describes the extent and depth of the snow in an areal form. The change in these two variables describes the amount of water yielded into the drainage system and into storage in the basin underground water. This calculation of the snow water yield is done by hydrological models.

The Evaporation module.

The evaporation module defines the amount of evaporation occurring over the study area. The data is defined for each day once from one measurement (infrared images of the basin during midday). The data series of evaporation collected from remote sensing should be long in order to dampen the effect of anomalies in accordance with Seguin and Itier [1983] recommendations.

### 3.2.4 Work carried out.

The above mentioned global proposal was envisaged as an operational system for a water resources organisation interested in the monitoring of the water cycle over an area of interest. The area of interest could be on a regional level or a national one. A project of such magnitude is ambitious and certainly exceeds a Ph.D. research project. Whilst the work here was restricted, due to understandable limitations on manpower, resources and time allocated for a study of this kind, the global proposal remains as a an objective for an operational situation.

The project undertaken in this thesis is concerned with the setting up of a procedure for the production of the following parameters, Precipitation, Temperature, Evaporation and Snow cover then storing the product parameters for retrieval and further processing by hydrological models.

This proposal covers all the basic hydrological parameters. It stops short of attempting to provide all parameters that might be needed, and some of the functions suggested in the global proposal. The design of this project was influenced by the global proposal as it was paramount in the design stages. However, the extension of the system to cover the residual elements of the global proposal will be straight forward as the basic theory and implementations of the project have been tested and tried out. This is made easier as the design of this system took into consideration the requirements for future expansion.

This study concentrates on the building of a coherent procedure, starting with raw data of satellite imagery aided by conventional data in order to produce estimates of the desired parameters for the study area. Some conventional data is required for the processing of remote sensing data in order to estimate some hydrological parameters. The next step of this procedure is the storage of the processed data in a database. The last operation of this process is the retrieval of data from the database for use as input to a hydrological model. This is a 'pilot study' investigating problems in the building of such procedures. Preferred structures, recommended features, protocol for the utilisation of remote sensing data for hydrological parameters were established. A study for further development was also conducted. Thus this thesis comprise a suitable body of work which should provide a core for future growth and expansion.

### 3.2.5 An Overview on the Project.

The proposed system envisaged the production of a series of parameters and included some operational features. The establishment of the system depended upon the successful building on the already available and established procedures for the production of the different parameters. The methods that are available for the production of the different parameters were reviewed in Chapter two. A selection of these methods is incorporated in this system. The different methods deal with remote sensing data for the derivation and the estimation of the different hydrological parameters. Remote sensing data are stored digitally, hence computer programs are the tools for the production of the different hydrological estimates.

The reproduction of computer programs which have already been written and described in literature by other researchers through personal trials is rendered futile. It would not have been cost effective and a waste of time. A better policy was to acquire them from the different researchers. 'Acquire' in the sense that to be permitted to use their programs, methods and ideas for the aims of this study under the condition of acknowledging what is essentially their intellectual property. However extensive modifications to these programs were necessary before incorporating them in the system. Not all the required source programs were available hence these programs had to be written 'in house'.

The project involves the assembling of the different methods in a compatible package. Problems of compatibility of various methods were solved. Remote sensing data has been processed and the processed data extracted, then assimilated and delivered in an acceptable format to the database.

Files for different kinds of data have been created and stored pending disposal or saving. Saving of the files was done through loading onto the database. The database had to be capable of receiving data from any source whether remote sensing, digitised data, synoptic, or from simulation. The database was used for the storage and manipulation of the data of the different modules.

### 3.3 Sensor used in this project.

#### 3.3.1 Choice of sensor.

Many sensors exist for the collection of environmental data. Each of the sensors is designed to achieve certain pre-planned tasks. No sensor has been specifically designed to cater for the needs of hydrologists. They have relied on meteorological satellites and land observation systems to detect and to try to estimate the hydrological parameters. A multi sensor approach to the study of the hydrological parameters is desirable especially if the user wants the maximum benefit from remote sensing sources. The use of many sensors for an operational system will probably produce the best description available of the different parameters.

Different sensors, multi spectral and microwave sensors, complement each other. The use of microwave sensors in this study is constrained because of two reasons. These are the availability, or the lack of them, of microwave remote sensing images and the small resolutions of these sensors. (See Section 2.3) This factor has resulted in the limited the use of these sensors in hydrological studies. Multispectral sensors on the other hand have provided a steady source of images of Earth for the past decade on various levels of resolution and repeat rate of coverage. These sensors furnish a comprehensive set of platforms which provide varied temporal, spectral and spatial coverage of the planet earth. The visible and the InfraRed spectrum is covered by many channels of these sensors. The globe is covered by a combination of spatial resolutions ranging from 10 metres to 8 kilometres. Thus providing the ability to acquire the desired information in a way that ranges from detailed to general inventory. These arguments are also valid for microwave sensors. They provide a varied spatial resolution, a collection of bands, and the capability of collecting data irrespective of weather conditions. It should be noted that Microwave sensors do not duplicate the information collected by multispectral sensors; they complement it by providing a structural description of the observed object.

A multi-sensor approach will involve a multitude of sensors, methods, parameters, hardware and software. An organisation that might undertake a task of studying the water cycle employing remote sensing will be a highly specialist one with considerable resources of money, manpower and technology. Users select the optimal system providing combination of parameters rather than the optimum combination of systems providing different parameters. The definition of the organisations operational system objectives and realistic requirements is essential for the choice of the required platform.

The observational requirements for remote sensing hydrology are listed in Table 3.2 which was prepared by Herschy et al, [1988]. The table was derived from a draft table of observational

| Required Hydrological Data | Frequency of sensor | Type of sensor | Remarks |
|---|---|---|---|
| Precipitation | Hourly<br><br>Daily | GOES, METEOSAT<br><br>NOAA-AVHRR | Extent and depth of precipitation |
| Snow Cover | Daily<br><br>Weekly | SeaSat K L bands 1978 NOAA-AVHRR ERS-1 C band 1990 !!<br><br>SMMR - Nimbus 7 | Mapping of extent - estimation of depth and snow characteristics Global coverage. |
| Water Equivalent | Weekly | ERS-1 SMMR | |
| Evaporation | Daily | NOAA-AVHRR Meteosat GOES | Radiation and Evaporation |
| Drainage systems | Yearly | MSS - TM - SPOT - SAR | Rivers slopes creeks canals |
| Land use classification | Seasonally and Yearly | MSS - TM - SPOT - SAR | |
| Aquifer systems identification | | MSS - TM - SPOT - SAR - AVHRR | Geological formation |

Table 3.1 Some hydrological requirements and the proposed sensors for delivering the required information.

Table 3.1 lists some of the Hydrological parameters, the sensors that could provide such estimates and the repeat rate of the coverage available using these sensors.

requirements for hydrology prepared by the world Meteorological organisation, and from a canvas of hydrology and water management specialist.

| Parameter | Resolution | | | Frequency | | | Accuracy | | |
|---|---|---|---|---|---|---|---|---|---|
| | max. | min. | opt. | max. | min. | opt. | max. | min. | opt. |
| _A. Precipitation_ | 100 m | 10 km* | 1 km | 5 min | 1 M* | 1 h* | 10% | 30% | 20% |
| _B. Snow-Land_ | | | | | | | | | |
| Depth | 30 m | 10 km* | 0.2 km | 12 h | 1 M* | 24 h* | 2 cm | 10 cm* | 5 cm* |
| Snowline | _30 m_ | 10 km* | 1 km* | _12 h_ | 1 M* | 24 h* | _1%_ | 5%* | 2%* |
| Snowcover | _30 m_ | 10 km* | 1 km* | _12 h_ | 1 M* | 24 h* | _2%_ | 10%* | 5%* |
| Water equivalent | 30 m | 10 km* | 1 km | 12 h | 1 M* | 24 h* | 1 mm | 100 mm* | 10 mm* |
| Free water content | 30 m | 10 km* | _1 km_ | 12 h | 7 d* | 24 h* | 1% | 5%* | 2% |
| Snow surface temp. | 30 m | 10 km* | 1 km* | _12 h_ | 7 d* | _24 h_ | 0.2°C | 1°C* | _0.5°C_ |
| Snow albedo | 10 km* | 100 km* | 25 km* | _1 d_ | 30 d* | 7 d* | 1% | 10%* | 5%* |
| _C. Lake & River Ice_ | | | | | | | | | |
| Ice line | 10 m | 100 m* | 30 m* | 1 h | 7 d* | _12 h_ | _1%_ | 5%* | 2%* |
| Continuous ice cover | 10 m | 1 km* | 25 m* | _12 h_ | 7 d* | _24 h_ | 1% | 20%* | 10%* |
| Ice concentration | 10 m | 300 m* | 30 m* | 12 h | 7 d* | _24 h_ | 1% | 5%* | 2% |
| Ice movement | 10 m | 300 m* | 30 m* | 12 h | 7 d* | _24 h_ | 5 m | _30 m_ | _20 m_ |
| Thickness | 10 m | 1 km* | _25 m_ | 12 h | 7 d* | _24 h_ | 1% | _20%_ | _10%_ |
| Surface temperature | 10 m | 1 km* | _25 m_ | 12 h | 7 d* | _24 h_ | _0.5°C_ | 2°C* | _1°C_ |
| _D. Glaciers_ | | | | | | | | | |
| Inventory/dimensions | 10 m* | 500 m* | 25 m* | 1 y* | 10 y* | 1 y* | _1%_ | 5%* | 2%* |
| Snow cover | _10 m_ | 500 m* | 25 m* | _1 d_ | 30 d* | 7 d* | _1%_ | 5%* | 2%* |
| Variation-length | _10 m_ | 100 m* | 30 m* | 1 M* | 1 y* | _6 M_ | _10 m_ | 300 m* | 30 m* |
| Mass balance | _300 m_ | 5 km* | 1 km* | 7 d | _1 y_ | _30 d_ | 5 mm | 50 mm* | 10 mm* |
| Surge monitoring | _10 m_ | 100 m* | 25 m* | _1 d_ | 30 d* | 7 d | _1%_ | 20%* | 10%* |
| _E. Surface Water_ | | | | | | | | | |
| Areal extent | 10 m | 100 m* | 30 m* | 12 h | 7 d* | 24 h | 1% | 5% | 3% |
| Sat. soil area | 10 m | 100 m* | 30 m* | 12 h | 7 d* | 24 h | 1% | 5% | 3% |
| Flood extent | 10 m | 1 km* | 100 m* | 6 h | 24 h* | 12 h | 1% | 5% | 2% |
| Flood plain | 10 m | 30 m* | 20 m | 1 y | 5 y* | 3 y* | 1% | 5% | 2% |
| Lake/river stage | 1 m | 30 m* | 20 m | 0.5 h | 4 h | 1 h | 1 cm | 10 cm | 5 cm |
| Waves, seiches | 10 m | 30 m | 20 m | 0.5 h | 6 h | 1 h | 10 cm | 1 m | 20 cm |
| _F. Groundwater_ | | | | | | | | | |
| Aquifer maps | 50 m | 1 km | 100 m | 1 y | 5 y | 3 y | 5 m | 30 m | 10 m |
| Disch. loc. rivers | 10 m | 100 m | 30 m | 1 d | 30 d | 7 d | 5 m | 30 m | 10 m |
| Disch. loc. lakes | 30 m | 100 m | 50 m | 1 d | 30 d | 7 d | 5 m | 30 m | 10 m |
| Location springs | 5 m | 50 m* | 15 m | 1 y* | 5 y* | 2 y* | 1 m | 10 m | 5 m |
| Groundwater level | 50 m | 1 km | _100 m_ | 1 d | 30 d | 7 d | 1 mm | 10 mm | 5 mm |
| Soil type | 50 m* | 1 km* | 100 m* | 1 y* | 10 y* | 5 y* | 10 | 2 | 3 |
| Moisture content | 10 m | 1 km* | 100 m* | 3 d* | 30 d* | 7 d* | 2% | _10%_ | 5% |
| Temperature profile | 50 m | 1 km* | 500 m* | _12 h_ | 7 d* | 24 h* | 0.2°C | _0.5°C_ | _0.5°C_ |
| Infiltration | 100 m | 1 km | 300 m | 1 d | 7 d | 3 d | 5% | 15% | 10% |
| Percolation | 100 m | 1 km | 300 m | 1 d | 7 d | 3 d | 5% | 15% | 10% |
| Frost depth | 100 m | _1 km_ | 300 m | _1 d_ | _7 d_ | 3 d | 5% | 15% | 10% |
| Permafrost area | _100 m_ | 1 km* | 300 m* | 1 y* | 5 y* | 3 y* | 5% | _10%_ | 5% |
| _G. Evaporation_ | | | | | | | | | |
| Evaporation | _100 m_ | 10 km* | 1 km* | 12 h* | 10 d* | 1 d* | _10%_ | 30%* | 20%* |
| Evapotranspiration | _100 m_ | 10 km* | 1 km* | 12 h* | 10 d* | 1 d* | _10%_ | 30%* | 20%* |
| _H. Water Quality_ | | | | | | | | | |
| Turbidity | _30 m_ | 300 m* | _100 m_ | _3 h_ | 24 h* | 6 h | _10%_ | 50%* | 20%* |
| Suspended solids | _30 m_ | 300 m* | _100 m_ | 3 h | _24 h_ | 6 h | _10%_ | 50%* | 20%* |
| Colour | _30 m_ | 300 m* | _100 m_ | 3 h | _24 h_ | 6 h | | | |
| Algal bloom | _50 m_ | 500 m* | _100 m_ | 6 h | _24 h_ | _12 h_ | 10% | 50%* | 20%* |
| Surface film | _30 m_ | 300 m* | 100 m* | 3 h | _24 h_ | 6 h | 10% | 100%* | _20%_ |
| Surface water temp. | _100 m_ | 10 km* | 500 m* | _6 h_ | 30 d* | 7 d* | _0.2°C_ | 1°C* | _0.5°C_ |
| Temperature profile | 0.5 m | 10 m | 5 m | 1 d | 60 d | 15 d | 0.2°C | 1°C | 0.5°C |
| _I. Drainage Basin Characteristics_ | | | | | | | | | |
| Drainage area | 10 m | 100 m* | _20 m_ | 3 y* | 10 y* | 5 y* | 0.1% | 1% | 0.5% |
| Channel dimensions | 5 m | 100 m* | 10 m | 1 y* | 5 y* | 3 y* | 1% | 5% | 3% |
| Overland flow length | 5 m | 100 m* | 10 m | 1 y* | 5 y* | 3 y* | 1% | 5% | 3% |
| Surface slope | 5 m | 100 m* | 10 m | 1 y* | 5 y* | 3 y* | 1% | 5% | 3% |
| Land cover type | 50 m* | 100 m* | 200 m* | 3 m* | 1 y* | 6 M* | 0.1% | 1% | 3% |
| Albedo | _20 m_ | 100 m* | 50 m* | 1 h* | 7 h* | 6 h* | 2% | 10% | 5% |

**Legend**

_Frequency:_
min = minute; h = hour; d = day; M = month; y = year

_Requirements:_

maximum — The highest resolution, frequency or accuracy of defining a certain parameter which can be used in a beneficial manner. A value higher than this maximum could be considered as providing more data than can be beneficially used considering the state of the science. Cost need not be considered.

minimum — The lowest resolution, frequency or accuracy of defining a certain parameter which can be used to provide a meaningful service. A value lower than this minimum would be considered as useless. Consideration of cost could be a significant factor in this case.

optimum — The resolution, frequency or accuracy which is expected to provide the best relationship among technical, scientific and economic factors.

_Feasibility:_
100.00* = Requirement usually fulfilled with existing satellites.
_100.00_ = Requirement may be fulfilled with near-future satellites.

_Note:_ When a value is neither asterisked nor in italics, this observational requirement cannot usually be met either by existing or planned future satellites, given the present state of the art in satellite hydrology.

Table 3.2 _Observational requirements for hydrology which satellite remote sensing might be usually expected to meet, classified in terms of the feasibility with which these requirements may be met by present, and planned future, satellites._

Three of the four hydrological parameters considered in this thesis are listed in Table 3.2. These parameters are precipitation, snow, and evaporation. Although temperature, the fourth parameter, was not listed in this table the measurement of evaporation and the processing of snow data is intertwined with it. The observational requirements for temperature is linked to the observational requirements of those two parameters.

The resolution of the sensors required for the measurement of the different parameters for the four parameters vary from 30 metres to 10 kilometres. The optimal resolution of the sensor, for each of these parameters, is 1 km.

Another observational requirement of the sensor is the repeat rate of the coverage. Hydrological parameters are listed in Table 3.1 along side the repeat coverage and the sensors that are capable of delivering the required images. Three of these sensors appear for all the required parameters; Meteosat, NOAA and GOES. Meteosat does not provide the desired resolution of 1 km. The case study of this project is in the United Kingdom which is high in latitude where GOES images suffer great distortion as the GOES satellite is stationed over the equator. This leaves the NOAA-AVHRR satellite as a sole provider of satellite images with the required resolution and repeat rate. It should be noted here that AVHRR provides an optimum solution for the required parameters and is restricted in its applications, as it cannot provide adequate coverage of rain storms because of the limited slots per day available from this sensor. The sensor to use for these cases should be either GOES or Meteosat. During cloudy days, AVHRR cannot provide snow mapping or temperature estimates. A case for microwave sensors, alas there is no microwave imaging satellite in orbit currently.

AVHRR provides the required coverage, within the realm of this project, on both levels of time, repeat rate, and resolution. It is capable of providing estimates of the desired hydrological parameters as it will be explained later in this Chapter. Thus, AVHRR is an optimal system for use in this project. Other considerations for the selection of AVHRR as the sole provider of parameters estimates range from the technical to economic factors. Integrating several sensors estimates into one system is a huge task that requires considerable funds and extensive case study to cater for the various repeat rates of the different sensors.

AVHRR physical characteristics and properties were illustrated in Chapter two Section 2.3.3.2. The price of AVHRR imagery is relatively cheap and is readily available. The resolution of AVHRR imagery restricts the use of it to basins that are $\geq 200$ $Km^2$. The repeat rate of an AVHRR is twice a day thus limiting daily images to four, as there are two AVHRR instruments flying at a time, thus reducing the accuracy of the precipitation estimations in comparison with geostationary sensors. On the other hand, the resolution of geostationary satellites degrade as the position of the basin under study geographic latitude increases towards the south or the north.

### 3.3.2 Description of the AVHRR instrument.

The Advanced TIROS-N (ATN) NOAA series house among other sensors the Advanced Very High Resolution Radiometer (AVHRR)

[Schwalb 1978]. This sensor is comprised of five modules which are assembled together to form a single instrument.

1- Scanner modules.

2- Electronics modules.

3- Radiant cooler.

4- Optical system.

5- Baseplate.

*The scanner module* houses the part of the AVHRR instrument that generates the scan lines of an image. This module is composed of the following an 80-pole hysteresis synchronous motor, the motor housing, and the scan mirror. The mirror is rotated continuously at 360 rpm by the scan motor. The rotating mirror scanning the field of view and the satellite motion along the orbit generate successive scan lines contiguous at the subpoint.

*The electronics module.* Electronic functions are carried in this module. These functions include data processing, temperature control, telemetry generation, and scan and motor logic.

*The Radiant Cooler* Provide constant temperature for the functional operating of the instrument of $105^0$ K.

*The Optical subsystem* consist of an afocal aperture telescope combined with secondary optics which separate the radiant energy into discrete spectral bands which are then focused onto their respective field stop.

*Baseplate* is the structure that the different modules are secured to.

### 3.3.3 Data generation, image and telemetry.

The mirror in the scanner module rotates as the sensor is in motion producing a across track scan lines. The instrument uses three kinds of detectors to measure radiation intensity for the different channels. (See Table 3.3) The detectors register the incoming rays. A series of functions are carried, illustrated in Figure 3.2, on the electric signal before its registration.

| | | | | |
|---|---|---|---|---|
| Detector ➡ | Pre - Amplifier ➡ | Post - Amplifier ➡ | Multiplexer ➡ | A/D Convertor ➡ |

| | |
|---|---|
| Output Register ➡ | Buffer Manipulation Information rate processor (MIRP). |

Figure 3.2 Flow of electric signals from detector to storage.

| Channel No. | Wavelength µm | Detector type | Purpose of channel |
|---|---|---|---|
| 1 | 0.58 - 0.68 | Silicon | Cloud mapping |
| 2 | 0.725 - 1.0 | Silicon | Surface water boundaries |
| 3 | 10.3 - 11.3 | Hg-Cd-Te | Thermal mapping |
| 4 | 3.55 - 3.95 | In-Sb | Water vapour correction. |
| 5 | 11.5 - 12.5 | Hg-Cd-Te | Water vapour correction. |

Hg-Cd-Te Mercury Cadmium Teluride
In-Sb Indium Antimonide.

Table 3.3 Spectral channels, detectors, and design purposes.

Every time the scan line is completed the detected energy is restored to a preset zero level. The electronic signals are sampled at 40-KHz by MIRP. An internally generated ramp is internally produced, for validation of linearity of the instrument, by an on board voltage divider. The electronic signal is then converted by the A/D converter to counts ranging between zero and 1023.

During each scan line the instrument view cold space and its housing. The housing portion acts as a black body target for instrument calibration. Four Platinum Resistance Thermometer (PRT) are used to monitor the temperature of the black body.

### 3.3.4 AVHRR Data Formatting.

The AVHRR data is beamed down to earth together with the data generated from the other sensors on board the satellite. It is located in two sections of the High Resolution Picture Transmission HRPT. The images are send to users in the U.K. on magnetic tape. Each image contains two sections header and video data. The radiometric calibration data and telemetry information are contained in 103 word long header. The radiometric earth view data are located after the header information in the video data section. The length of the video section is 10240 words made up from 2048 ten-bit words per channel. This data is channel multiplexed. See Appendix 1 for a detailed description of the header and video data.

The spectral response of the AVHRR imagery is registered between zero and 1023. Thus, the maximum spectral response that AVHRR can register is 1024. Ten bits are needed to register this number, 1111111111 base two = 1023, the sensor transmits this information to ground receiving stations in this format. No modification on this data is done on the satellite. The reasons behind this are the following:

1- reduce the amount of unnecessary processing on the platform.

2- Less data to be transmitted to ground stations.

3- Conserves satellite usage of energy

4- The saving in computing and power facility produce reduces the weight of the platform.

See Section 4.4 for information on the representation of this data in computer memory.

### 3.3.5 Orbit configuration of AVHRR.

AVHRR orbits the Earth in a near-polar sun - synchronous orbit. The altitude of this sensor is 833 km with a period of orbit of approximately 102 minutes thus, completing around 14.117 orbits per day with a $25.5^{O}$ distance between successive orbits. As the number of orbits per day is not an integer the sub-orbital tracks differ from one day to the other. The sub-orbit is repeated every 4 to 5 days for even numbered NOAA missions, -6 -8 & -10, and 8 to 9 days for odd numbered missions -7 and -9. However, the local solar time for the satellite passage over any latitude remains unchanged [Kidwell K.B., 1986].

The swathe width of the sensor during any particular orbit is 2400 km. The resolution of the image degenerates as the registered pixel is further away from the the nadir. The IFOV at nadir is of a 1.1 X 1.1 km while it degenerates to 2.4 along track X 6.9 across tack km. The comparative position, of an individual point on Earth, varies from one AVHRR image to another. Hence, the relative pixel size varies for the same point on the different images. The rectification of this situation is done through the use of geometric correction. (See Section 4.3)

At any time there are two NOAA satellites orbiting Earth. The two satellites used in this project were NOAA -8 and NOAA-9. The equatorial crossing times, north-bound crossing, for the two sensors are 19h 30min and 14h 30min respectively. The south bound crossing times are 07h 30min and 02h 30min respectively. The two sensors provide four images, some times called slots, per day for any point on Earth.

### 3.4 Choice of Methods.

Different methods are used for providing estimates of the different hydrologic parameters. In order to build the procedure proposed in the last section individual methods had to be selected to work with. The method selected for each parameter, are listed below as well as methods for the processing and storage of the produced data:

1 - The Bristol Method (PERMIT) for precipitation.

2 - Seguin & Itier for evaporation.

3- Algorithms advised in NOAA Technical Memorandum NESS 107 for the estimation of temperatures of remotely sensed images utilising the infrared channels of the satellite .

4 - The Snow Runoff Model (SRM) for the hydrology model.

5 - ORACLE Database for storage and data manipulation.

6 - Harrison and Lucas Method for Snow mapping.

The following aspects of each method will be discussed in the reminder of this Chapter:

1 - Theory behind the work.

2 - Reliability and convenience of the method.

3 - Criteria for selecting the method.

4 - How does the method fit in this work.

A common feature of all the methods selected and used in this project is the fact that they use, or had the potential to use, AVHRR imagery. This was an influencing factor for the selection of these methods. The compatibility of input information is an important feature that provides a pragmatic approach to the integration of different methods in a unified system.

## 3.5 Precipitation.

### 3.5.1 Introduction.

Numerous methods exist, for the production of satellite estimates of precipitation. A selection of the different methods were previewed in Section 2.5. The method selected for use was the Bristol method. It is a cloud indexing method i.e. remote sensing images are assigned indices relating to cloud cover and probability and intensity of associated rain. The theory and the different techniques of the Bristol Method will be discussed and commented upon in this section.

### 3.5.2 Theory behind Satellite Rainfall Estimation of the Bristol Method.

Polar orbiting and geostationary satellites provide images of the cloud cover throughout the day. Twice for the polar orbiter and significantly more from the geostationary. It has been shown, [Moses & Barrett 1986], that cloud imagery can be used as a guide to rain falling some time before or after the observation, and obviously during observation time.

The relationship between the rainfall and time can be approximated in the following form:

$$R = (1/n) \sum_{i=1}^{i=n} Rt_i + \sum_{i=1}^{i=n} ARt_i$$

Where

- $R$ = the rain fall observed over a period of time.
- $Rt_i$ = is the rainfall per unit period at satellite observation time $t_i$.
- $i$ = observation time.
- $n$ = number of observations.
- $ARt_i$ = an allowance for rainfall, from analysed clouds, that have developed between observation times.

The central assumption in the Bristol Method is that the rain fall is a function of several parameters

$$R = \sum ( C_t, C_a, S_w, M_c )$$ where

- $R$ = Rainfall,
- $C_t$ = Cloud Type according to Specially prepared menu,
- $C_a$ = Fractional cloud cover of a prescribed grid square,
- $S_w$ = Synoptic weather,
- $M_c$ = Terrain Influence on rainfall.

[Barrett 1989]

### 3.5.3 Techniques of the Bristol Method.

The Bristol Method was first envisaged and used on hard-copy polar orbiting satellite imagery. It was later on supplemented by an interactive version BIAS, the Bristol/NOAA Interactive Scheme, for the use in the AgRISTAR program, an objective version was also introduced ADMIT. The ADMIT is a bispectral technique. It rely on the assumption that clouds producing rain has the following characteristics high cold cloud tops. This could be detected in satellite imagery in the visual (VIS), and InfraRed (IR) bands. Clouds which are bright in the VIS (highly reflective) and the IR (high altitude of tops of cloud indicating coldness) band are highly likely to be producing precipitation. A less complicated objective technique was introduced the PERMIT (Polar-orbiter Effective Rainfall Monitoring Integrative Technique).

The PERMIT technique is the one used in this thesis. It was firstly introduced for aggregating rainfall over selected areas for general monitoring and inventory purposes.

PERMIT is a thresholding technique relying on the following assumptions:

a) - The daily cloud areas may be mapped from appropriate temperature thresholding for four infrared image slots per day for the polar-orbiting satellite.

b) - For periods of 10 days and upward, reasonable first approximations of estimates of rainfall can be achieved by multiplying the satellite derived maps of accumulated numbers of raindays by a mean rainfall per rain-day statistic derived from climatological atlases [Leroux 1983]. PERMIT can be used for polar orbiting and geostationary satellites. In the case of polar orbiting, four slots are used. Note that more slots could be used when using geostationary satellites images. The method relies on the availability of historic data. Which might not be available for some areas were satellite observations could be of most use.

The quality of PERMIT estimates is rough since it derive these estimates in the first place for 10 days or more. If it is to be used for daily estimates Barrett et al. [1986] advise the introduction of a subroutine to weight the estimates according to whether rain cloud was locally present for 1,2,3 or as many slots as there are per day.

This technique was only used for tropical weather systems and is being used in low latitude in a recent study. The PERMIT technique being an objective one is well suited for a fully computerised procedure of an hydrological study. This is the first time the PERMIT technique has been used for the production of precipitation estimates for high latitudes which will result in determining its suitability for these areas.

## 3.6 Temperature.

### 3.6.1 Introduction.

The measurement of temperature from a satellite is made possible through the utilisation of the IR channels. Heat is convected through Infrared radiation so it is only logical to use IR channels, which register the thermal brightness of a scene, to deduce temperatures of different scenes. This is done through the processing of the information collected of the scene. Calibration data are needed for this processing. In this section the information available on the IR channel and the calibration data will be described.

### .3.6.2 Physical collection of the data.

The theory behind measuring temperature of a distant object is universal. The detailed process of temperature measurement is instrument dependent. The satellite used for this project is the Advanced Very High Resolution Radiometer AVHRR. A section will be devoted later on to talk about the physical properties of AVHRR and argue the case for its use. Still in this section the mechanism of collecting data, calibration and scene, for Tiros/N AVHRR is described in order to establish the understanding of the detailed process of temperature measurement.

In order to measure temperatures from a distance it is needed to measure

1 - The intensity of the thermal radiation emitted by that body,

2 - Have a system of reference to serve as a standard, a black body, a perfect absorber of incident radiation. [Siegel & Howell,1981]

The first conditions is provided for in a satellite by the infrared channels registering images as thermal radiation are transmitted in the infrared region of the electromagnetic spectrum. The system provides, the standard, the black body which is flown on the satellite fulfilling the second condition.

The infrared region, on the spectrum of electromagnetic radiation, falls between 0.7 and 1000 um; the near infrared being in the range 0.7-25 um. The spectral registration of the AVHRR is as follows

| Channel 3 | Channel 4 | Channel 5 |
|---|---|---|
| 3.55-3.93 um | 10.3-11.3 um | 11.5-12.5 um. |

This implies that the range of all the AVHRR-IR channels lie in the near infrared region.

Each AVHRR image contain the necessary information to carry out the calibration of the image for temperature processing purposes. Those being the reading of the on board blackbody and space view of a scene. The AVHRR data is organised in the following manner a header and following that the image of the scene. The header contains the radiometric calibration and the telemetry information. The radiometric Earth view data which follows are labelled AVHRR VIDEO. (See Appendix 1)

The temperature of the internal blackbody is monitored by four Thermistors or Platinum Resistance Thermometers PRT.

### 3.6.3 Thermal Channels and Temperature Calculation.

The process of calibrating and calculating the temperature of an AVHRR scene is long and complicated. The information on this process is scattered all over the publications of NESS-DIS National Environmental Satellite, Data and Information Service. The following is an attempt to present the information in a structured way that will help a non-expert to follow the process. To start from the end product and work from the back to the beginning is the simplest of ways.

Temperature is calculated from the following formula:

$$T(E) = C2*V/\ln(1+C1*V^3/E) \qquad [Eq.3.1]$$

Where T is the temperature in Kelvin.

V is central wave number of the channel filter.

C1, C2 are two Constants.

E is the Energy Value.

E is calculated from the following equation

$$E = G*Ç+I \qquad \text{[Eq. 3.2]}$$

Where Ç is the Count reading of the VIDEO data of a thermal channel.

G is the Gain of the corresponding channel.

I is the Intercept of that channel.

Gain and Intercept are both calculated for each channel. This is done from the calibration information, internal blackbody and space radiances.

The equations for the calculation of G and I are both derived from Equation [Eq. 3.2].

$$E_T = G * Ç_T + I \quad \text{AND} \quad E_{SP} = G * Ç_{SP} + I$$

$$\Rightarrow \quad G=(ET - E_{SP})/(ÇT - Ç_{SP})$$

$$I=N_{SP} - G*Ç_{SP}$$

Where $E_T$ = radiance of the blackbody.

$E_{SP}$ = radiance of deep space.

$Ç_T$ = mean count of internal target observation.

$Ç_{SP}$ = mean count of space observation.

$Ç_T$ and $Ç_{SP}$ are calculated by averaging telemetry data for internal blackbody and space respectively. $E_{SP}$ is provided by NESS-DIS this leaves $E_T$ as an unknown. $E_T$, the blackbody radiance, can be calculated from the average temperature of the blackbody. This is done as follows:

$$T_i = \sum A_{i,j}*(PRT_i)^j \qquad \text{[Eq. 3.3]}$$

Where $T_i$ is the temperature for PRT counts, i=0,1,2,3,4 and j=1,2,3,4. Values for Ai,j are provided by NESS-DIS. PRT's are available in the header information as described in section 3.3?. The average temperature T is of the black body is calculated from the summation of Ti with the use of weighting factor Bi.

$$T=\sum B_i * T_i \qquad i=1,2,3,4$$

The radiance of the blackbody is calculated, using the average temperature, by substituting in [Eq.3.1] and solving for $E_T$.

The above process resulted in the calculation of the gain and intercept of the image. In order to calculate the temperature of a pixel in a scene, the count of the video data, of the desired channel, referring to this pixel is used to calculate energy value of the pixel using equation 3.2, the energy value is the substituted in equation 3.1 resulting in the temperature value.

The calculation of a scene's temperature is dependant on implementation of the above mentioned theory. Their is no alternative as this procedure is particular to AVHRR imagery. The only variation that could be applied on the result of these estimates is by manipulating the calculated temperatures using empirical equations to correct for the distortion of the spectral response due to the existence of the atmosphere between the AVHRR instrument and the object which temperature is being measured, ground or clouds.

## 3.7 Evaporation.

### 3.7.1 Introduction.

As in the case of temperature the estimation of evaporation from space born platforms is dependent on the use of the thermal infrared data. Evaporation estimates depend on many factors ranging from the type of soil air, humidity, air pressure, net radiation and air and soil temperatures. Regardless of this fact, recent studies [Vidal et al. 1987, Lacaze 1987, Seguin & Itier 1982] have shown that evaporation could be estimated employing a simplified equation incorporating air temperature net radiation and satellite estimate of land temperature. One scene per day was found to be enough to carry on the exercise.

### 3.7.2 Basis of remote sensing of evaporation.

The theory of thermal inertia properties of the soil and the radiation budget of the air provides the basis of remote sensing of evaporation. Thermal inertia is related to soil porosity. Soil porosity is related to two factors, water content and the diurnal thermal cycle the soil experiences. Water has a higher thermal capacity than soil by virtue of having a higher specific heat. The wetter the soil the higher its thermal capacity. [Gillespie and Kahel, 1977]

Hence the thermal inertia, thermal inertia = conductivity X (thermal capacity)$^{1/2}$, of the soil can be obtained. The picture of the ground surface temperature is complicated by other factors like wind velocity, land characteristics, type of vegetation.

The large number of micrometeorological parameters complicates the process of using the concept of thermal inertia in remote sensing of evaporation. Seguin & Itier [1982] showed that it is possible to use midday surface temperature to estimate daily evaporation. This is done by utilising a simplified relationship

$$ET_d = Rnd - B(Ts - Ta)$$

where $ET_d$ = daily evaporation.

$Rn_d$ = daily net radiation

B = a constant.

Ts = temperature as measured by satellite.

Ta = air temperature.

The constant B is specific to each region. At least one correct ground reference is needed for calibration purposes.

The use of this relationship results in modest precision of results over 2-4 weeks. However the results compare favourably with methods describing spatial variation of evaporation.

The reasons behind selecting this method are listed below:

1- The simplicity of this method over the thermal inertia method.
2- The limited use of the satellite imagery.
3- The spatial description of evaporation estimates.

Those reasons are also complemented by the fact that all other methods that use one image per day to deduce evaporation use the same formulae. The variations between the different methods lie in the quntification of the parameter B. This parameter is dependent on the various physical conditions prevailing in the study area.

## 3.8 Snow Mapping.

### 3.8.1 Introduction.

Snow extent is affected by the prevailing physical conditions of the basin the morphology of the basin, temperature, and wind, speed and direction, affects the variation in the depth of the snow pack. The characteristics of the falling snow is variable from one day to the other as it is dependent on several factors, atmospheric temperature, wind cycle and type of the snow storm.

The delineation of the snow extent could be done using different sensors. A survey of the different sensors and their effectiveness were discussed in Chapter two. Different approaches, also exist, of utilising sensor data for the mapping of the snow cover.

Different techniques are available for the utilisation of NOAA - AVHRR data. These techniques range from pattern recognition, spectral signature of snow, and the employment of multiple wave bands. The method chosen for the mapping of the snow extent is a method introduced by [Harrison and Lucas, 1989]. Their method applies a multi-spectral approach for snow detection using the AVHRR instrument. It utilises three channels, channel -1 channel -3 and channel -4, to discriminate between snow and cloud. The work is carried on using a clustering technique available on the International Imaging System ($I^2S$) (details of the operational execution of the mapping are provided in Section 4.6). This method is the last of several methods utilising the multispectral capability of AVHRR.

### 3.8.2 The hypothesis behind multispectral classification of Snow.

Snow/Cloud discrimination is primarily dependant on the thermal infrared channels 3 and 4 of AVHRR. Snow appears darker than clouds in channel 3 images. This is attributed to the size of the particles that constitute these clouds. If these particles size exceed the wave length of channel 3 (3.55 - 3.93 μm) light waves of this wave length will be reflected causing the cloud to appear very bright in comparison with snow. If the cloud was composed of particles smaller than the channel's wave length snow and cloud will overlap.

The tops of clouds are much colder then snow. This is clearly registered in channel four permitting the separation of cloud and snow. Low clouds have relatively higher temperatures than high clouds thus their spectral response overlap with that of snow. The spectral response of snow and cloud overlap considerably in Channel 1, however the snow/no snow contrast for land areas is strongest in this channel. Heavy canopy, i.e. forests, may also obscure the appearance of snow.

The above characteristics are shown in Figure 3.3. The spectral response of a scene in the north of Britain is plotted in the feature space of channel 3 and channel 4 against channel 1. The spectral response is separated into different classes according to the type of the observed features.

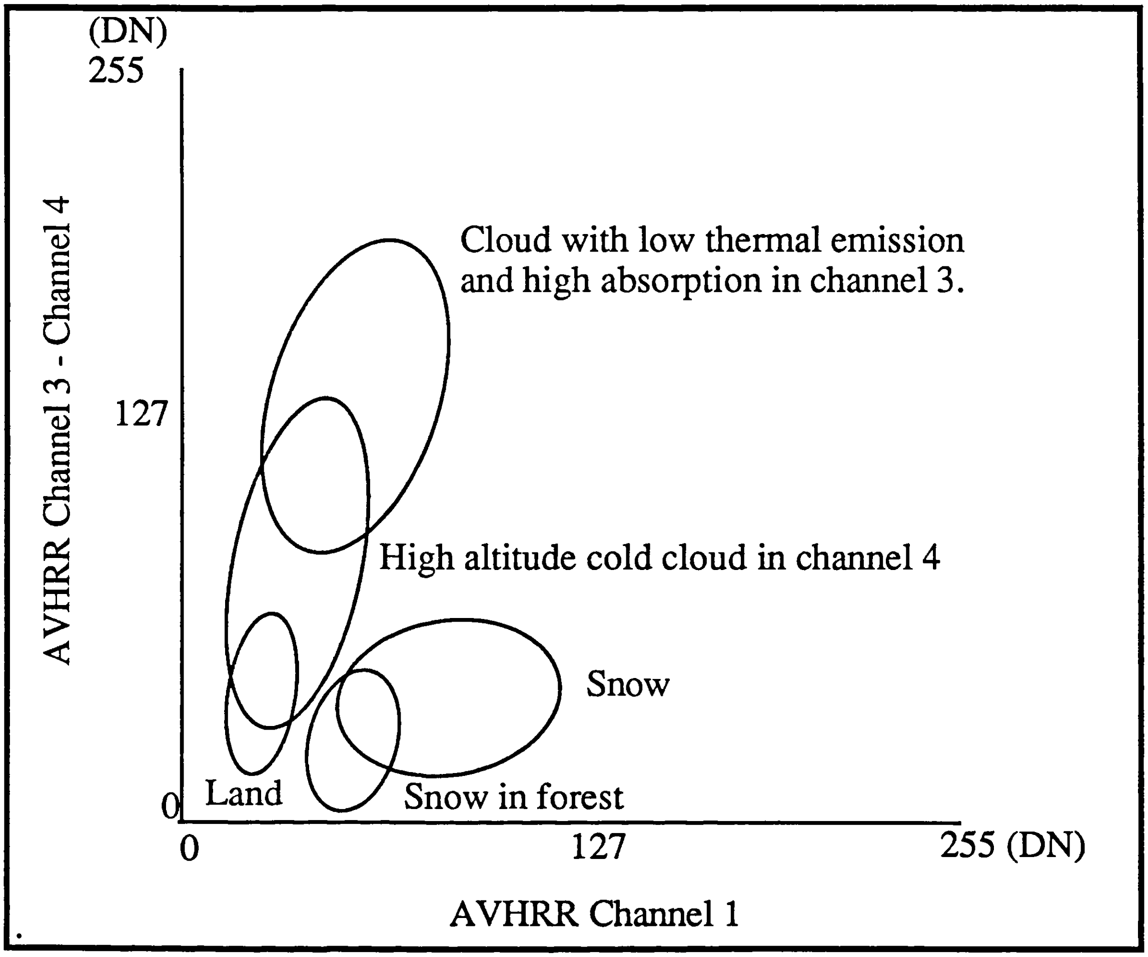



Figure 3.3 Modelled ellipse of class distribution within the feature space of Channel 3 and channel 4 for northern Britain (10 February, 1986) showing the distribution of cloud, snow, snow free surfaces, and snow in forest.(Source Lucas and Harrison 1989)

With the above knowledge an unsupervised multi spectral classification was considered utilising a clustering technique available on the $I^2S$ System 575 software package. The results of this technique were reported in the literature in three papers in which they claim error rates of less than 2 per cent.

### 3.8.3 Appraisal of multispectral classification and mapping of snow.

The reliability of this method is closely linked to the cloud cover, since the sensor is hindered by cloud cover and is not like microwave sensors which can map regardless of the cloud cover. On the other hand the frequency of imaging and the high resolution of the AVHRR coverage, in comparison with radiometric sensors, compensate for the loss of mapping days. This state of affairs will not stay the same as with the introduction the ERS-1 and the Japanese ERS. Both will be capable of using their radar system to deliver snow mapping capabilities regardless of the cloud cover. ERS-1 will use the L band which is not the best system for snow mapping as it is intended for sea applications. The Japanese ERS, intended for land applications, will carry a SAR system equipped with an X band sensor which flight experiments had suggested is suitable for snow mapping.

This method was selected for inclusion in this project because of its deliverance of the delineated snow in a reliable way, for all cloud free day during the snow fall period. The resolution of the AVHRR imagery relates the snow mapping to basins that are at least 200 $Km^2$. The basin of this project is 282 $Km^2$.

Processing the AVHRR imagery on the $I^2S$ system facilitates the extraction of the snow data of the study basin, in a manner compatible with the rest of the hydrological parameters as discussed earlier (details of the extraction procedure are explained in Section 4.3).

This method relies heavily on user intervention after the classification process has been performed. The user has to identify manually the snow classes and the cloud areas.

The identified snow classes yield two kinds of information, the location and extent of snow classes, and the type of snow classes. The different classes of snow could be related to a certain physical status of the snowpack, wet snow, hard snow, degree of melt etc.. These data are deduced either by the availability of ground truth or through the user's individual proficiency. The use of this information is varied in our case, hydrological modelling is dependent on the hydrological model being used. However, the mapping of snow is of great importance for other applications such as land classification and degrees of saturation of the subsurface strata.

## 3.9 Hydrological Model.

### 3.9.1 Introduction.

The parameters produced by the different methods are intended for the use of a hydrological model. The model selected is the Snow Runoff Model SRM. The available types of hydrological models were listed in the last Chapter Section 2.4. In the following the selected model will be discussed and categorised.

### 3.9.2 Categorisation of the Snow Runoff Model (SRM).

Models are usually classified into one of the general headings mentioned previously. Some models may fall into one or more of the generalised headings. The model used in this study is The

Snow Runoff Model (SRM) falls into several categories namely conceptual, lumped, continuous or event, and general model. The SRM simulate the discharge of the basin through the utilisation of an empirical formula thus rendering it as a conceptual model. The basin area representation in the model through the division of the basin into zone areas. Zone areas are selected according to elevation/area ranges. Data input for each zone area are lumped into a single value. Thus the model is also in the lumped models category. The model can be used either as an event model or a continuous model because the SRM can simulate or forecast for either the snowmelt period or around the whole of the year. Although outside the snowmelt period, special attention will be needed to incorporate the effect of evapotranspiration. The model was first developed and used on small European basins. It was later used on basins ranging from 2.65 $Km^2$ to 4000 $Km^2$. Hydrologic parameters are entered individually for each of the basins. Thus the model is a general one. The snowmelt runoff model (SRM) developed by [Martinec 1975] for mountain basins <50 $Km^2$ has been recently extended to large river basins (200 - 400) $Km^2$ and been used with MSS images by Baumgartner and Seidel et al. [1986]

In addition to the snow cover data, daily temperature and precipitation data are required inputs for the (SRM) model. Other parameters must be determined for the model operation: degree-day factor, runoff coefficient, recession coefficient, temperature lapse route and discharge time lag.

This model can be used for a variety of conditions including rain on snow situation. The average absolute error between actual and simulated runoff for nine basins was 3% [Rango 1983]. Further details of the SRM are available in The Snow-Runoff Model (SRM) User's Manual 1983.

### 3.9.3 Evaluation of SRM Characteristics in relation to this study.

The SRM is a flexible and a versatile model. As seen in the previous section the model is capable of running in simulation mode and forecasting mode. The model can be operated for both snowmelt and non - snowmelt situations for up to 366 days. Eight basin zones are accommodated. The model can run in the forecasting mode from one day to several weeks. The data requirements for operation are versatile and flexible. Input can be entered by zone or for one zone and then extrapolated.

The SRM was selected for use in this study because of its versatility on both levels, operational and data input. The capability of using the model for non-snow runoff situations eliminates the need for a surface runoff model. The capability of running for short periods and long ones provides the flexibility of running the model for isolated events and for a year long. The data input requirement of the SRM are not very rigourous. Two or three satellite scenes are enough for mapping of snow extent. The data for the missing days is interpolated. Temperatures are entered as either max - min or as degree days and can be interpolated to other zones.

On the other hand, the lumped approach of the SRM towards the simulation of the hydrologic process, strips remote sensing methods, i.e. the methods of estimating hydrological parameters utilising remote sensing, from their major advantage of providing a distributed description of the different parameters over the basin. A disappointing factor of SRM in this study is its failure in utilising all the information available through the use of remote sensing data.

The system built in this study should be capable of providing data for any kind of hydrological model. Hence, the compatibility of SRM should not be a problem. It would have been beneficial to use a distributed model rather than a lumped one. However the use of SRM provided the chance to take into consideration the data requirements of lumped models.

### 3.10 Summary and overview.

This chapter has set the stage for following and a description of the execution of this project. It has defined the project undertaken and selected a method for the production of estimates per hydrological parameter. Thus, the different components of this project are now defined. At the outset of this Chapter the mechanism of the proposed project was presented in Figure 3.1, more details can now be included in this figure, as a result of the presentation of the last chapter. The result is Figure 3.4.

The methods chosen here for incorporation in this project have a common feature of using the images of AVHRR. This feature unifies the input data source. The output of the different parameters is thus compatible and can be integrated and geographically referenced in a uniform way.

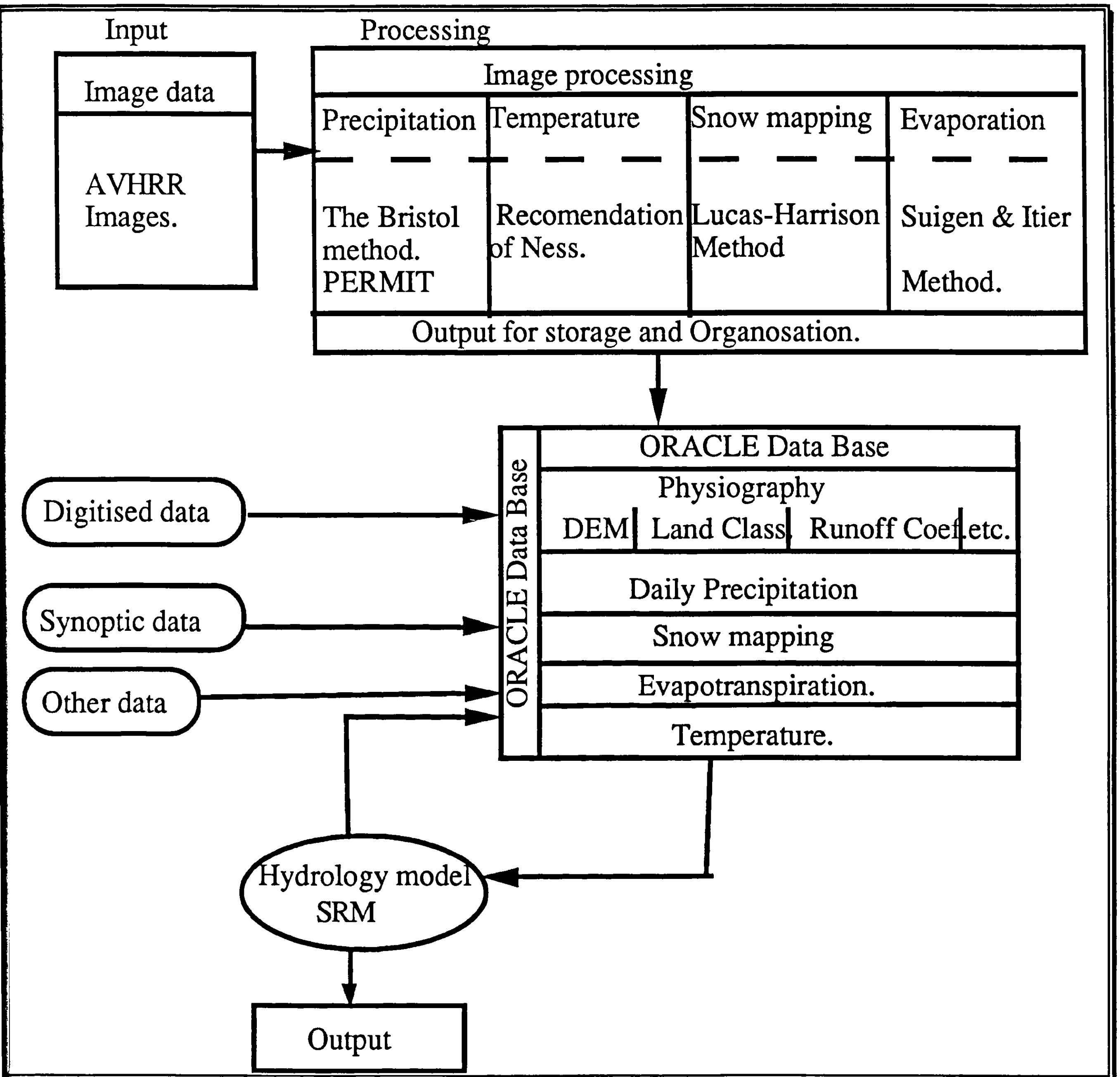



Figure 3.4. Details of the different components of the project, as defined after the presentation of Chapter Three.

The convenience of having a unique sensor as a source of information was not gained on the expense of quality of the provided information. The reasons behind the selection of AVHRR are as follows.

1- Derived parameters are expressed in the same dimensions thus the varying accuracies originating from combining different resolutions are eliminated.

2- The data provided by AVHRR can provide the desired information without a detrimental effect on the degree of accuracy on the resulting estimates.

3- The data generated from AVHRR imagery is relatively detailed, i.e. in comparison with sensors of lower resolutions. Learning how to manage and effectively use it will be the first step in learning how to manage and maintain more detailed sources of data.

4- The use of other sensors for the provision of additional information is restricted by two factors:

a- The additional information is not useful for the processing of the other hydrological information by the hydrological model.

b- The increased sensitivity in recording information, resulting from the use of better resolution, will not produce an increased efficiency of the overall hydrological modeling.

The different methods selected for use in this project are the state of the art in the technology for the processing of AVHRR information.

# Chapter Four.

## Processing of Image Data to Hydrological parameters.

### 4.1 Introduction.

The required data for a hydrological model is composed of several varied components making the provision of a sensor system that provide all these information that much more desirable. At the same time this presents a difficulty in advising different methods for estimating different parameters using the same device. The instrument chosen and used in this project is NOAA/AVHRR. The benefits of using AVHRR imagery has already been established in Chapter Three. This thesis is concerned with the establishment of a process for the production of estimates of the following parameters, precipitation, temperature, evaporation, and snow cover.

This study concentrated on the building of a coherent procedure starting with the raw satellite imagery and ending with the hydrological parameters of the modelled basin being delivered to the hydrological model. This procedure is composed of several stages. Each stage incorporates a set of steps.The first stage of this procedure, Figure 4.1, is concerned with the preprocessing of the raw imagery. This process involves the following functions :

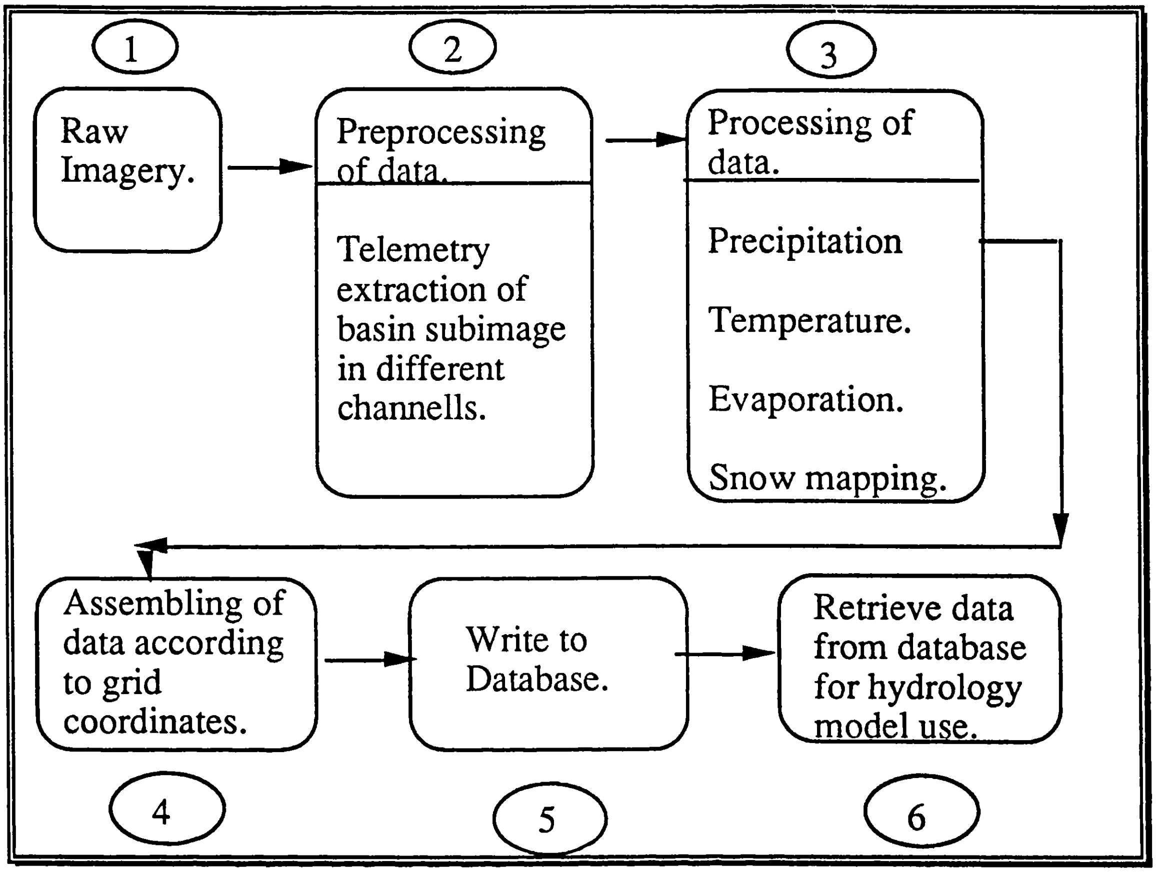



Figure 4.1 Flow of data in the different processing stages from raw imagery to hydrologic modelling.

1- Extraction of telemetry data.

2- Geometric correction of the image.

3- Extraction of the pixels, for all channels, corresponding to the study area of this project. (refer to end of this introduction) These pixels compose part of the whole of the AVHRR scene referred to as a subimage. AVHRR imagery is composed of five channels, the extracted subimage is also composed of five channels.

The second stage is the processing of the subimage data to the different hydrological parameters namely:

1- Precipitation.

2- Temperature.

3- Evaporation.

4- Snow mapping.

The product of this step is a binary image of the basin for each of the different parameters. The snow mapping is done for the whole of the image. The extraction of the subimage of the basin is done afterwards. (See Section 4.7)

The third stage of the procedure is the assembling of the data in the numeric format of a grid. The product of this stage is a file of numeric data where each parameter estimate, refers to a corresponding grid coordinate.

The fourth stage is the loading of the data to the database. The fifth stage involves the retrieval of the data from the data base and assembling then it in a form compatible with the hydrological model.

The first two stages are the subject of this chapter. The last three stages, comprising the processed data manipulation section of this project, will be dealt with in the following chapters.

A case study was carried on a basin in Great Britain. A detailed description of the basin and the reasons of selecting the area and date of study are provided in the following chapter. All that is needed to be known at this stage is that the basin is on the River Aire in Yorkshire and it is enclosed in a rectangle of 20 by 27 kilometres.

## 4.2 Hardware and Software used.

The preprocessing stage needed a set of hardware and software facilities. The hardware and software available at department of Photogrammetry and Surveying were:

1 VAXstation II/GPX.
2. Digitising table, DATATAB of Laser Scan Laboratories Ltd.
3. Lites2 software from Laser Scan Laboratories Ltd.

The hardware and software available in the department of Geography were:

1. VAX station II
2. International Imaging System ($I^2S$) Model 75

The VAXstation II/GPX is a stand-alone, 32-bit workstation based on the MicroVAX II processor. It has two operating systems ULTRIX-32 and MicroVMS, the later was the one used for this project. The operating system offer workstation software, networking software, and a wide range of tools and applications. A video subsystem is based on Very Large Scale Integration System (VLSI) graphics coprocessor which handles computation intensive graphics tasks through the use of parallel processing. The graphic facility is provided through the use of a Color Video Monitor. A Graphic Kernel System (GKS) acts as the graphics interface for the VAXstation II/GPX.

The Lites2 software is an interactive graphical editing program designed for use on cartographic data. It might be used with or without graphic interaction. For Graphic interaction it needs an LSL-supported GKS workstation configuration. It can run on a VAX series computer under the VMS operating system. The software also runs a digitising table ALTEK DATATAB with a 16 button cursor.

The $I^2S$ Model 75 is a sophisticated refreshable display unit, handled by the VAX host computer as a peripheral. It is composed of a large Fortran program, the $I^2S$ system 500, which is the software part of the system, and system 75 hardware.

The Model 75 display images have 512 X 512 8-bit pixels which sit on a refresh memory board (channel). The standard purchase has 16 channels arranged in pairs on eight circuit boards, from which 10 MHz data streams leave to be passed on to the three pipeline processors. Each of the channel pairs is connected to each of the three pipelines [Settle & Briggs, 1987].

The software part of system can run from any terminal that is used for the processing of remotely sensed images. It interacts with the user, interpreting instructions, managing image catalogue and carrying out standard operations on images such as Geometric rectification, Classification, Graphic display, image statistics etc., etc... . Most of these functions employ the system 75 hardware for image display while few other functions can be carried out without the use of the display unit.

The display unit is restricted to 512 X 512 pixels images as the processing of the display dependent functions is done in the channel pair utilising the refresh memory. If an image is bigger than 512 square the handling of the image has to be performed without the use of the screen. If the desired functions are display related, the functions have to be carried out in portions where the biggest portion used is 512 X 512. The $I^2S$ Model 75 allows the user to carry on some functions on an image in parts.

## 4.3 Preprocessing of raw data.

### 4.3.1 Introduction.

The raw AVHRR imagery, as supplied by the receiving station in Dundee; is composed of two sections the header section and the video data. (See Appendix 1)

The header section contains information about the image: namely Spacecraft identity (ID), Time Code, Telemetry, Internal target data, space data. The video data is the image packed in a compact form and channel multiplexed.

The header information provides the data for the calculation of gains and intercepts. The video data is the image that needs to be geometrically corrected to facilitate the extraction of the basin image.

This section will detail the processes involved in the execution of the above.

### 4.3.2 Telemetry.

The telemetry data is the data generated by the scanner module. For every time it scans a line on earth the scanner also registers the temperature of the four Platinum Resistance Thermometer which act as a black body. (See Section 3.3.3) This data provides information about the prevailing temperature of the sensor, providing the needed information to calibrate the information registered by the sensor. Telemetry data is needed for the processing of the infrared channels to produce estimates of the temperature of a scene. The utilisation of the telemetry data for temperature estimation is provided in Section 3.3.3.

The extraction of the header information and the expansion of the image are done using a special program TIROS (named TSRTEL in this project to indicate its use, Tiros SoRting TELmetry) that was modified and updated for the special requirements of this work. The initial program was written for use with NOAA 7, hence it was updated to cater for the NOAA 8 and NOAA 9. The details of the modifications and the updating will be described later on. Two versions of this program were available, a program which was initially written in 1981, by Saunders R. of the Laboratory of Planetary Atmosphere, University College London, and updated in 1985.by Tietema E. of IPIPS lab. Imperial College; the other program was available in an image processing facility which is composed of a library of programs the Transportable Application Executive. (TAE) the author of that version was Harris C., 1987. The two programs were compared. They both provided the same function although the TAE program was more sophisticated and provided the better facility for the extraction of the information of the header of the AVHRR image.

The program was written to be run under the TAE operating system while the intended use of this program was as a part of the program library HyRSIS. The program was changed and adapted to run at the Digital Command Language (DCL) level of the VMS system.

The program performs bit manipulation functions on the AVHRR compact data and transform it into half word format. The telemetry data is extracted and the gains and intercepts are calculated. The bit manipulation is also performed on the Video data and five separate files could be produced in half word format of the image. Each of the files contains one band of the image.

In this step the telemetry data is collected, reformatted and processed in order to calculate the gains and intercepts for each channel. The image format is expanded and written in half word format. Channels are separated and collected individually in separate files.

The separation of the different channels for this application was done using the $I^2S$ system rather than the program TSRTEL. The $I^2S$ system was used to read the AVHRR images off Computer Compatible Tapes CCT. The function used for this process readily separates the image into the corresponding channels. As this function is fuliled the need to use TSRTEL to perform channel separation is eliminated.

### 4.3.3 Geometric Correction and Basin Image Extraction.

#### 4.3.3.1 Introduction.

AVHRR imagery are generated as explained in Chapter Two Section 3.3.3. through the use of a rotating mirror as the satellite is moving. This way of registering an image will result in a geometrically distorted image.

In order to extract the pixels referring to the basin map, geometric correction of the AVHRR image is needed. This exercise was carried on the $I^2S$ system. A special function, WARP, of the $I^2S$ system is used. Function WARP utilises a control file to perform a spatial warp of individual pixels of the AVHRR image. The control file is the definition of the pixel positions for a set of points that are well defined features on the AVHRR image and the corresponding positions of these points on a control image. These features are usually of the coast lines of the image. A control image, an image that is geometrically correct and the position of the each pixel can be defined either in latitude and longitude or National Grid Reference, was created for this purpose. The next section will discuss the process of creating the control image. If the AVHRR image was covered with cloud the generation of a control file will not be possible. (See Section 4.3.3.5)

### 4.3.3.2 Generation of a control image for use in the process of geometric correction.

An image of the British Isles incorporating the basin of the study area was produced for use as a control image. The following were available for its generation.

1. Digitised map of Great Britain, Ireland, the Netherlands, Belgium, Western France and some of Norway coasts. {File IOS1.IFF }
2. Lites2 software.
3. Digitising table.
4. Map of the Aire Basin.

The departmental library contains a digital version of a Bathymetric map (Sheet 2) by The Institute of Oceanographic Science Natural Environmental Research Council U.K. Stored as an IFF File (IOS1.IFF) on the Departmental Vax. IFF stand for Internal Feature Format, which was written at Laser-Scan in 1975/1976 to be used as a compact efficient means of storing graphical data in digital form. This digital Map was too big, containing excessive information for the purpose of generating a control image. The specifications and need for the control file were discussed in the last section. The functions available in the Lites2 software were used to generate the control file desired.

The generation of the control file involved the creation of an image in which the position of every pixel is known and could be expressed in a universally acknowledged reference. The choice was between latitude and longitude and the British national Grid reference numbers, the latter was chosen. As the case study was in the British Isles so it is only logical to use the standard referencing system of the Ordnance Survey.

The process of generating the control image progressed in the following manner: As the Bathymetric digital map was very big in size and details so the desired features, the coasts included in the map sheet, were extracted to reduce it's size and details. Then the projection of the map was changed from latitude and longitude to National Grid Coordinates.

The Map sheet of the basin of the river Aire was digitised and then was included in the product of the above process. After this the IFF file was converted to an image, resulting in the desired control image. The details of the functions used to carry this exercise follows.

Progression of functions applied.

*Creation of Coast Line:* The coast line was extracted from file IOS1.IFF. This was done by applying function ISELECT. The file was reduced in size by reducing the amount of details of the coast line, function IFILTER was operated. Then the projection of the map of the file was transformed from latitude - longitude to national grid reference coordinates.

1. Function ISELECT creates a new file which is a subset of the file it is being applied to. The features required are defined when performing this function which will select the desired features and output them a new file. The function ISELECT was applied on file IOS1.IFF selecting Feature Code 3 (FC3) and Feature Selection Number 6 (FSN6), thus selecting the coasts in this file. The number of points in the first file was 142805. This was reduced after the application of function ISELECT to 60133 points. These points represent the coast line. (See Image 4.1)

2. The resultant file of the above function is still large so a filtering function was applied, IFILTER, This function filters or smooths an IFF file using one of two filters or one of four smoothing options. Several attempts were made before selecting a filter, Douglas_Peuker filter, which produced the best results. Function IFILTER was applied on the file produced in step 1. with the qualifier DP60, producing a file with reduced number of points, from 60133 to 4714. This

was done without impairing the details of the coast line.

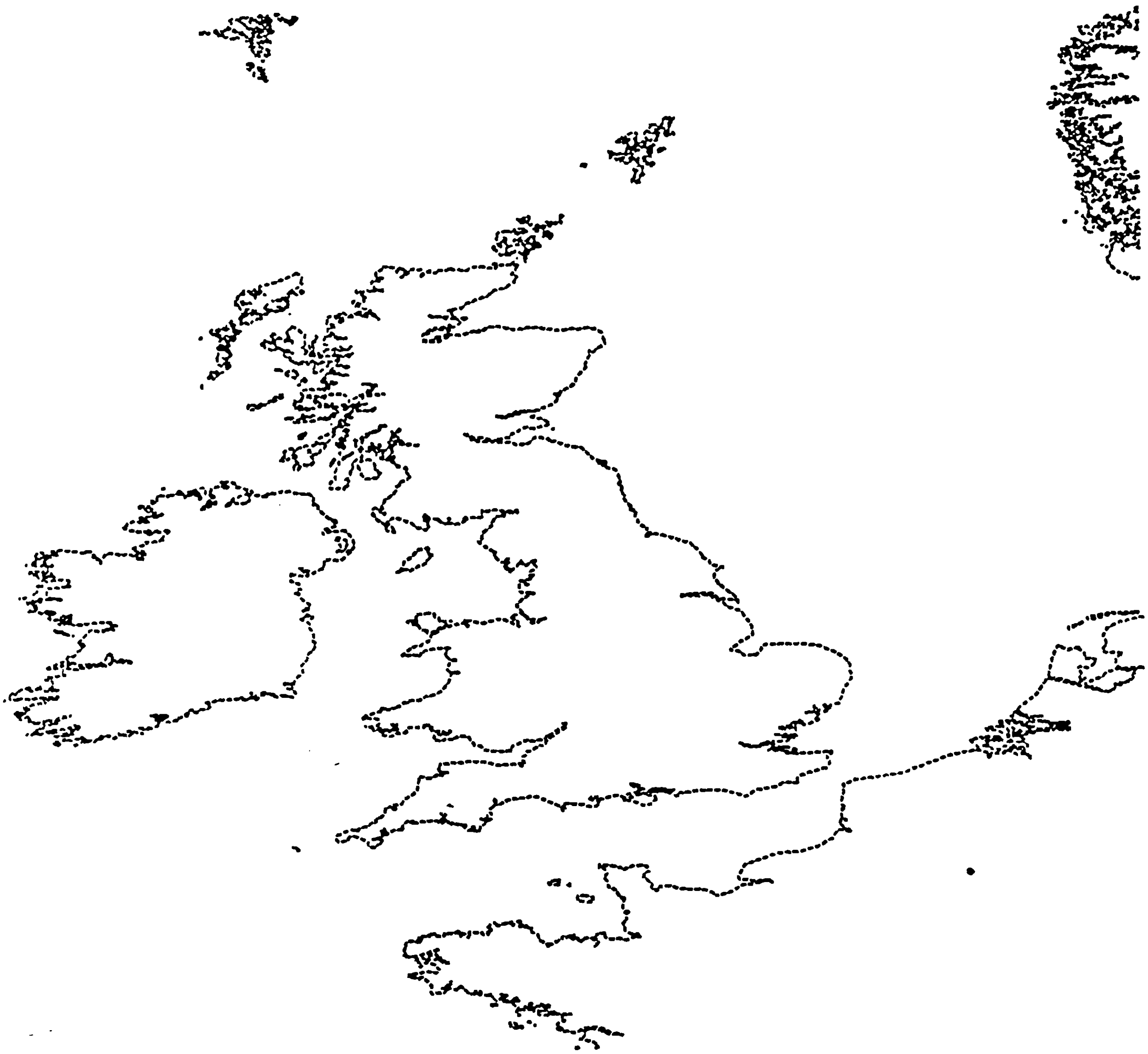


Image 4.1 The extracted coasts features from the digitised Bathymetric map IOS.IFF.

3. The coordinates of the file produced in step 2. are expressed in latitude and longitude. Function ITRANS is a general map projection program. It allows transformation between spheroidal data (Latitude and Longitude) and specified map projections. Function ITRANS was applied to transform the projection of the file from latitude-longitude to National Grid producing a map of the coast line national grid referenced. (See Image 4.2)

The result of the above process is an IFF file of the coasts incorporated in the Bathymetric map condensed and projected to National Grid Coordinates.

*Incorporation of Basin Boundary in the file of the coast line.* The basin boundary was digitised and the scale of the resulting digital map was changed to that of the Bathymetric map.

1. A map of the basin boundary was available at a scale of 1:50,000 in National Grid Coordinates. This map was digitised using the digitising table and Lites2 software. The digitised boundary of the basin is now stored in an IFF file. (See Image 4.3)

2. The scale of the digitised basin was transformed from 1:50,000 to 1:1,000,000 using function ITRANS in order to match the scale of the bathymetric map..

*Coast Line and Basin Boundary control file.* The digital boundary of the basin was incorporated in the digital map of the coastline and then transformed into image format.

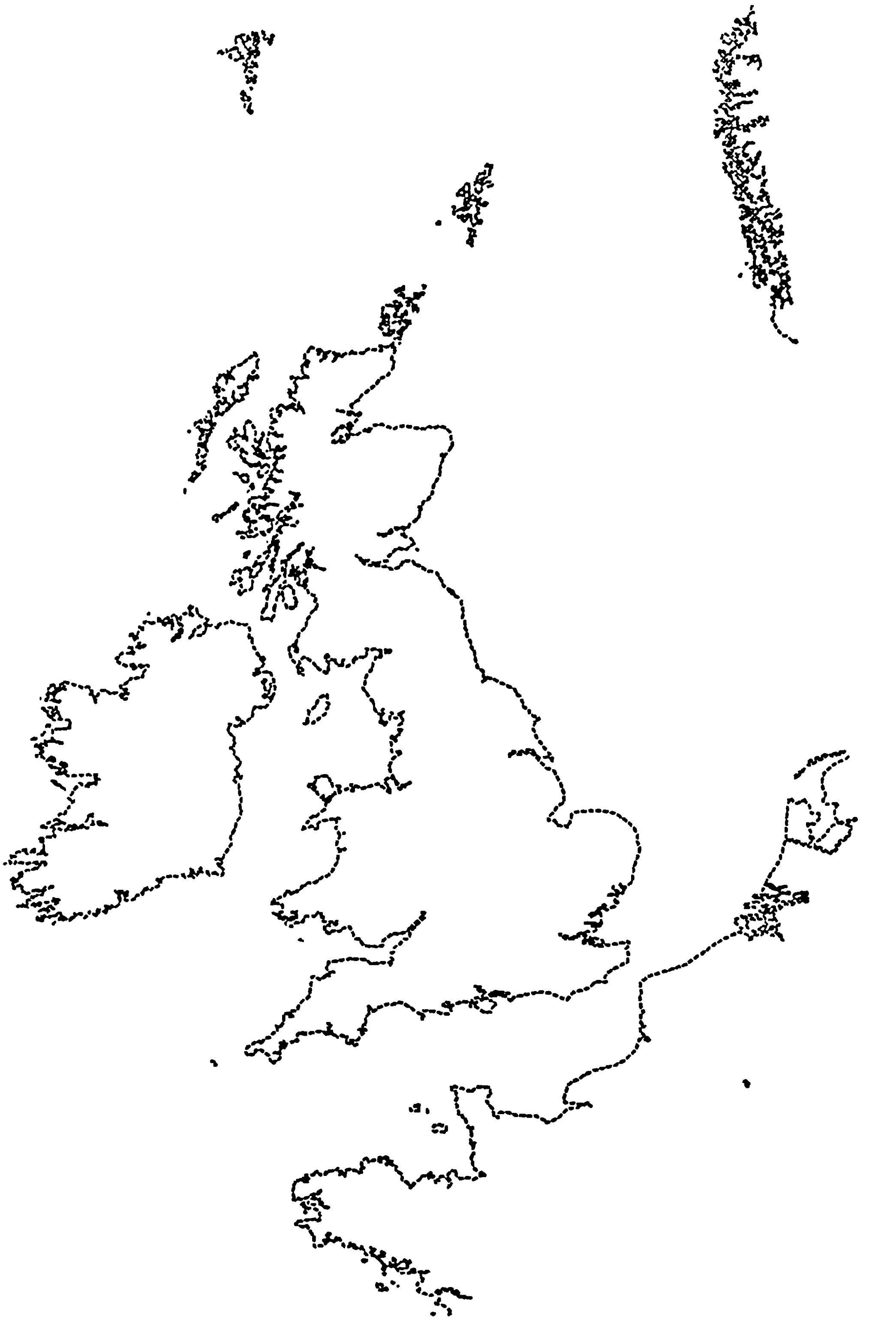


Image 4.2 The filtered and transformed image of the coast.

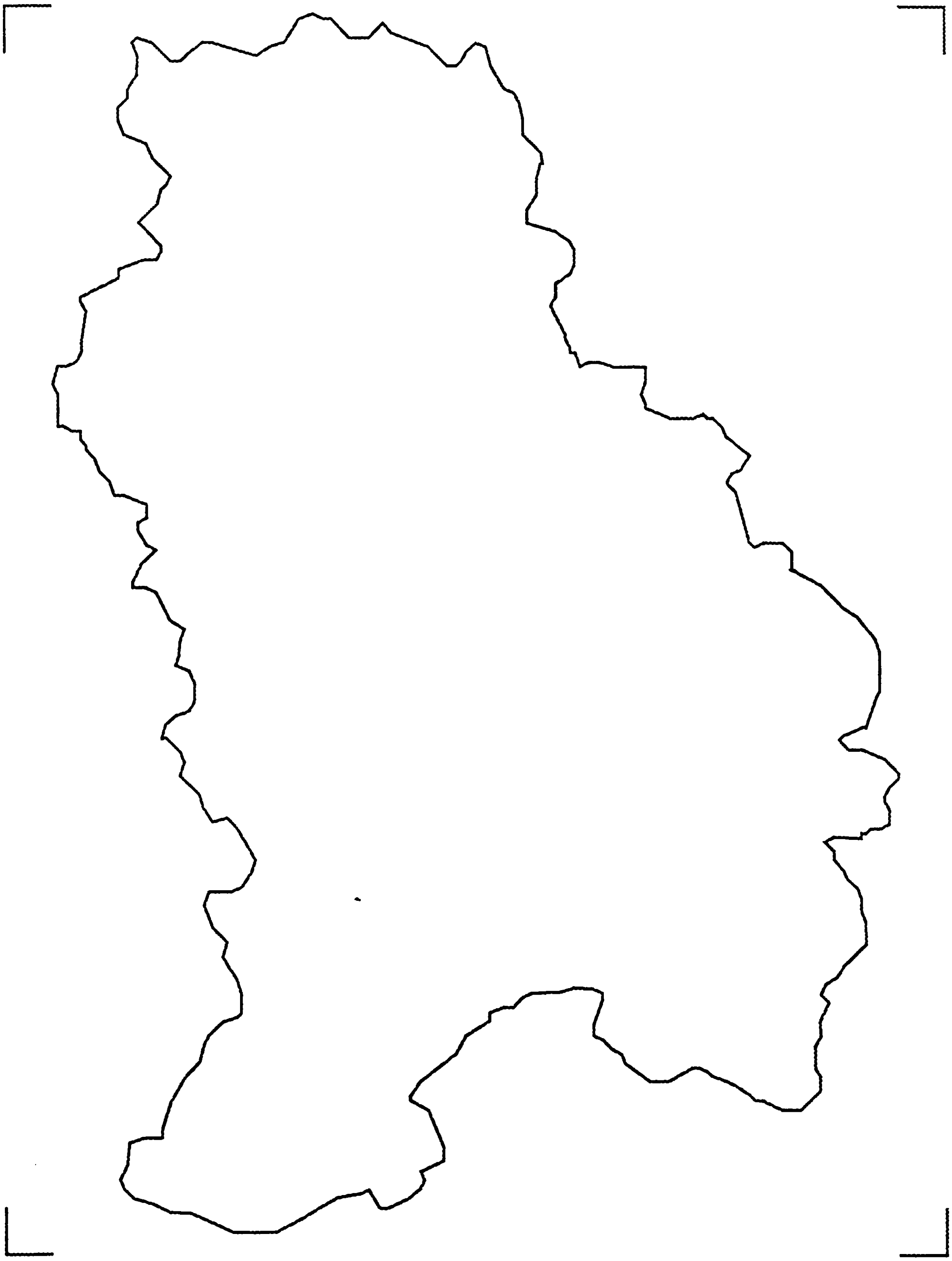


Image 4.3 Digitised image of the basin of the river Aire.

1. The coast line and the basin boundary are now stored in two different files. In order to merge the two files into one file function IMERGE was used. This function may be used for several applications the one used here was to merge two IFF files into one. The two files were merged to produce a merged file which is the control file expressed in IFF format. (See Image 4.4)

2. An image file was produced of the IFF control file using function I2GRID. This function converts data from Laser Scan's IFF to Digital Terrain Image (DTI). The data is translated from a VECTOR to a GRID image form i.e. the IFF file is rasterised. Care should be taken here in the selection of the parameters in order to insure the compatibility between the image produced and AVHRR imagery. The Pixels produced in this image were of the dimension of 1 X 1 km. The resultant image was of 1050 lines and 602 samples.

The image file was converted to the appropriate format for the usage as a control image on the $I^2S$ system.

The accuracy of the control image is dependent on the accuracy of the original data, used for creating it, and the effect of the functions carried on to get it. The original file IOS1.IFF is a lat-long file whose scale is 1/1,000,000. No information is available on the accuracy of this file, however, it is reasonable to assume that it is the best attainable for the corresponding scale. In any case the accuracy of maps at the above scale is usually considered to be around one kilometre. The application of the function ISELECT on

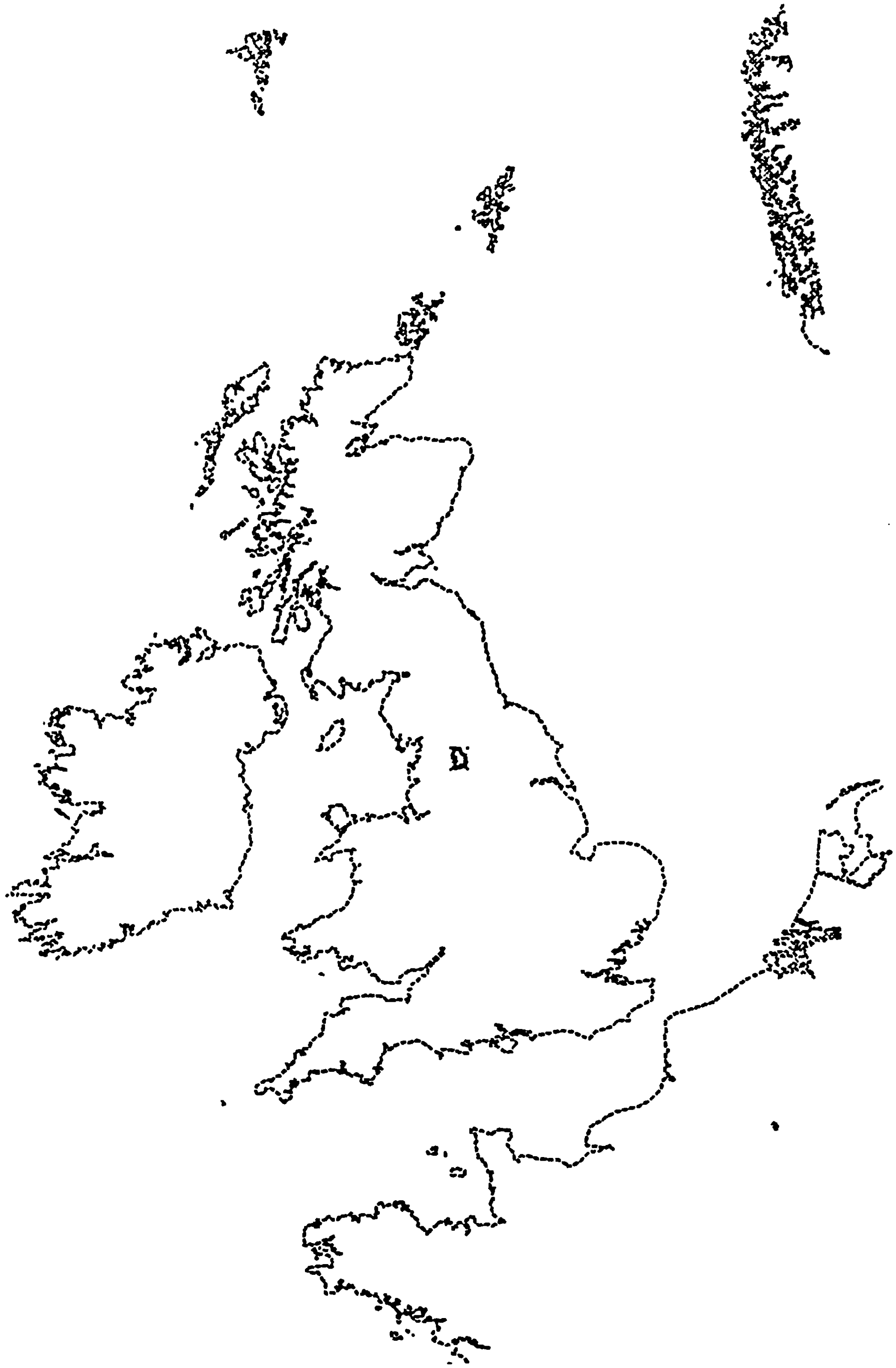


Image 4.4 The basin Aire incorporated in the basin map. This map was then used to produce the control image using function I2GRID.

this file has no effect on the accuracy on this file as it does not carry any numerical processing on the data. Although function IFILTER perform some processing on the data contained in the file it does not shift the position of the points constituting the coast line in the file. ITRANS projects the coast line to the U.K. National Grid. This grid is a particular case on the Transverse Mercator projection which produces a true scale along the central meridian with the accuracy deteriorating away from it. In the case of the National Grid a scale factor is applied which redistributes the errors along the lines perpendicular to the central meridian. Thus, the zero distortion is located on two lines 180 km away, and approximately parallel, from the central meridian which is 2 degrees west passing straight through the middle of England. The error at the central meridian and at the edges of the national grid is 0.04%. This error could be considered negligible and of no real relevance to our case. From the above the it could be deduced that the degree of reliability of the control file is basically dependent on the accuracy of the original data used for its creation. This accuracy could have been improved if the a larger scale digitised map was used, however, this was not available.

#### 4.3.3.3 Geometric correction.

In order to execute the geometric correction on an image a control file is needed. This file is generated by identifying distinguishable points on both the control image and the image being corrected. The CONTROL_POINTS function of the $I^2S$ is used for this operation. The output file of this function is used by the warping function of the $I^2S$.

WARP performs a spatial warp of the displayed image using the set of tie points generated by the control points. This function utilises a polynomial function whose power is determined by the number of tie points. The algorithm polynomial power is as follows

| Number of tie points | Power of polynomial |
|---|---|
| 1 - 7 pairs | bilinear |
| 8 - 19 pairs | quadratic |
| 20 - 49 pairs | cubic |
| 50 or more | quatric |

The warping function produces a figure expressing the average error expressed in multiple, or fraction, of pixels. The errors are computed for each tie point. The algorithm uses the tie points to formulate a function for the warping of the whole image. The position of the tie points is then calculated together with the rest of the image. The difference between the value of the tie points positions, before the calculation of the pixel positions for the whole image and after, constitute the calculated error. The algorithm produces the calculated errors for the tie points and then averages it as a representation of the whole image. If the tie points are spread over the whole of the image the average error could be taken as representative of the whole image. In cases where the tie points are clustered in a certain area of the image the average error will be more representative of that section of the image. See Section 8.2 for the accuracy of the results of this project.

The warped image is now geometrically correct and the coordinates of a point on it correspond to the control file. The coordinates of the basin are known on the control file hence the identification of the pixels corresponding to the basin is straight forward. These pixels were subsectioned and written to a file. This is done for every image and all channels of the image, producing five files, one for each channel, for each image.

#### 4.3.3.4 Notes on the geometric correction of images.

The reader might remember that the resolution of the AVHRR image varies across the scan line, with the resolution at nadir 1.1 km square and at the edge of the scan line at 6.9 km (cross track) X 2.4 km (along track) while the pixel dimensions of the geometrically corrected image is 1 X 1 $km^2$.

During the process of generating a geometrically corrected image the AVHRR image information are 'resampled' onto the control file. For example suppose a pixel at the end of the scan line is being warped, it represents an area on the surface of the ground of 2.4 X 6.9 $km^2$. This information on this pixel will be copied into several pixels on the warped image. The information contained in pixels of the warped image are the same as the nearest pixel of the original image.

#### 4.3.3.5 Background to the method of extraction of basin subimage data.

The method employed in this thesis for the extraction of the desired pixels data is a tedious one. It is not a practical way for solving the problem at hand. The other method of performing this task is the usage of the information provided by the satellite, regarding the time and physical orientation of the satellite, height of satellite, inclination of orbit to the surface of Earth, yaw of platform, etc ... as the scene is recorded. The utilisation of this technique will provide image rectification regardless of the existence of cloud as it is independent of ground control points. A procedure to utilise this information for the purpose of data extraction is available at University of Dundee. This technique produces errors within 2-3 km which is bigger than an individual pixel, i.e. smaller than 1 km, accuracy acquired by the ground control points technique. [Brush 1988] Understandably they treat this procedure as an intellectual property and is only available on commercial basis for non NERC funded research. Accordingly it was not used in this work which only used software that was freely available and those written ‘‘in house’’.

Another automated method could be applied for the geometric correction. This method uses a library of ground control points. The AVHRR image is scanned, this process is carried automatically without the intervention of the user, points on it are coupled with ground control points thus identifying them as tie points. It is claimed that this method only needs to identify three points to produce a geometrically corrected image of subpixel accuracy [Cracknell & Paithoonwattananakij, 1988]. The same restriction for usage also apply to this method as the above mentioned method.

In any case, the method used in this thesis is needed for the extraction of mapped snow data. A geometrically correct image of the coasts of England and Wales would be sufficient to use as a control image, as explained earlier on Geometric correction, to extract data in Yorkshire. As it is only possible to map snow on cloud free days for which the coast of England and Wales would be free of cloud cover. In the case of cloud cover days geometric correction of an image may not be possible to be carried out by only using the coasts of England and Wales as it is most likely that most of the coast will be covered and not enough control points may be generated to perform a WARP with reasonable accuracy. For the purposes of this thesis a sequence of images were selected, such that parts of the coast of Great Britain and Ireland were recognisable in order to facilitate the geometric correction. Consequently a large control image was needed. The creation of this control image was summarised in Section 4.3.3.1. For some of the cloud cover days the two images, control and AVHRR scene were bigger than 512 Pixel X 512 record, the maximum dimensions which is easy to use on the $I^2S$. These images were extracted from the bigger frame images so that to include as much coast line as possible. The generation of the control file was done in stages. A warp was then executed and the image of the cloud cover over the basin was extracted.

#### 4.3.3.6 Extraction of basin image.

The basin boundaries were mapped on to the control image file. The basin boundary may be enclosed in a rectangle of national grid coordinates as follows (384000 442000, 404000 46700) (SE corner, NW corner). This box is 20 kms X 27 kms. The pixels enclosed in this box, 20 samples by 27 records, were extracted from geometrically corrected images. This was carried on the $I^2S$ using function Disk_transfer. The result of the extraction process is an image of the basin in a binary format. This is done for each image where the different channels are kept in separate files. The following channels are used for the different processes:

| Process | Channel |
|---|---|
| Precipitation | 4. |
| Temperature | 4,5. |
| Evaporation | 4,5. |
| Snow Mapping | 1,3,4. |

In the rest of this thesis when the word 'image' is used it will refer to the geometrically corrected and extracted subsection of the image of 20 by 27 pixels, unless otherwise indicated.

**4.3.3.7 Notes on the unpacking of AVHRR pixel data.**

The extracted images of the basin used in this project were the product of the procedure mentioned above which was carried on the $I^2S$ system.

The reading of the information from the tape as provided from Dundee receiving station was done on the $I^2S$ using software known as Tardis utilising function DUNDEE.

Computers represent integers in their internal memory in 15 bit format, 14 bits for data representation plus one reserved for the sign of the number. In order to economise in computer storage and to speed the flow of information beamed from the satellite to ground station AVHRR data is packed in 10 bit data. This fact consequently presents some difficulties using the packed data regardless of the existence of special software to unpack the compact data. Function DUNDEE, is used for reading the images from tape to computer storage. It has several options for the way an image is read in order to cater for the unpacking of the compact data. Special attention should be given to the effects of the different options on subsequent usage of the unpacked data.

Scale and Clip are the two options concerned with the representation of the pixel information. Option scale was used. This option means that the information read are divided by four. Accordingly the values registered by each pixel of the extracted scene is divided by four. Multiplying pixels values by four will not restore the initial values unless the initial value was a multiple of four. Instead the resultant image is in steps of four. The other option available is Clip. This option will clip the Most Significant Bytes (MSB) of the ten bit data and register the rest of the bits. This means that all pixel information less than 255 are registered as they are whilst any value higher then that will be truncated to become 255. SEE Figure 4.2.

Option scale will not affect the quality of the product drastically and will provide a more accurate representation of the information as the spectral response of the scene is saved from the minimum (0) to the maximum (1023) but in a graded manner. While option clip truncates any spectral response higher then 255 and saves all information below that threshold.

Pasting redundant bits to the compact data will produce the most accurate information as no information is lost and all the spectral information are restored. This procedure will produce images that occupy large space in computer memory. This function is not available for the $I^2S$ system.

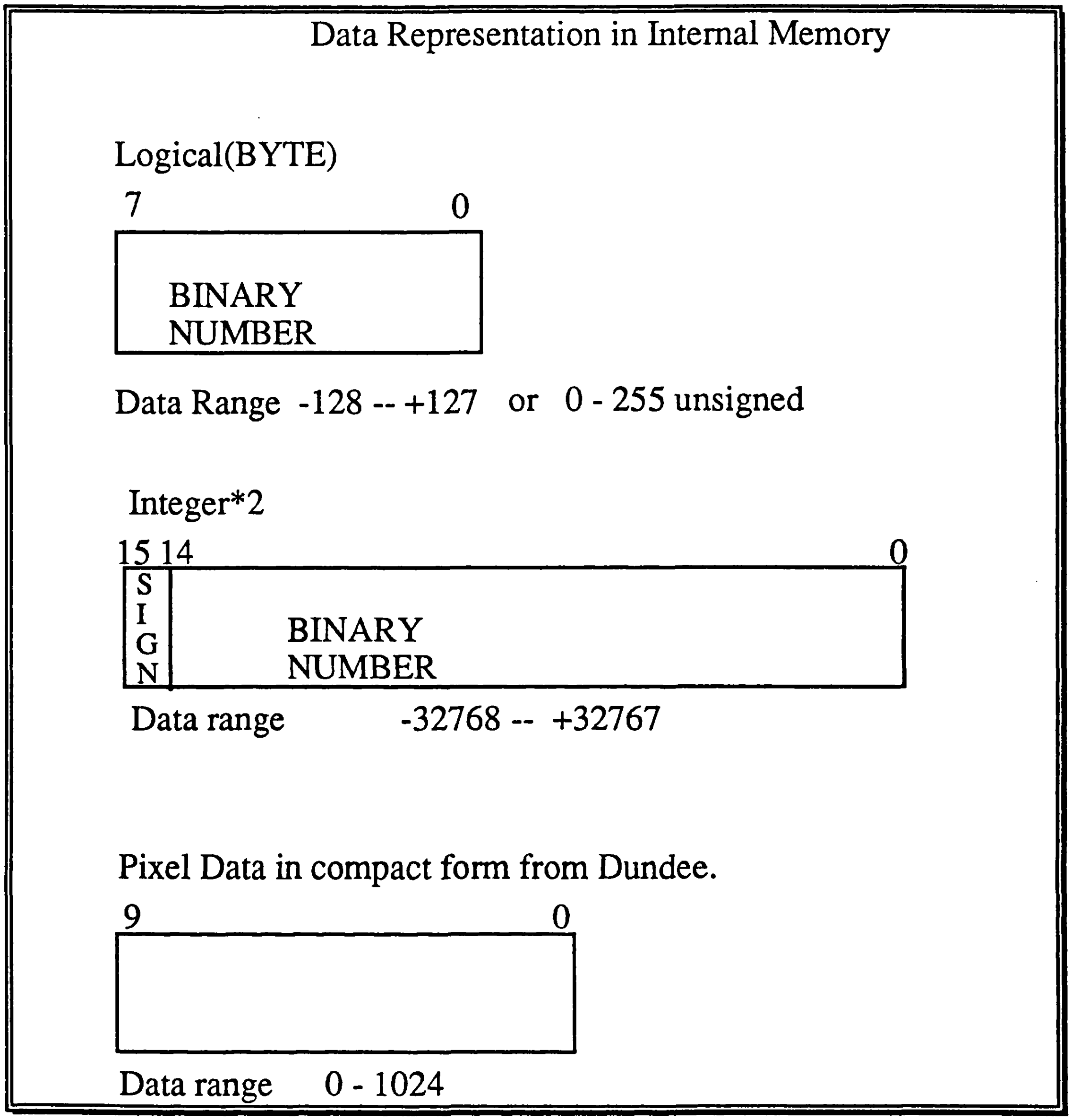



Figure 4.2-a Data representation in computer memory.

As it can be seen, the data range of the pixel values of the AVHRR image is between 0 and 1024. The computer can only 'recognise' pre-defined number representation. In order to make the Dundee compact data readable, it is either compacted to a Byte format or expanded to fit in an Integer*2 format. The graphical representation of the solutions follows in Figure 4.2-b.

Methods for expanding the compact data:

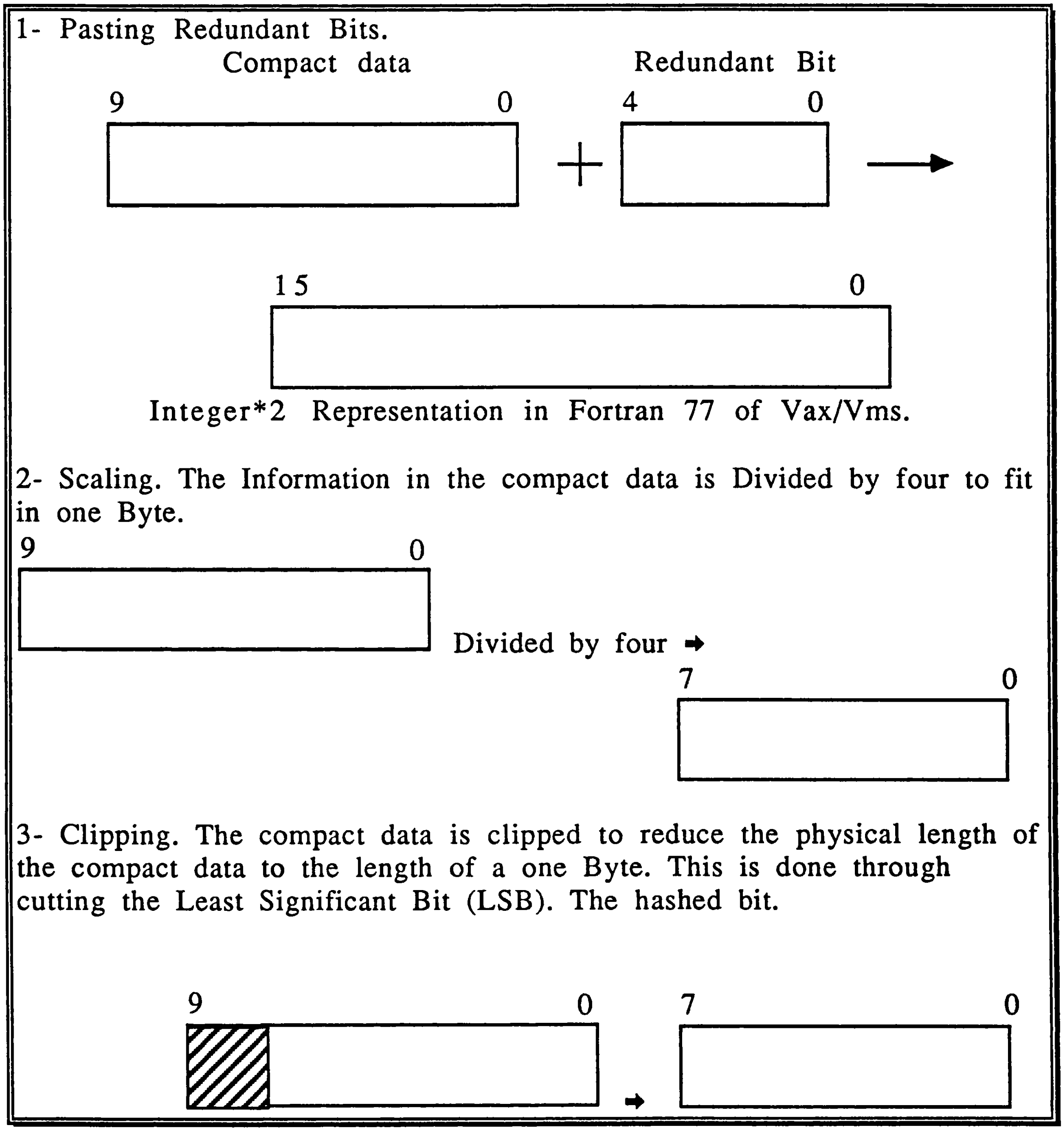



Figure 4.2-b Methods of extracting AVHRR compact data.

## 4.4 Preface for Processing of Image Data to Hydrological Parameters.

In the last section pixels referring to the basin under study were extracted and stored as binary images in different files for different channels. The information contained in these images are the spectral responses registered by the AVHRR instrument. The second part of this Chapter will detail the different processes that leads to the estimation of the hydrological parameters. It goes without saying that when processing for precipitation, cloud imagery are used. When no clouds are present over the basin temperature, evaporation and snow processes may be carried out.

The different programs used in these processes were either acquired from the researchers using them or by a process of reproduction. Nearly all the programs received were not running. This was due to two factors,

1- The programs call subroutines that are not available on the hardware used in this study.

2- Some programs had unreadable characters it was presumed that mistakes in the copying of the programs had happened.

The programs received were those of the Precipitation Method, and TSRTEL for temperature estimate. These programs were debugged and then overhauled and reconditioned in order to be used as building blocks of the system. Compatibility of input of the different programs was ensured. The consistency of interface of the different programs was paramount. All the other programs were written 'in house'. These programs will be pointed out individually.

## 4.5 Precipitation.

### 4.5.1 Processing of image data to precipitation estimates.

The method used for the estimation of the precipitation parameters is the Bristol Method. The theoretical aspects of the method were described in Section 3.3.2. The application of this method will be detailed here. The PERMIT technique, employed by the Bristol Method, utilises three programs DAY.FOR, ADD.FOR, and MULT.FOR to produce precipitation estimates.

Program DAY.FOR transform the slots of every day into day aggregates using an infrared threshold of 192-254. Slot here means an image of a sequence of images of the same day. Pixel values in the range of the threshold are supposed to be producing rain. For geostationary and polar orbiting satellites the number of slots are 8 and 4 respectively. This program reads all the files for a certain date and applies a threshold on each one of them. Every file is read and pixel readings in the range of 192 and 254 are registered and assigned a number, in an array equivalent to the pixel array, relative to its slot number $2^{**(n-1)}$ where n is the slot number of the sequence. The assigned numbers, for each slot, are added as the pixel value is in the range of the threshold. Thus identifying rain producing pixels and producing a map of rain/no rain map of the basin

Slot 1 (1)

| | |
|---|---|
| 195 | 100 |
| 74 | 192 |

Slot 2 (2)

| | |
|---|---|
| 199 | 157 |
| 69 | 199 |

Slot 3 (4)

| | |
|---|---|
| 207 | 167 |
| 82 | 205 |

Slot 4 (8)

| | |
|---|---|
| 150 | 98 |
| 68 | 221 |

Pixel Number

| | |
|---|---|
| 1 | 2 |
| 3 | 4 |

Slot 5 (16)

| | |
|---|---|
| 101 | 150 |
| 110 | 245 |

Slot 6 (32)

| | |
|---|---|
| 153 | 178 |
| 170 | 197 |

Slot 7 (64)

| | |
|---|---|
| 198 | 189 |
| 176 | 196 |

Slot 8 (128)

| | |
|---|---|
| 189 | 190 |
| 192 | 207 |

| Slot Number (n) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| Assigned Number 2**(n-1) | 1 | 2 | 4 | 8 | 16 | 32 | 64 | 128 |

| Pixel Number | Assigned Number for each slot. Å=2**(n-1) | | | | | | | | ΣÅ |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
| 1 | 1 | 2 | 4 | 0 | 0 | 0 | 64 | 0 | 71 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 128 | 128 |
| 4 | 1 | 2 | 4 | 8 | 16 | 32 | 64 | 128 | 255 |

→

| | |
|---|---|
| 71 | 1 |
| 128 | 255 |

| | |
|---|---|
| 71 | 1 |
| 128 | 255 |

→

| | |
|---|---|
| 71 | 1 |
| -128 | -1 |

Figure 4.3 Graphical representation of program day

Program ADD adds a number of individual rain/no rain maps, i.e. for several days, to form a composite number of rain-days map. This is done through screening each rain producing pixel in each rain/no rain map. For each pixel a count of the number of days rain occurred in its space is recorded in an array. This array is in a form of an image of rain-days map.

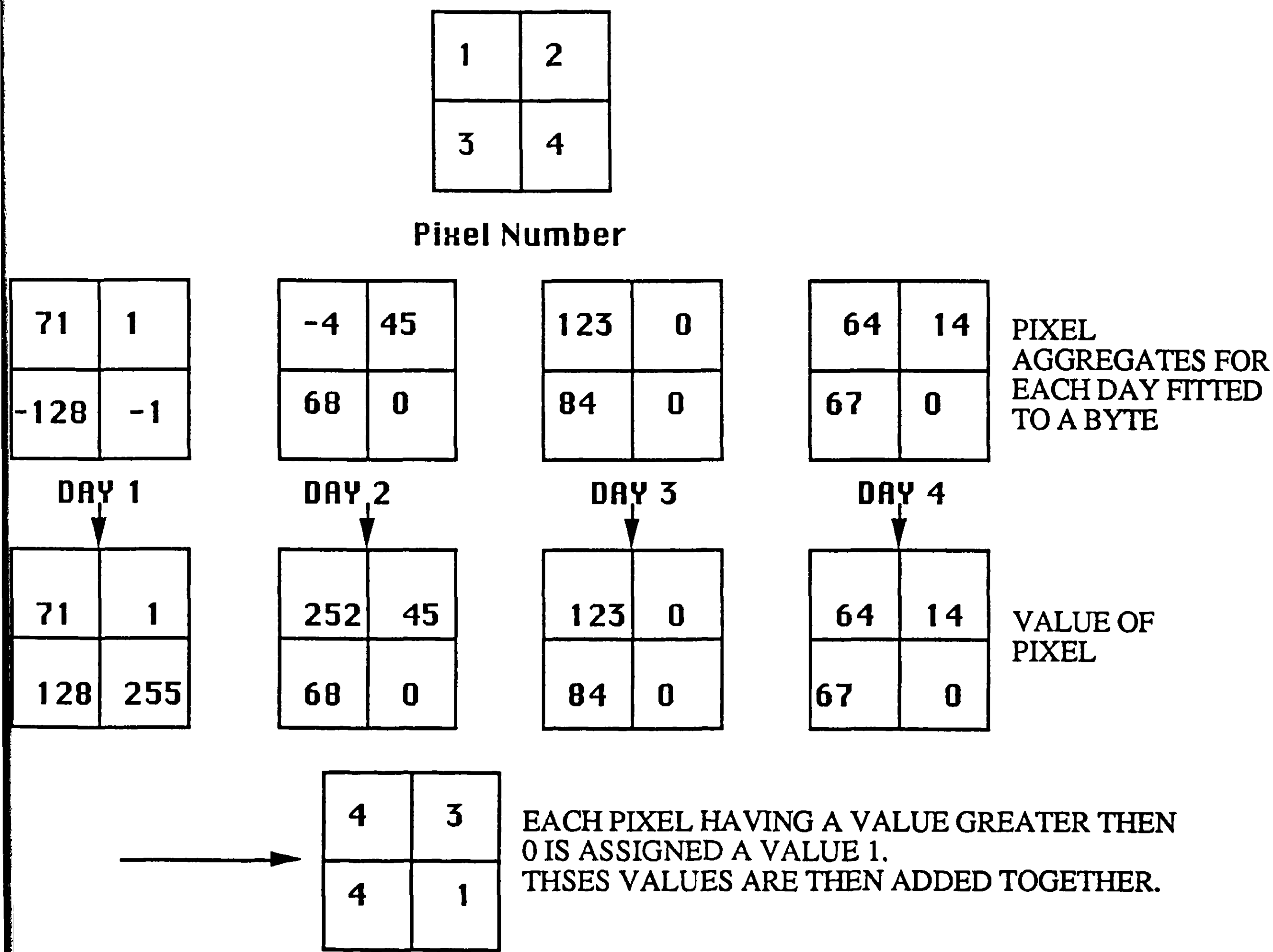



**Figure 4.4 Graphical representation of ADD program.**

In order to produce precipitation estimates, the rain-days map is multiplied by a compiled image of historic data. This is done using program MULT. Each pixel is multiplied by its corresponding historic data producing an estimate of the precipitation that occurred over the period covering the days added in program ADD. The product of this multiplication is a precipitation estimate. This estimate represents the total precipitation over the period of days summed by program ADD.

A graphical interpretation of the functions carried on by the three programs are presented in Figures 4.3. 4.4. and 4.5.

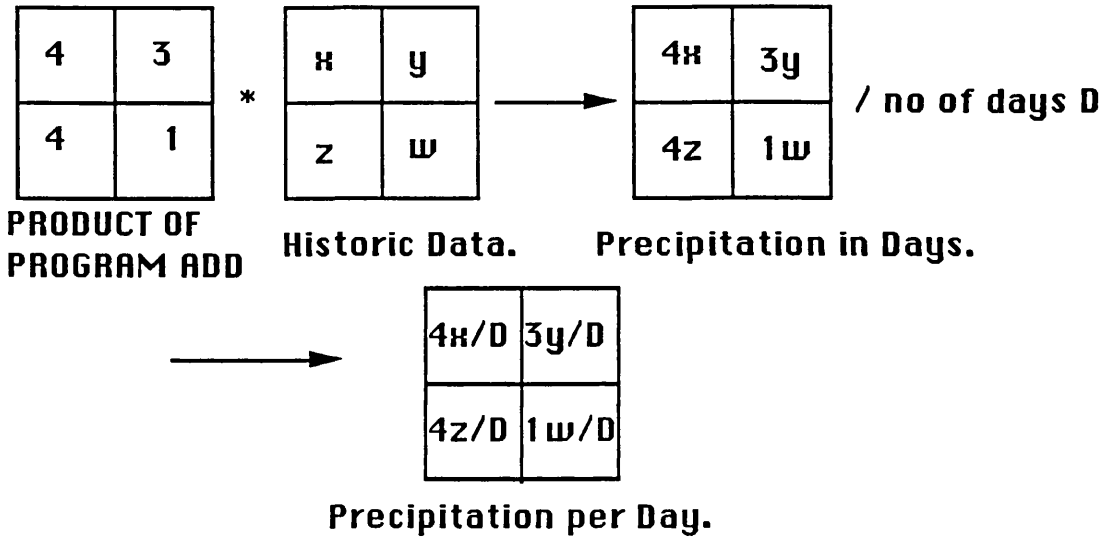



Figure 4.5 Graphical representation of program MULT.

### 4.5.2 Process of producing the historic data image.

Program MULT uses a file of historic data in order to produce precipitation estimates. A file was compiled for this purpose, then a program was written for establishing this function.

The historic data is the long term average interpolated rainfall. Each pixel of the basin image has national grid coordinates. A figure representing the average rain fall could be associated with every national grid coordinate. This areal coverage of the average rain fall is produced through the interpolation of rain fall data registered by rain gauges spread over the British Isles. The interpolated average rain fall is divided by the number of rain days to produce a map of rain per rain day.

In order to produce a binary image map of the basin a program was written. Program MULT requires the data to be in a binary image format. This program reads in the interpolated historic data, obtained from the Institute of Hydrology, for the month of January and outputs a binary file in image format for use with the PERMIT technique. This could be carried for the different months of the year. It was only done for the month of January as the modelling period falls in that month.

### 4.5.3 Notes on the PERMIT Technique.

The PERMIT method surveys the values of the pixels of the image. If the value of the pixel falls within the range of the selected threshold the pixel is registered to be producing rainfall. This screening of the pixel values is done for all the images of a day. The process is repeated for every image for every day. The product of the different days are added and then multiplied by the average rain per rain day to produce precipitation estimates.

The screening of the pixel values for several images in a day is in effect only searching for any pixel over the threshold at any time during the day. Although the method registers the cases of pixels that are considered producing rain in more than one image, the method does not take this fact into consideration. The multiple registry of 'rain producing' for pixels does not give a weight to the pixel.

## 4.6 Temperature.

### 4.6.1 Introduction.

The theoretical grounds for the estimation of ground temperatures were discussed in chapter three. The programming of the mathematical formulations was done through building on and developing previous programs and writing some new programs. These programs were written upon the recommendations of Ness's Technical memorandum 107. The processing of the infrared data to temperature estimates pass through three stages telemetry, temperature estimates for infrared Channels and atmospheric correction. This section will discuss each step on its own.

### 4.6.2 Telemetry.

Telemetry data are found in the header of every AVHRR image. It is basically a data set of the temperature of the blackbody, Platinum Resistance Thermometers PRT, on board the AVHRR instrument as each image is being registered.(See Section 3.3.3.) This data is essential in the processing of the infrared pixel values to temperature estimates. A program in the Transportable Applications Executive (TAE) TIROS was available. The program collects the PRT's and processes the collected data to Gains and Intercepts. The program, before usage in this project, was working under the TAE operating system. For the specific use in this project the program was made to work under VMS operating system. The initial program was made to process telemetry data for NOAA - 7. The program was then updated and adapted to process NOAA - 9 images, the sensor used for producing temperature estimates, telemetry data and was renamed TSRTEL. (See Section 4.3.2.)

The TSRTEL program is capable of achieving several tasks. The first, and most important for our use, is the extraction of telemetry data and then processing it to produce gains and intercepts. Telemetry data are packed in the same way as the pixel data. Details of the arrangement of the packing are available in Ness - 107. A special function in the Vax FORTRAN, mvbits, is used to perform bit manipulation to unpack the compact AVHRR data. The same function can be applied on the video data to perform the unpacking of the pixel values. This leads us to mention the second function of the program, the unpacking of the video data on two levels

from the compact form to half word format

and from the channel multiplexed data to out put each channel in a separate file.

This second facility was not used in this project as the unpacking of the image into the separate bands was done using the I2S system. Each AVHRR image occupy a large computer space. TSRTEL could be run on an image input from a tape. As mentioned before the tape drive in the Photogrammetry Department is not directly attached to the Vax which the program is running on. Hence the running of program TSRTEL was done on the Vax Computer in Geography. The results of running the program were transported to the Photogrammetry and Surveying Department Vax where they were used.

### 4.6.3 Temperature processing.

A program for processing the video data to temperature estimates was written using Planks mathematical formulation. See section 3.3.3. The programming is straight forward but there are some points to take into consideration.

Gains and intercepts, video data are read in respectively then the Planks formula is used to convert infrared video data to temperature. The video data was multiplied by four in order to reverse the effect of scaling during the reading of the image using the $I^2S$. The temperature estimates were then converted from Kelvin to Celsius. The output file of this process is a temperature image file of the basin.

Since the spectral response of AVHRR is limited between 0 and 1023 the programmers usually calculate the temperature of all the different spectral responses, for each image using its calculated gains and intercepts. The result of these calculation is stored in an array known as a look up table. Then each spectral response of each pixel is looked up in the table in which the corresponding temperature has already been calculated. The calculation of temperature is usually done in the preceding manner. This process is used because it is faster and computation time is reduced. This method was not used for the program written for HyRSIS. The dimension of the images used in this project are too small to require this treatment. The number of pixels in the study area is 540 per image which is far less than the range of the spectral response. Two programs were written for this application one was included in HyRSIS while the other was prepared in case the need arises for it.

### 4.6.4 Atmospheric Correction.

The theory of calculating target temperatures from a distance was discussed earlier. The simplification and redundancies of the theoretical approach always results in distortions of the 'exact' results of the application. One of the simplifications considered, in the theory of remote detections of temperature of a body, was the assumption that the infrared radiations of the body are received by the sensor undistorted. This is not the case of the remote sensing of the earth. The existence of an atmosphere between the sensor and Earth results in distortion of the infrared emitted from the earth's ground.

Several empirical equations have been suggested for the correction of the atmospheric distortion. Several of equations are reported here. All the equations utilise channel four and five in an attempt to correct for the distortions. The symbols used in the equations are as follows:

T6 Atmospherically corrected temperature.

T4 Temperature from Channel Four.

T5 Temperature from Channel Five.

$$T6 = 1.0346 \times T4 + 2.5779 \times (T4 - T5)$$ [BOWER 1989]

$$T6 = 1.11 + T4 + 1.43 \times (T4-T5)$$ [PILLING 1989]

$$T6 = -2.2 + 3.6 \times T4 - 2.6\ T5$$ [DESCHAMPS 1980]

The last formulae is a linear relationship for sea temperatures. Hence it not necessarily transportable for usage for land applications. According to Price [1984] in a study in Texas it underestimated the temperatures by 2 to 3 degrees; Lagouarde et al., [1985] reported 4 degrees difference in their observations in the Crau of south-east France.

A program was written for atmospheric correction ATC. The program gives a choice of usage of any of the three formulas. The input images to the programs are the temperature image of the basin for both channels four and five. The output of the program is a corrected temperature image of the basin.

## 4.7 Evaporation.

The production of evaporation estimates is dependent on two sources of information remote sensing temperature estimates and gauge information from the area of study.

The estimation of evaporation is done in one step through the use of program EVAPO as temperatures were derived earlier. The input image to the program is the atmospherically corrected temperature image of the basin. The program prompts for other variables needed for the production of the estimates as net radiation and air temperature. These parameters are collected from in situ sensors. The product of program EVAPO is an evaporation image of the basin.

## 4.8 Snow Mapping.

### 4.8.1 Introduction.

A multispectral approach to the snow mapping was used. Three channels were used for mapping the snow, Channels 1,3,4. The information contained in a 20 X 27 pixel area is not enough to produce a classified image containing a set of classes in which the snow classes are clearly distinguishable. The range of spectral responses in such a small sample will produce a fine classification which might result in overlooking some of the classes as non snow. An image of the size 512 records X 512 pixels was used. An image of this size includes all of England and Wales and parts of the seas surrounding them.

The processing was carried on the $I^2S$ system. Some knowledge of the $I^2S$ system is needed to understand some of the details of the snow processing.

### 4.8.2 Processing Image Data.

For free clouds days a three band image is displayed. Each band is displayed on one of the channels of the $I^2S$. The clustering function, CLUSTER, was used to carry on an unsupervised classification of the image using the three bands. The number of classes was set to thirty and the number of iterations before quitting the clustering function one hundred. The clustering function is also stopped if the migration of the classes is 0.1, which indicates a stabilised set of classes, or less. The result of the clustering function of the three band image is a classified image.

The classified image is displayed and the function POINTS is used to locate the snow classes. This function is done manually. The user examines the value of the pixels that he/she identifies as snow and registers the corresponding number. The user should carry on surveying the classes until all snow classes are located. Usually three classes of snow can be located. The existence of more than one snow class is indicative of the state of hardness of the snow class.

After the snow classes were identified the 512 X 512 image should be geometrically corrected. The image of the basin is then extracted and transferred to a file. (This process was explained in section 4.3)

### 4.8.3 Notes on the distinction between clouds and snow.

Each class is supposed to represent a set of pixels that share the same spectral response. On the assumption that snow will register the same spectral response the clustering function should classify snow in the same class. Cloud and snow are bright because of their high reflective properties. This causes snow and clouds to be classified in the same class. To distinguish between clouds classified as snow, for any pixel and especially on the border line of clouds, the visible response of that pixel is subtracted from the infrared one if the result of the subtraction is positive the pixel is snow otherwise it is cloud.

## 4.9 Overview.

The production of the hydrological parameters and relating them to land referencing system was discussed in this chapter. The basis of the different methods used has been established in other research projects, however, the reproduction and the modification of the different programs occupied a substantive effort in this project. The need to:

a) compile a library of programs, dealing exclusively with hydrological parameters, to incorporate in the intended system;

b) produce hydrological estimates on a continuous basis, as the collection of hydrological parameters is needed on a daily basis;

necessitated this reproduction of the different methods. The methods used in this project are the product of researchers of extensive expertise who are in the fore front in their fields. One of the methods used is the product of a Ph.D. thesis being written at the same time as this thesis. The different methods were not improved upon, from a theoretical point of view. Any attempt to do so would have put the research of this project in dangerous position. However, the different methods were analysed in depth, their limitations were identified, and their accuracy were established. The different methods were tested rigorously and their results were compared with conventional data. The above functions will be manifested in Chapter Eight.

# Chapter Five.

## Case study & Study Area.

### 5.1 Introduction.

#### 5.1.1 Introduction.

HyRSIS is intended to be used in operational conditions at a water resources organisation. A paramount feature is universality of use, i.e for any basin. However a case study was needed to establish it's working order. A study area was selected in Yorkshire. A modelling period was also selected.

This chapter will discuss the need for a case study, describe the study area and the conventional and remote sensing data that was available for the conduct of this study. Factors affecting the selection of the study area and the modeling period will be discussed.

#### 5.1.2 Constraints of HyRSIS.

The idea of universality of use of HyRSIS is dependant on the different modules incorporated in this system. No system can claim or aspire to cater for every conceivable state of affairs. HyRSIS is limited in operation and application to the limitations of its different modules. The different methods incorporated in this project are at their best when running for long periods. The resolution of AVHRR is also a limiting factor as it limits applications to basins that are equal or bigger than 200 $km^2$.

The hydrology model used in this project is basically a snow run off model which could run, with diligent use, for non-snow situations. Although SRM is a very powerful hydrological model, SRM is being used in this study as a panacea solution for hydrological models, its optimum conditions of performance are within certain physiographic and climatological conditions.

The above constraints does not impair the universality of HyRSIS as what is meant by it is that the system could be extended to incorporate new methods. Where these methods tackle the hydrological problem on two levels, data collection, and hydrological modelling. Another feature of the idea of universality, which is catered for in this project, is the processes involved in storing and retrieving the hydrological data. This data is stored in such a way that it could be retrieved for any hydrological model to be incorporated in the system.

The research of this project is a 'prototype' where the basic desired outcome is the establishment of the protocol for the design processes of an exclusively remote sensing based hydrological system. The extension of this system according to the conclusions of this research are detailed in Section 9.5.

The selection of the case study, both basin and period, are going to be restricted according to the constraints of the different methods, model and sensor which constitute the system.

As for any project the case study is designed to bring out the best of the different methods. However, this should not affect the degree of representation of the case study with regards to real life situation. The shortcomings of the different methods should come out and be stated clearly for the best understanding of the effectiveness and the restraints of the system.

### 5.1.3 Contents of Chapter Five.

This chapter will start with discussing the factors affecting the selection of the component of the case study, study area, modelling period, and the hydrological parameters. These parameters will be compared with the requirements of SRM. A detailed description of this data will be presented. The data required for the processing for the conduct of this project will be discussed as well as the data actually received from the different sources which was ultimately used here.

## 5.2 Case Study.

### 5.2.1 Introduction.

A case study is needed for the process of building any system otherwise the system will not be any more than a mental exercise. The mental modelling of any system is of utmost importance as it is the basis of any scientific advances. However, if a system is needed to be used in operational conditions it needs to be built, tested and refined with actual data. Some aspects of the proposed model will not be completely defined or understood without the interactive procedure of actually building and testing it with an application in mind.

The process of selecting a river basin as a study area for the application of this system will be presented in this section. The selection of the modelling period will also be discussed. The definition, and the data required for the modelling period will be presented first.

### 5.2.2. Parameters selection for a case study application.

The selected application for this project is a catchment of a river. Two sources for the river flow are of interest, snow melt and water precipitation. The basin and the data should satisfy a certain set of conditions for a representative application procedure. The parameters that could be supplied by the different submodules are, as explained in the last chapters, precipitation, temperature, snow mapping, and evaporation. Evidently not all these parameters could be used at the same time. Two of these parameters do not occur at the same time, i.e. not in a way they could be remotely sensed or of any direct significance to the actual hydrological modelling. Those two parameters are snow fall and evaporation. When snow fall occurs evaporation is at a minimum only occurring due to the level of humidity in air. This slight change can not be quantified by gauges let alone remote sensing. On the other hand if the basin is covered with cloud, snow mapping, temperature, and evaporation estimation cannot be carried on. The only parameter that could be estimated is precipitation. It can be seen from the above that not all the parameters can be estimated at the same time.

The hydrological modelling of a basin could be carried on for short or long periods. The acquisition of remote sensing images, for the purpose of estimating different hydrological parameters, costs around £40 a day. This constitutes the price of the Computer Compatible Tapes (CCTs) needed to contain the images of a day. Two CCTs are needed for the four images available for each day. Other costs like computing time, use of equipment, time allocation, and man power for the conduct of this study are other factors that contribute to the need to limit the period of hydrological modelling. However this limitation should not affect either quality or the minimum quantity of processing needed for a worth-while project. The maximum number of parameters should be used in the case study. This is achieved here by selecting a period in the winter when snow, precipitation, and temperatures could be measured from remote sensing sources. This case is further supported by the fact that SRM, the used hydrological model, was primarily designed for snow fall situations though modelling for the summer can be done using SRM. Evaporation has to be carefully incorporated for such cases in the runoff coefficients used in the model.

Since the duration of the case study is short it should constitute cloud free days, to facilitate snow mapping and temperature estimates, and cloud covered period for precipitation estimates.

### 5.2.3 Basin selection.

A basin was picked for the application of HyRSIS. The process of deciding on a particular basin was conducted after thorough discussions with Mr. Blackie and Mr. Blyth of the Institute of Hydrology. The discussions focused on the type of this project, the operational characteristics of SRM and the possibilities of finding a basin adequate for this study. The discussions also involved the selection of a period for modelling.

Early on in these discussions it was realised that the characteristics of the Hydrology model will influence the selection of the basin and the period of modelling. Hydrological models usually are purpose built. Each model is built under special considerations to cater for a special type of basin and the prevailing climatological conditions. SRM was essentially designed for snow runoff situations. Where the climatological conditions and the physiography are of the following nature.

1- The snow fall is continuous over a period of time.
2- The snow pack melts slowly over the melting season.
3- The terrain of the basin is of mountainous nature.

As SRM was designed for mountain basins, the basin selected was to be in an area of a relative relief margin and not effected by urbanisation.

Climatological conditions for the British isles does not match SRM conditions. Snow falls and melts several times during winter. Although SRM would be of modelling these circumstances it is was thought, for comparison purposes with results achieved by SRM in different basins, it would be more beneficial to run SRM for a case which simulate the above mentioned climatological conditions. In order to match the climatological conditions a period of snow fall and melt that corresponded to these conditions was considered whether it covers the whole of winter or any part of it. Several years were considered when considerable snow falls occurred over the British Isles. Those years had to be married with years where both AVHRR imagery and remote sensing snow mapping for that period were available. (See next section)

Other considerations also influenced the decision of selecting the basin. The basin and the respective data should have the following characteristics:

1- It's size should exceed 200 $km^2$. The resolution of AVHRR imagery restrict its use for snow mapping applications to basins of areas exceeding 200 $km^2$.

2- It should be adequately covered with conventional sensors.

In the experimental and building stages of any system the data needed and used for testing should be complete. The use of gauge information is essential for providing enough information to compare with the derived estimates of the hydrological parameters. The comparison process is needed to assess the functionality of the different processes of HyRSIS. As a result of the above restrictions, conditions, and considerations a basin named Aire at Kildwick bridge, was put forward as a possible study area. The confirmation of this selection had to await the availability of snow and remote sensing images depicting the existence of snow in the basin.

### 5.2.4 Modelling Period Selection.

At this stage it was envisaged that snow mapping was going to be done by a researcher at Bristol University. A visit was arranged in order to combine the findings of the discussions in the Institute of Hydrology with the availability of remote sensing snow mapping. The meeting in Bristol University, Department of Geography Remote Sensing Unit, was with Dr. Andrew Harrison and Mr. Richard Lucas. The unit was involved, and still is, in snow mapping of the U.K. using AVHRR imagery and had a collection of images for several dates during the years 1985, 1986 and 1988. The conclusions of the discussions in the Institute of Hydrology were put forward. The physiographic conditions largely affected the selection of the basin. While the climatological conditions will affect the year of the test data.

*Selection of cloud free days.*

It was obvious that the snow melt conditions were not going to be met. However, it was suggested to try and select a short period that simulated the conditions of SRM, i.e.snow falls and then melts over a certain period of the winter season, as snow tends to fall and melt several times during the winter season in Britain. This state of affairs is further complicated as snow falls sometimes even before the melting of the previous snow pack was complete.

The different AVHRR images for the available dates were tested with special attention given to the area of the Aire river basin. A period, January 24$^{th}$ 1986 to January 26$^{th}$ 1986, was identified as fulfilling the criterion mentioned above for the cloud free days of the period.

*Selection of cloud covered days.*

The cloud covered days before and after this period were examined in order to select days where remote sensing methods could be used to produce precipitation estimates. Quick browse files of the days preceding and following the cloud free days were examined, days 20, 21, 22, 23, 27, 28 and 29 of January 1986. Two criterion were important in the selection of the cloud cover days.

1- precipitation occurred for those days.

2- parts of the coast line of England and Wales could be identified. (See Section 4.3)

While rain occurred on all the above mentioned days the coast line was only distinguishable on most of the slots of the days following the cloud free days. These days were 27, 28, 29. While one slot was of use for day 27, three were available for each of the remaining days 28 and 29.

Thus the basin of the river Aire was taken as the region of the study area where the modelling will be carried on for the period 24 - 29 January 1986.

## 5.3 Description of the Basin and Station.

The basin is the catchment area that feeds a gauging station, Aire at Kildwick Bridge, on the River Aire. The geology is mainly Carboniferous Limestone with some Millstone Grit series. It is a rural catchment, draining part of the eastern Pennines. The basin area is 282.3 $km^2$. The level of the measuring station is 87.3 metre Over Datum (mOD).

The Aire at Kildwick Bridge gauging station number is 027035; its grid reference is 44 (SE) 013 457. The station is a velocity-area station rated by current meter cableway 150 m downstream. Low flow control is the sills of the bridge. Washland storage and headwater reservoirs influence the flow pattern.

## 5.4 SRM data requirements.

### 5.4.1 Introduction.

This chapter is dealing with the case study of this project and consequentially with the data requirements of the hydrological model used for the project. In order to discuss the parameters that could be supplied to it from remote sensing sources and relate them to the case study they are reviewed in this chapter. SRM characteristics were reviewed in Section 3.3.6. Its data requirements were briefly mentioned, the detailing of these requirements will be presented in this section. This section will start with explaining the data requirements of SRM, which are categorised into three types. Then each category will be discussed on its own and related to remote sensing if possible.

### 5.4.2 Listing and categorisation of SRM parameters.

SRM data requirements can be classified into three categories

1- Climatological data.

This data is the product of the climatological conditions occurring over the basin.

2- Basin data.

Data that describe the physiographic conditions of the basin.

3- Operational data.

Operational data contains the options for running SRM as chosen by the hydrologist.

A listing of these parameters is provided in Table 5.1 below. The different parameters are classified and listed according to the above categories.

The basic input parameters for SRM are extent of snow covered areas, temperature and and precipitation. These are the parameters derived from remote sensing information in this project.

SRM was designed for mountainous areas. It expects this situation to be prevalent for snow covered conditions. SRM allows the division of the basin area into different elevation zones, up to eight zones. Although input is accepted on a non zone basis it prefers the provision of the different parameter as they occur for the different zones.

| Category | Climatological Data | |
|---|---|---|
| *Variable* | *Description* | *Remarks* |
| PRECIP | Daily measured precipitation. | R.S/ CON. |
| T | Temperature data expressed in degree day | R.S/ CON. |
| S | Snow cover area in each elevation zone. 1.0=100% | R.S/ CON. |
| ND | Number of snow melt days. | |
| ACTUAL | Actual stream runoff. | CON |
| TMAX | Maximum daily temperatures recorded at base station. | CON |
| TMIN | Minimum daily temperatures recorded at base station. | CON |
| TCRIT | Temperature conversion factor for rain/snow check. | CON |
| PDR | Previous day runoff at stream gauge. | CON |
| PDM2 | Previous day-1 runoff at stream gauge. | CON |
| QNS | Initial runoff value Actual data value for the first day. | CON |

| Category | Basin Data |
|---|---|
| BASIN | Basin name. |
| IYEAR | Modelling year. |

| | |
|---|---|
| NZ | Number of elevation zone. |
| AREA | Area of each of the elevation zones. |
| X | Parameter for calculating recession coefficient |
| Y | Parameter for calculating recession coefficient |
| DTLR | Adjustment for temperature lapse rate. |
| AN | Degree day factors |
| CS | Runoff coefficients for snow. |
| CR | Runoff coefficients for rain. |
| IPR | Precipitation method option |
| ZMEAN | Hyposometric mean elevation for each zone. |
| STATN | Elevation of base station. |
| MAXMIN | Temperature input flag. |
| IEXT | Temperature interpolation flag. |
| IDEDGY | Temperature computation flag. |
| **Category** | **Operational data.** |
| ISTMTH | Start month of model. |
| IEMNTH | End month of model |
| IRUN | Run Sequence number. |
| MODE | Snow melt mode. (Simulation or Forecast) |
| IPLT | Plot option. |
| IPRINT | Print option. |
| UFLAG | Units Flag. English or Metric. |

| | |
|---|---|
| ACTFLG | Actual data flag. |
| IZONE | Zone data flag; Indicate if data available by zone or not. |
| IDTFLG | Temperature lapse rate flag. |
| MTHD | Flag to indicate the Method for computing Degree day temperatures |
| ITPROC | Temperature Pre-processing flag. |
| IPRUN | Print runoff values per zone. |
| MNTH | Number of days in each month |

R.S. = Remote Sensing data. CON = Conventional data.

Table 5.1 Listing and categorisation of SRM parameters.

### 5.4.3 Climatological data

The climatological parameters required by SRM are basically composed of two categories, hydrological parameters, and runoff information. SRM favours the provision of these parameters for the different elevation zones of the basin.

The different climatological parameters are available both in conventional means and from remote sensing sources. Conventional data are available for the selected basin but not on zonal basis. On the other hand if the data is available from remote sensing sources they are provided in an areal description.

Precipitation can be provided for every day it occurs. Snow and temperature can only be provided for clear days. Conventional data are required for the provision of temperature data when not available, while snow data are not required for cloud covered days as they can be interpolated for these days between cloud free days. However, conventional registration of the snow fall is necessary for extensive periods of cloud cover, to give the modeler an idea of the behaviour of the snow pack for these days and to cater for remotely un-registered snow storms that might melt before a cloud free day is available for mapping it. Remote sensing data provides temperature data for the basin simultaneously with snow mapping. These information provide additional information of the status of the snow pack.

Temperature data can not be provided on a maximum minimum basis using remote sensing. This data is important as it provide the margin of temperature the snow pack is being subjected to. This illustrates the importance of combining remote sensing information with conventional data for a maximum return of information about the basin leading to better knowledge and understanding of the hydrological phenomenon.

River runoff is gauged down stream obviously by conventional means. Table 5.2 Provides a list of climatological parameters and relates them to SRM. It describes the conventional requirements of SRM. A small description on how remote sensing provides these estimates and under what conditions.

| Parameter | Precipitation |
|---|---|
| Frequency | Daily measured precipitation |
| Conventional data | Optimum condition: measured at mean elevation, if not could be extrapolated from base station. |
| Remote Sensing | Provide areal description. Processing requires conventional historic data. |
| Remarks | If precipitation occurs, temperature should be recorded as this in turn decides how precipitation participates in flow calculation. |
| **Parameter** | **Temperature** |
| Frequency | Daily |
| Conventional data | Optimum conditions: measured at mean elevation could be extrapolated. |
| Remote Sensing | On Cloud free days temperatures could be measured at the time of the satellite overpass. No conventional requirements. |
| Remarks | Temperatures are input in two ways. Mean measurement or maximum - minimum. |
| **Parameter** | **Snow Cover.** |
| Frequency | Daily values for snow cover area for each zone. |
| Conventional data. | Provides information about the the snow pack such as water equivalent and density. |
| Remote Sensing. | Areal description of the snow coverage. more than one class of snow could be detected. |
| Remarks | Mapping on cloud free days.The daily values of snow cover are deduced by extrapolating between cloud free days. |
| **Parameter.** | **Evaporation.** |
| Frequency. | Daily. |
| Conventional data | |
| Remote Sensing | Estimated values should be averaged over ten - twelve days to subdue anomalies. |
| Remarks | *NOT AN SRM REQUIREMENT.* Evaporation can be incorporated in the modelling of SRM through incorporation the runoff coefficients. |

Table 5.2 Remotely sensed data. in relation to SRM requirements.

### 5.4.4 Basin Data.

Basin data consists of two categories, physiographic information, and information about the basin and the parameters. The physiographic data are rather modest and constitute basically information about the mean height and area of the different elevation zones and most importantly runoff coefficients for the different zones for both snow and non-snow covered areas.

Runoff coefficients can not be provided directly by conventional means. They can only be provided in an indirect way such as measuring the runoff of a certain area and then comparing it with the estimated input of water, in the light of this comparison runoff coefficient can be estimated. However, this information could be estimated from remote sensing sources. Images of the basin could be analysed and relations between the various spectral responses of the land parcels could be established. This information could be related to runoff coefficients. This study was not included in this project because of imposed limitations as discussed in Section 3.2.3. These parameters were estimated, for use in this project, using the recommendations of the SRM manual.

The rest of the parameters of this category either describe how other parameters are input or are parameters required by the different equations of the model.

### 5.4.5 Operational data.

These requirements are provided by the individual modeller. They describe the period of the modelling, options on how to perform the modeling, input data options, and output options.

Non of the above data is provided by remote or conventional means.

## 5.5 Data requirements for the conduct of a case study.

When introducing a new system for the production and management of data which is required to replace or complement an already established practice several consideration should be established:

1- The data introduced should be of comparable accuracy if not better than the old one.

2- Old data is not just duplicated. New data should provide a new insight into the physical conditions of the observed parameter.

3- New sorts of data which are not provided by the old system should be identified. These data should be incorporated in the existing methods which utilises the old data, or new models should be established.

4- The new sources of data are cost effective and worth the investment of resources and man power.

5- The hydrological model should be run using different sets of data. Three modes are stipulated

- a- Data input is provided solely by conventional means.
- b- Data input is provided solely by remote sensing sources.
- c- Data input is provided from a combination of the two sources.

In order to establish the above conditions a case study should have maximum details of data for all the parameters under study.

This means that the basin of the case study should be covered with conventional sensors in a regular and uniform grid. These gauges should register all the parameters that remote sensing sources are going to provide. The description of the variation of these data should be detailed both in time and space. The product of the remote sensing methods are then compared with these collected. Having established and carried out the above for a significant length of time, conclusions could be reached with a high degree of certainty.

The above theoretical proposal for such a study will only be available for a premeditated project undertaken by a specialist and dedicated organisation. The research of this project relied on existing data sources which was not detailed as desired. All the available data was sought. Some required data was not available as the bodies responsible for collecting hydrological parameters did not store the relevant data. This fact is attributed to two factors, the first that the use of such data is not envisaged as a need, or the area of the basin was not covered for that particular parameter.

## 5.6 Data requirements for the case study of this project.

### 5.6.1 Introduction

The definition of the data used in this project passed in different stages of formulation. The requirements changed as the details of the project were determined. With hindsight the requirements were formulated in three stages. The first set of requirements were established after the theoretical formulation of the project. Changes to the data required were introduced after the determination of the satellite platform to be used, the basin, and the period of simulation. This section will review and provide a description of the data required after the sensor had been selected.

### 5.6.2 Required data according to the theoretical study.

The requirements for the case study consist of three sets of data.

a- Conventional data for use in hydrological modelling.

b- Remote sensing data for derivation of hydrological parameters.

c- Conventional data necessary for the processing of remote sensing data.

The third set of data is needed as deriving some remote sensing hydrological estimates requires the use of some conventional data in particular precipitation and evaporation estimates. The Bristol method, for deriving precipitation requires historical data of the precipitation. This data is only available from gauges, i.e. conventional source. Remote sensing of evaporation requires two conventionally measured parameters for each set of estimates. These parameters are daily net radiation and air temperature of the basin.

The following section is a summary of the required data for a case study using SRM as a hydrological model. Each of the data sets corresponds to an SRM requirement, listed in Table 5.1, which will be pointed out:

*a- Conventional Data.*

1- Daily readings of runoff at stream course on the perimeter of the basin, and at the intersection point of the stream course and the zone elevation perimeters. This data corresponds to ACTUAL, PDR, PDM2, and QNS.

2- Hourly readings of runoff and temperature every 15 days or every month, in order to determine the time lag of the basin. Time lag is the time taken by falling precipitation on the basin to reach the stream course. This data is not listed in either of the Tables. The determination of the time lag decides the form of the modelling formula of the SRM.

3- Daily reading from snow pressure pillow or lysimeter for different snow elevation zones. If this is not available, daily readings of the density of snow for different elevation zones. This data will help in the determination of the CS, Runoff Coefficients for the snow.

4- A topographic map of the area. For determination of NZ, AREA, STATN and ZMEAN.

5- Daily temperature precipitation and evaporation readings at the different mean hyposometric elevation zones. The temperature readings should either be in max-min or mean. The corresponding parameters for the above data are T, TMAX, TMIN, and PRECIP. While evaporation is incorporated in CR Runoff Coefficient for rain.

*b- Remote sensing.*

1- Daily AVHRR images of the basin (at least four slots a day) for precipitation (PRECIP), evaporation (CR), temperature(T) and snow mapping (S). These images can also be used for the estimation of (CS).

*c- Conventional Data needed for the processing of the remote* *sensing data.*

1- Mean monthly rainfall readings for all rain gauges of the basin.

2- Mean number of rain days of the basin.

[1&2 for compiling regression charts for the Bristol method]

3- Daily readings for the Air temperature of the basin for different elevations.[Evaporation requirement (Ta) ]

4- Daily estimates of Net Radiation. [Evaporation requirement, Meteorological data ($Rn_d$) ]

[ See section 3.7 for description and details of of 3&4]

## 5.7 Received data.

### 5.7.1 Introduction.

The data acquired for the purpose of conducting this study are split into two categories, Conventional and Remote sensing. The conventional data was acquired from the different sources while the remote sensing images were acquired from University of Dundee AVHRR receiving station. This section will detail the sources and describe the different data.

### 5.7.2 Conventional data.

The ultimate set of data used to conduct this project was constrained to the available data from the different organisations that store and can provided the desired information.

A compilation of the desired data, all the conventional data listed in the last section, was sent to the different bodies that store this information. Three organisations store different parts of the needed information, Institute of Hydrology, Yorkshire Water Authority (Yorkshire Water plc.), and the Meteorological Office.

The data was finally supplied by the first two as they, between them, provided all the data available. Most of the desired data was acquired. Appendix 2 Provides a record of all the data received from the different sources. However some of the data was not available, the following is a listing of these data:

1- Precipitation, temperature, and snow data was only available for one station. No data was available for the different elevation zones.
   Snow data was available for two stations but was inadequate as very little information was available.
2- Hourly readings of temperature were not available.
3- Air temperatures were not available.
4- Net radiation as such was not available. Radiation, from which net radiation could be estimated, was available for some days by the meteorological office but was not acquired as no evaporation estimates were carried out.

*[3 & 4 are data for the estimation of evaporation which was also sought]*

The acquired data was not available for different elevation zones in the basin. SRM requires the input of data on zonal basis however, if it was not available SRM interpolate the data from the measuring station to the different elevations. Thus the absence of zonal information will not affect the use of SRM. The conventional data is also used for the purposes of calibrating and comparing remote sensing estimates of the hydrological parameters. The absence of conventional data will result in the restriction of the comparison of the remote sensing derived data, which covers all the basin in an areal form, to a single conventional reading. This will reduce the degree of certainty of accuracy of the remotely sensed estimates.

The non availability of the hourly readings of the temperature resulted in the estimation of the lag time of the basin. A process which depends on trial and error of different times.

Items 3 & 4 absence were of no real significance as evaporation estimates were not derived for this case study. However, these are vital information for the production of evaporation estimates.

### 5.7.3 Remote sensing data.

The remote sensing data constituted of AVHRR images. These images were ordered from the Satellite Receiving Station of Dundee University. The data received from this source composed of two sets of data. Quick browse files and Images on CCT.
The quick browse files are a contact prints of AVHRR scenes. All Slots available for the period between 20 and 29 January were received. These prints were used to define the useful cloud covered days. Image 5.1 is a print of quick browse file for January 29.
The CCTs received were for the period between 23 and 29 January. One slot for days 23, 24, 25, 26, and 27. Three slots for days 28 and 29. The one slot images registration time was the early afternoon platform pass. While the three slots registration times varied throughout the day. Each image is composed of 720 scan lines, where each scan line extend for the whole swath of the AVHRR sensor. The density of the written data was 1600 Byte Per Inch BPI.

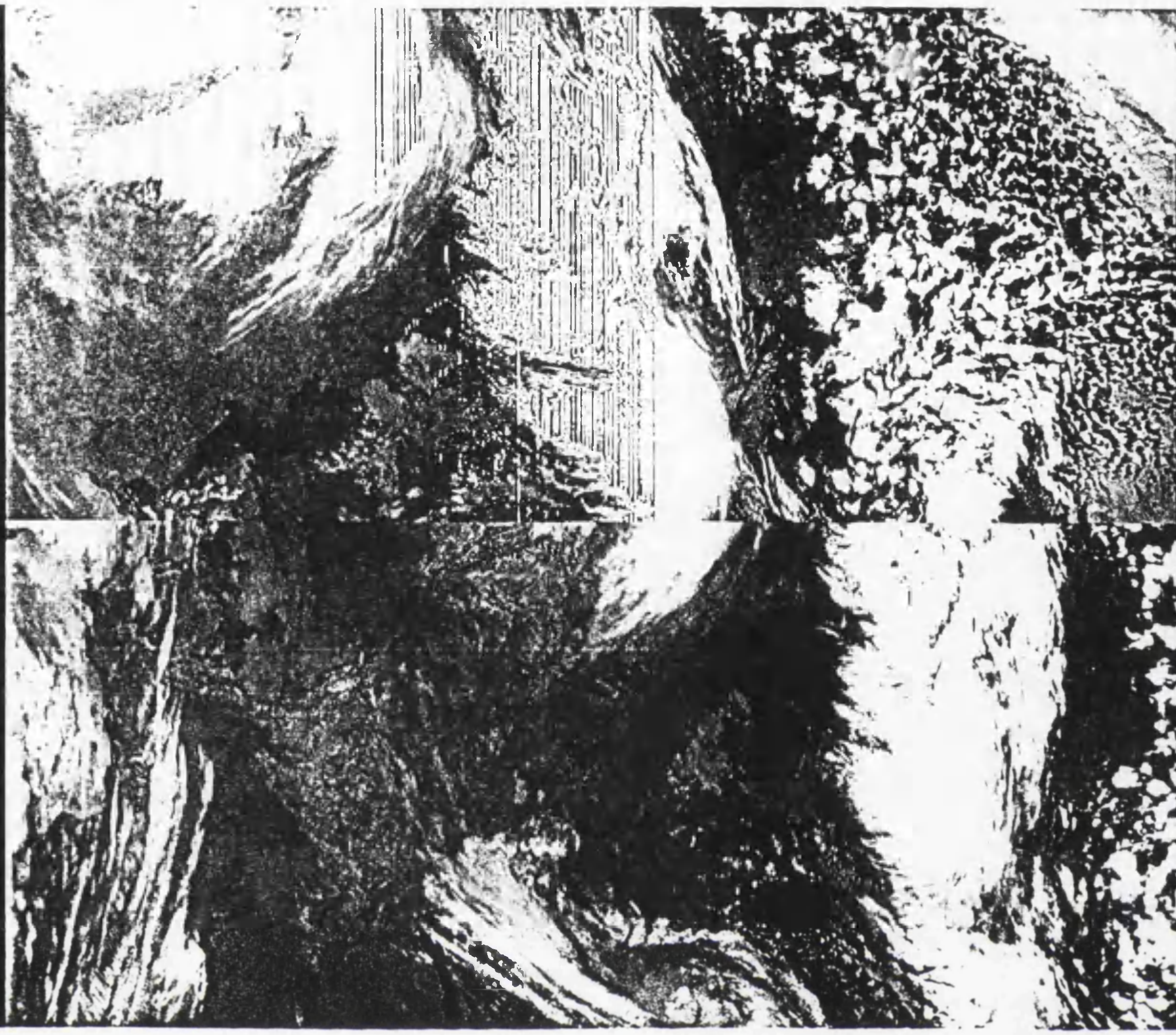


Image 5.1 is a print of quick browse file for January 29.

The above mentioned images came from two satellites of the NOAA series, NOAA-8 and NOAA-9. NOAA-9 provided the images for the days were one slot was used. The pass time of NOAA-9, for these images, is in the early afternoon @ 14h 30min. The other pass time of NOAA-9 is @ 19h 30min. The three slot images were provided by NOAA-9, the afternoon slot, and NOAA-8, slots of the two passes, i.e. @ 07h 30min and @ 02h 30min.

### 5.7.4 Processed data received.

Snow mapping was also performed for the clear days by a researcher in Bristol University. His results for mapping the snow for the same basin are provided and discussed and compared with the results achieved in this project in Section 8.5

| Parameter | Ideal data | Received data | Comment |
| --- | --- | --- | --- |
| Precipitation & Temperature. | Data of several gauging stations throughout the basin. | Data from one station. | Comparison of satellite estimates is restricted to one ground reading. |
| Snow | Areal description of snow extent and density. | Snow density from two gauging stations. | Accuracy of snow mapping is wholly dependent on the use of satellite data. |
| Basin Runoff | Daily readings at different elevations. | Daily reading for the base station. | No detrimental effect. |
| Lag time of the basin | Hourly readings of runoff and corresponding temperature. | Runoff readings were available no temperature readings | Lag time has to be estimated. |
| Net radiation and Air temperature | Daily readings | No data available | Remote sensing Evaporation estimates cannot be derived. No detrimental effect on this case study. |
| Historic data for precipitation | Areal mean monthly rainfall over the basin. | Received for the Month of January. | |

Table 5.3 A summary of the ideal data and those received

## 5.8 Conclusion and comments.

### 5.8.1 Introduction.

This chapter has defined the case study. It determined the duration and the location of the case study. The ideal data sets and those received were discussed and presented. The Basin selected for the case study is the basin of the River Aire, while the period of the case study was a week in January 1986, 24 to 29 of January. A summary of the ideal and the received data is available in Table 5.3.

### 5.8.2 Viability of this project.

The determination of the worthiness of this project branches into two topics of discussion, the first is the quality of the derived parameters in general and the effects of the differences between the ideal data set and the received data.

The quality of the derived parameters stems from several conditions and the setting of the project. The size of the study area with respect to the AVHRR imagery, the length of the period of the simulations, and the existence of extensive periods of rain which might have an adverse effect on the extraction of the data referring to the study area, all have direct effect on the project.

The area of the Aire basin is 282 $km^2$. This area falls within the limits of the minimum area required for an adequate snow mapping from remote sensing sources.(See section 2.7) An area of this size might be considered as a very small study area in comparison of the wide swath width of the AVHRR instrument.

The width of the basin, 20 kilometre, represents less then 1% of the swath width of AVHRR. However, if results can be presented for an area of this size the viability of the AVHRR instrument for areas bigger then the above area is secured. A case which has been proven by the results obtained in this project (Details follow in Chapter Eight).

Hydrological study of basins are usually of long duration. A period of at least a season is usually needed. The duration of the period for which estimates are derived presents the minimum acceptable. As the processing of satellite imagery for a whole season is not feasible in this project, a period which includes the weather conditions catered for in HyRSIS is necessary. The period selected in this project contains two types, clear days and rainy days (moderate rain). Rain storms, causing flood situations, conditions are not catered for in HyRSIS programs. Thus, the selected period presents adequate coverage for the methods included in HyRSIS. However, the exclusion of the rain storm methods reduces the accuracy of the daily precipitation estimates, on the other hand these daily estimates are balanced on the long term by the Bristol method of estimating precipitation.

The existence of extensive cloud cover over England and Wales will have detrimental effects on the precipitation estimates, derived estimates cannot be related to ground references resulting in gaps in the data, i.e. if the extraction of the basin image relies on the process of geometric correction described in this project. However, if the automatic procedures described in Section 4.3.3.5 are incorporated in HyRSIS the effect will be minimal and not more than the expected variations in the data.

The received data was less then the ideal data envisaged by the SRM requirements and those needed for a proper conduct of a case study. The SRM requires the data to be provided on zonal basis, (elevation zones). However, it caters for non-zonal data inputs, this is established in the model as it interpolates the input data from one station throughout the different elevation zones.

Satellite data provides areal information of the different parameters in the basin. The image of the basin provides 540 estimates for each parameter, an ideal study case should be able to compare the areal variation of satellite estimates with the areal variation of ''ground truth''. The received data was composed of data for one gauging station, thus, each derived parameter had to be compared with just one reading and the degree of accuracy of the satellite areal description is not fully established. The above does not mean that the areal description, provided by the satellites estimates, is not reliable. It just stresses the scientific need to establish this reliability on the basis of direct comparison between the mapped parameters and the ground truths rather then rely on an extrapolation process.

# Chapter Six
## Data Manipulation.

### 6.1 Introduction.

Chapter four described how hydrological parameters are derived. While chapter five argued the case for a case study. For every day of the modelling period, each of the derived parameters were stored in image format is separate files. These files are of the basin where the image size is 20 pixels by 27 records. This chapter will go through the different functions involved with the process of data manipulation, extracting the data from the image format, loading to database, and at the end the extraction of this data for the use of the hydrological model.

The chapter will start with the extraction of the data in the files and their formatting in real form, i.e. numbers, rather than the binary format of the files. Programs were written for this purpose. The resultant data were then loaded into a database. The choice of the database will be discussed, as well as the method of loading of the database. The database will be described as well as the sublanguage used by the database. The retrieval of the data and then organising it in a manner compatible for the use of the Hydrological model will also be discussed.

## 6.2 Transfer of parameters image file from binary to real Number Format.

### 6.2.1 Introduction.

The swath width of an AVHRR image is 2400 km. The dimensions of the study area basin are 27X20 km (Figure 4.3). The extraction process of the pixel data referring to the area of the basin was reviewed in Section 4.3.3.6. The products of this process are binary files which are then processed to produce estimates of the different hydrological parameters. These different parameter estimating processes were also reviewed in Chapter four. The end product of the different processes were image files of the basin in binary format for each of the different parameters. This section deals with the extraction of these parameters from the image files into files containing numeric data.

The organisation of image files in computer memory will be reviewed, as it is necessary to explain the method of extraction of the data and the formatting of the data from the binary to the real. This section is related to Section 4.3.

### 6.2.2 File organisation and access modes.

The programming language used in this project is FORTRAN. The computer used is a VAX station II/GPX. VAX FORTRAN support three kinds of file organisation: relative, sequential, and indexed.

*Sequential files* consist of records arranged in sequence.

Sequential files are supported by all VMS operating systems.

*Relative files* consist of numbered positioned called cells. The cells are of fixed equal length and are consecutively numbered. Each cell contains a single record or is empty.

*Indexed files* consist of two or more separate sections. One section contains the data records while the other(s) contain the index(es).

Relative and index files are used when the user wants to access information in a pre-planned way and not necessarily in the same order they were written in. The sequential files are used when the data is retrieved in a methodical way. As the data contained in the image files of this project are all going to be processed and no special mode of access is needed, the image files used in this thesis were sequential files. Another important reason for using sequential files is that files are designated to a certain type when created. The image files were designated as sequential when they were extracted from the original AVHRR imagery. The creation type of image files will always be sequential as long as the extraction method is done as in this project. Each image file was composed of 27 records. Each record was composed of 20 pixels. The location of each pixel in the file is defined by the record number and the pixel number. These locations are related to national grid reference numbers. Hence every pixel refers to a specific area on the ground.

### 6.2.3 File representation in computer memory.

Image files, sequential files in our case as explained, are organised in memory records containing pixels, Figure 6.2. Each pixel is composed of byte(s). A byte is a set of eight bits. Each bit can have either the value one or zero. Numbers are represented as a combination of bytes according to their type. The length of a number in computer memory varies according to its type. Hence, the record length is dependent on the type of the data it contains. Each image file had a fixed number of pixels all of the same type. This resulted in sequential files of fixed length records.

| | Data in each record.(pixel) | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| e | 2 | | | | | | | | | | | | | | | | | | | |
| c | 3 | | | | | | | | | | | | | | | | | | | |
| o | 4 | | | | | | | | | | | | | | | | | | | |
| r | 5 | | | | | | | | | | | | | | | | | | | |
| d | 6 | | | | | | | | | | | | | | | | | | | |
| s | 7 | | | | | | | | | | | | | | | | | | | |
| | 8 | | | | | | | | | | | | | | | | | | | |
| | 9 | | | | | | | | | | | | | | | | | | | |
| | 10 | | | | | | | | | | | | | | | | | | | |
| | 11 | | | | | | | | | | | | | | | | | | | |
| | 12 | | | | | | | | | | | | | | | | | | | |
| | 13 | | | | | | | | | | | | | | | | | | | |
| | 14 | | | | | | | | | | | | | | | | | | | |
| | 15 | | | | | | | | | | | | | | | | | | | |
| | 16 | | | | | | | | | | | | | | | | | | | |
| | 17 | | | | | | | | | | | | | | | | | | | |
| | 18 | | | | | | | | | | | | | | | | | | | |
| | 19 | | | | | | | | | | | | | | | | | | | |
| | 20 | | | | | | | | | | | | | | | | | | | |
| | 21 | | | | | | | | | | | | | | | | | | | |
| | 22 | | | | | | | | | | | | | | | | | | | |
| | 23 | | | | | | | | | | | | | | | | | | | |
| | 24 | | | | | | | | | | | | | | | | | | | |
| | 25 | | | | | | | | | | | | | | | | | | | |
| | 26 | | | | | | | | | | | | | | | | | | | |
| | 27 | | | | | | | | | | | | | | | | | | | |

Figure 6.2 File representation in computer memory. The file is composed of a number of records. Each record is composed of a certain number of data cells. The example shown is for the image files of the basin. The data cells in each record are composed of the 20 pixels, the width the basin. The number of records is 27 the length of the basin.

### 6.2.4 Extraction of pixel values.

Programs were written to read each of the pixel values. The Basic programming of each of these programs is the same. These programs were as follows

| Parameter file. | Extraction program |
|---|---|
| Precipitation | PRECIGRID |
| Temperature | TEMPGRID |
| Evaporation | EVAPOGRID |
| Snow classes | SNWCLS |

Different programs were needed because the values and type, in the sequential files, were different for each of the hydrological parameters. The user should be careful in the way the values of each parameter of a pixel are extracted. Errors could be generated from the misunderstanding of the type of parameter. For example, if a value is represented in memory as Byte and the programmer reads it in as an integer, the program will be reading in two Bytes in instead of one byte thus distorting the values of the estimates.

The way in which a file is read in the VAX/VMS system is by starting from the top left hand corner of the file. The program reads the values (Figure 6.2) starting with record one pixel one, pixel two and so on .... till the end of the record, then record two and so on. The program gives the facility of aggregating the pixels. If the grid spacing is bigger than one kilometre the program averages the values of the pixels between the spacing. In this project the spacing of the grid was 1 km. For each file the number of pixels extracted will be 20 X 27, 540 numbers.

All the above mentioned programs performed the same function except SNWCLS program which had two additional features. The program extracts the pixel values and screens them. If a pixel value is the same as the pre-defined snow classes the program keeps its value and write it to a file in a numeric fashion. If the value is different from the perceived snow classes the pixel is assigned a value of zero. The program outputs two sets of values. The first set contains the numeric values of the different classes, the second set contains the screened values where non snow classes have the value zero. The other feature is that no averaging of the values of the pixels is available. This is due to the fact that the values attributed to the pixels do not express a measured, or estimated value but rather indicate the existence of certain classes.

The extracted pixel values refer to a 'precise' location on the basin map. The result of the extracted values are files that are to be loaded into a database. The loading of the data will be explained in the following section.

## 6.3 Database Systems.

### 6.3.1 Introduction.

A database is a computer based record keeping system. The ultimate function of this system is to record, maintain and manage information. This information involves any data of importance to the owner organisation. A database is composed of four elements: data, hardware, software, and users. The data stored in this thesis is composed of various hydrological parameters, and physiographic information. The hardware used is VAX station II/GPX while the software used is ORACLE.

Several organisations are fully committed to databases for the management and storage of their information. The existence of some of these organisations is dependent on the continuous successful use of databases not in the least the financial sector. This is clearly exemplified by the fact that the City of London will soon start dealing in shares without the customary paper forms using a completely computerised system based on databases.
The reasons for developing and using databases have been addressed by many. Date [1986] discusses the advantages of using databases when compared with applications which use private files where these files are individual computer data files. These advantages are briefly stated below:

- compactness, bulky papers files are not needed?! {regardless of the introduction of computers, documentation paper files were still needed for keeping track of individual files. The database management system helps in reducing them.}

- speed, retrieval of electronic data is much faster than manual human one.
- less drudgery, eliminates the need to maintain files by individual operators.
- currency, up to date information available on demand.

centralised control of its operational data, which means that:

- redundancies can be reduced,
- inconsistency can be avoided,
- the data can be shared,
- standards can be enforced,
- security restrictions can be applied,
- integrity can be maintained,
- conflicting requirements can be balanced,
- data independence.

However, he points out the disadvantages as follows

- an error in one input data record may be carried throughout the database.
- traditional processing jobs may run more slowly.
- major attention must be given to the security of the system.

### 6.3.2 Types of Databases.

The term database refers to a large centralised collection of data that is stored for the purpose of retrieval and manipulation, in combination with other sets of data or not, as the need arises.

The governing relationships between different items of the data base define the type of a data base.

Many types of databases exist. The different types of databases depend on the kind of definitions one uses. Hursch and Hursch [1986] states that the exact number of data base types lies between two and seven, and while the mathematical distinctions between major types is clear, databases in the market place combine characteristics from two or more.

The two basic fundamental database systems are The Relational and the Hierarchical.

### 6.3.3 Hierarchical Database System.

The data in an hierarchical system is arranged into a logically related hierarchy. The structure of this kind of database could be represented in a tree format arrangement (Figure 6.3). Each parent element has a set of children. Children may be parents to other children but can not be parents to other elements in the level above them or in their level.

A special case of the Hierarchical system is the network system, Figure 6.4. In this system the parent elements have children. Children might have children with the same conditions of the hierarchical system, but they might be children of more than one parent. Data is accessed through the use of keyed attributes i.e. data are assigned keys in order to identify the location of the data.Hierarchical systems have the following advantages:

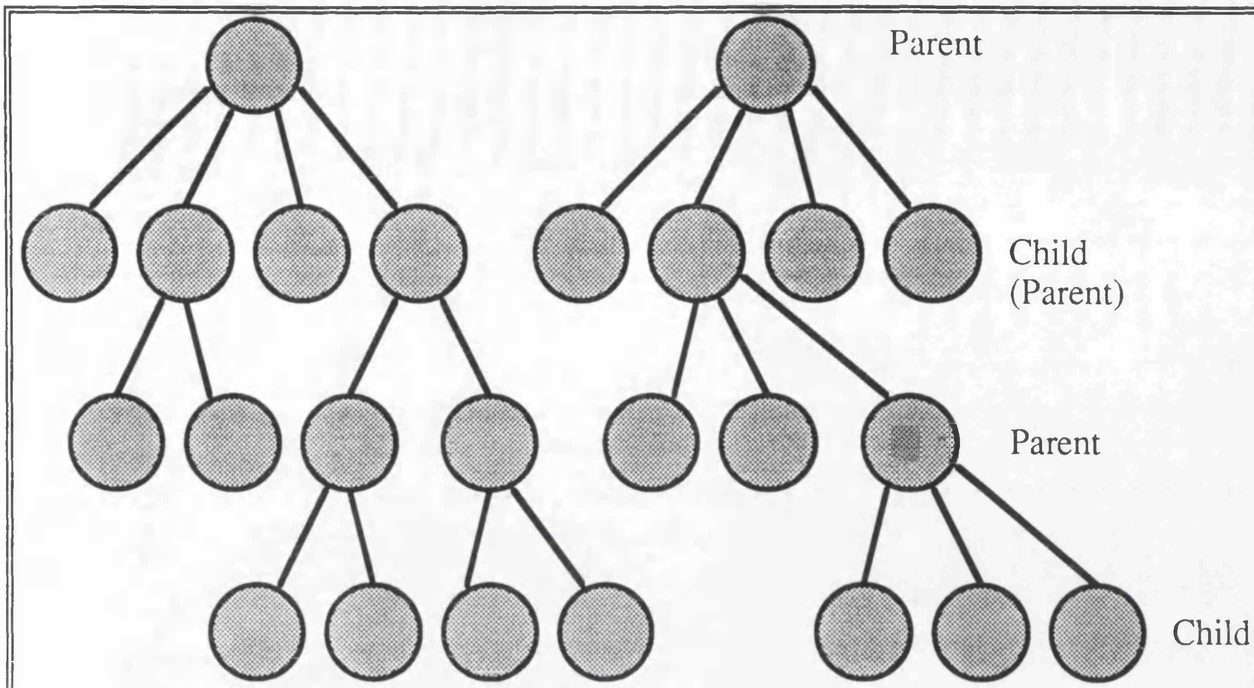



Figure 6.3 Two Hierarchical database systems graphical representation. Data is stored in a tree structure composed of a hierarchy of data records

- they are easy to update and expand

- they are easily accessible through the usage of the pre-defined keys resulting in quick retrieval of desired data.

The disadvantages are summarised as:

- large index files ,

- repetition of some attribute values,

- increase storage and access overheads.

The network structure reduces redundancies but on the other hand complicates the database structure through the increased number of pointers.

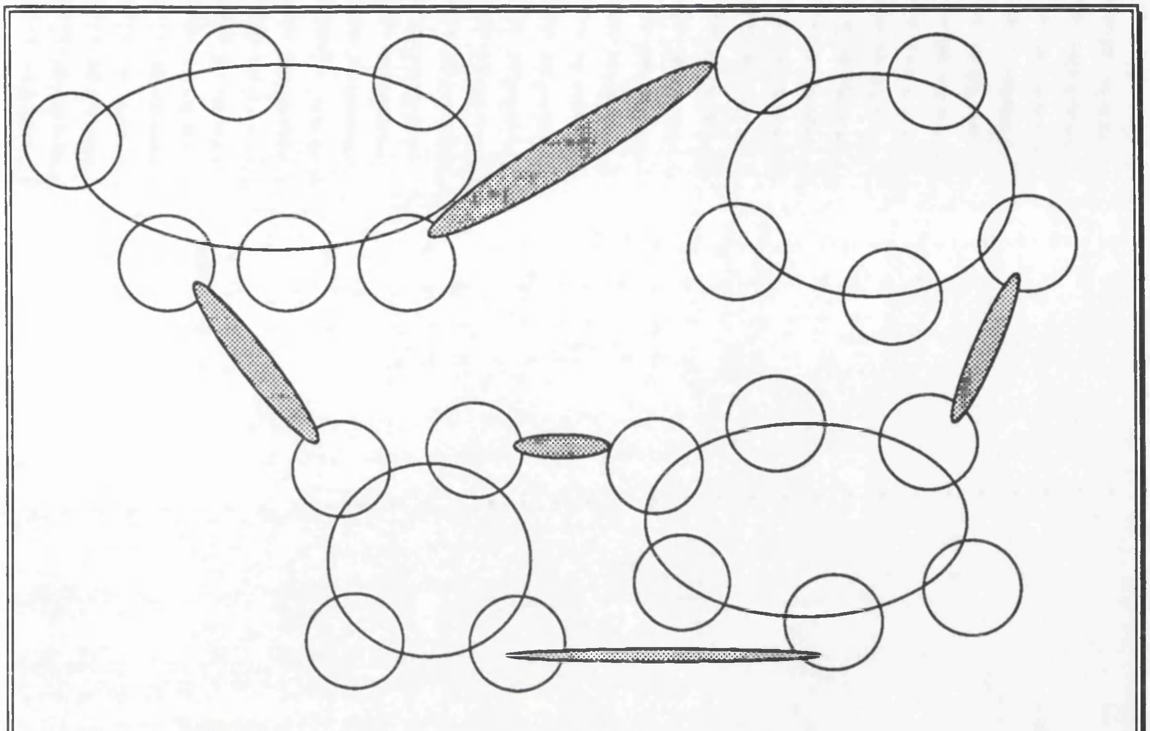



Figure 6.4 Network database systems. Data is linked together forming intersecting sets of data.

### 6.3.4 Relational Database Systems.

#### 6.3.4.1 A brief history and description.

The relational database systems are based on the a set of theoretical ideas known as the the relational model. This model was formulated by Codd, [1970]. He conceived the relational database as he applied mathematical discipline (Codd is a mathematician by training) to the field of database management.

A Relational database is comprised of a collection of related tables, and nothing but tables.[Date 1986] Two tables are said to be related when a relationship could be established between the data of the two tables. The table is composed of a row of column headings with zero or more rows of data values. It should be noted that in contrast with the Hierarchical system the relationships between related entities are not defined and do not all have to be established before entering the data. Since the Hierarchical system has pre-defined relationships it could be reduced to a relational form, i.e. the hierarchical is a very special case of a relational system which is locked and can not be altered with the same ease of the flexible relational system.

Relational databases seem set to become one of the major mechanisms for storing large collections of data.[Waugh and Healey 1987] This is consolidated by the fact that in the last decade or so all new database systems in the marketplace has been relational based. While the makers of the old Hierarchical systems have been trying, with varying degrees of success, to update their systems to support, and become compatible with relational systems.

#### 6.3.4.2 Relational database sublanguage.

The relational system in its theoretical form needs an interface language with the end user. IBM Research defined a language called the Structured Query Language (SQL). SQL was introduced to the commercial market first by ORACLE Corporation in 1979. This language has become the de facto standard in Data Base Management Systems (DBMS). SQL is not a full programming language. Hence SQL is a sublanguage in need of a host language, such as FORTRAN, so that SQL statements can be embedded into it in order to gain access to facilities and resources SQL itself does not provide. SQL commands can be issued without the need of a supporting computer language but the returned queries can not be used by any other program. However, records of a querying session could be written to a file which could then be edited on the machine operating level.

The language supporting the relational system, SQL, has been criticised by the father of the relational approach. Codd [1988] attacked SQL and exposed three flaws:

1- It permits duplicate rows in relations;

2- Supports an inadequately defined kind of nesting of a query within a query;

3- It does not adequately support three valued logic.

For our purposes in the use of the relational data base systems, these 'flaws' are purely academic as none of the above is of relevant importance.

The duplicate row problem could pose a problem for users of the databases if the variation of single value is of utmost importance. A share dealer wants to know an exact price or the precise figure for a companies profit. Duplicate rows will exist only if the user inserts them in the database tables. If the user is not using duplicate rows and makes sure not to do so, this problem will not arise. However the low statistical sensitivity of the hydrological data may allow some duplicate rows without an immediate effect the total accuracy of the data.

The 'relational model' has been a moving target as it has evolved.

According to the tightening rules of the relational model no language could be called relational or even semi relational. [Date 1981] The criticisms of SQL concerning the query nesting and three valued logic are primarily concerned with the adherence of SQL sublanguage to the envisaged relational model. These criticisms also supposes a very complex and highly sophisticated use of the database systems. The needs of this research with respect to database systems are relatively modest. Even for the future needs of this systems, SQL will still be more than enough.

Another failing of SQL is the existence of many versions of it affecting portability of the programs. Systems surveyed in the market place support different versions of SQL. The dependence of SQL on a host language makes the portability of programs also dependent on the portability of the host language. The above failings should be viewed in the light of Date's comment "SQL is great. But it could have been better." [Date 1987].

Beech [1989] stated that any application whose data can (without too much effort) be made to fit the rectangular model of the relational system stand to benefit from its intelligibility and flexibility of queries. This description of the data fits the bill for our requirements and the definition of the data that had been derived, extracted and produced in the last chapter. It is needless to state, a relational database was used in this project.

It is interesting to note the fact that a committee of the American National Standards Institute (ANSI) has endorsed the SQL as the standard language for the relational database management systems.

## 6.4 Database used.

### 6.4.1 Introduction.

Three companies dominate the commercially available SQL/relational databases. Oracle was the second after IBM to introduce them more than a decade ago. Oracle claims the largest user base and the largest number of supported machines. Ingres follows closely due to its strength in the VAX world while Informix claims the largest share of the SQL market on UNIX platforms. [Lewis 1990]

The relational database available in the Dept. of Photogrammetry is the Oracle database. This section will review the ORACLE database and provide a description of how data is accessed and manipulated using SQL.

### 6.4.2 The ORACLE relational database.

The ORACLE database management system incorporates various products.

1- The ORACLE Relational DataBase Manager System (RDBMS).

2- The SQL Language.

3- ''Easy'' ORACLE Products.

4- ''SQL'' ORACLE Products.

5- ''Pro'' ORACLE Products.

Users may not require the use of all these products. However all the above products, except the 'easy' product, has been used in this project in one form or another.

### 6.4.3 The ORACLE RDBMS.

The RDBMS is the kernel database utility. It includes the database manager and several features to assist the user in the maintenance, monitoring and use of the data.

The utilities included in the RDBMS are as follows: IOR, SGI, ODS, AIJ, CRT, Export/Import,and ODL. The features used in this project were the IOR and ODL utilities. The description of the above abbreviation follows:

IOR is the DataBase Administrator DBA utility to start, stop, and initiallise an ORACLE System.

ODL Oracle Data Loader utility used to load the data from O/S standard files. ODL is reviewed in more details in Section 6.5 as it was used here.

SGI ORACLE shared memory description.

ODS run time system statistics.

AIJ records database activity and for recovery in the event of system failure.

CRT for screen and key caps definitions.

Export/Import user utility to transfer data from database storage to system files and vice versa.

### 6.4.4 The basis of all ORACLE utilities: the SQL language.

SQL pronounced ‘sequel’ is a compact English like data language. The ANSI standard edition counts fourteen commands in SQL.

These commands are classified in four categories.

QUERIES Statements which retrieve existing data in any combination, expression, or order. Queries are done with the command SELECT followed by the data desired and the table or views containing source data. SELECT extracts specified columns (fields) and rows (records) from a table. The SELECT command has a variety of optional Clauses and sub-commands to perform aggregating numeric fields functions and querying across several related tables. Nesting is another feature of the SELECT command. The SELECT command is executed after the innermost part of the command has been evaluated. The SELECT command does not change the data. It just retrieves it.

DML Data Manipulation Language statements are used to change the data in three basic ways.

* INSERT new rows of data into a table.
* UPDATE column values in existing rows.
* DELETE rows from tables

DDL Data Definition Language statements are used to create and drop database objects and views. DDL Statements include CREATE TABLE, CREATE VIEW, CREATE INDEX, CREATE SYNONYM, ALTER TABLE, and corresponding DROP statements.

DCL Data Control Language statements are used by the DBA to grant and revoke access permissions to the database.

{not to be confused with Digital Command Language also DCL}

### 6.4.5 "SQL" ORACLE products.

The SQL* products are the main products in the ORACLE product line and offer a sophisticated means of accessing the data. These include SQL*Plus, SQL*Forms, SQL*Calc, SQL*Menu, SQL*GRAPH, SQL*Report, and SQL*Net.

The feature used in this project was SQL*Plus. SQL*Plus is an interactive command driven interface which allows ad hoc queries and report writing.

### 6.4.6 "Pro" ORACLE Products.

The pro* ORACLE products are programming interface products which allow programmers to develop applications in high level languages using ORACLE data. Programmers can use precompilers to embed SQL Statements in programs or pre-defined set of subroutine calls, which use a lower level calls to access data in the database. Several languages are supported:

Pro*C, Pro*COBOL, Pro*FORTRAN, Pro*PL/I, Pro*Pascal, Pro*Ada. and Pro*FORTRAN which was the one used in this project.

### 6.4.7 Comments on the use of SQL.

The relational system supports only one type of data structures: the table. The relational language SQL can produce new tables from old tables. This is done through subsetting and/or combining existing tables. A single command can retrieve, update, and delete a set of records from one or more existing tables into a new table.

The operations are set in commands that specify, *what* is needed to be done, *not how* to do it.

## 6.5 Database application in this project.

### 6.5.1 Introduction.

The benefits of the use of a database for handling and managing the hydrological parameters derived from satellite data are varied. These benefits are synonymous with those generated from using databases for large quantities of data. Special reasons also exist for database use in remote sensing hydrological applications. The descriptive powers of remote sensing data produce a relatively big bulk of data. AVHRR images provide hydrological estimates for every pixel. Databases are specifically designed to help in the management of big data sets.

The hydrological model used in this project is the Snow Runoff Model. One of the purposes of this project was the management of the derived hydrological parameters in a way that can be retrieved for any hydrological parameter use. This is accomplished by the use of the relational database. The relations between different parameters are not necessarily all defined at the beginning of the establishment of the relational database to host the different parameters. Different hydrological models use the hydrological parameters in different ways. Hence the methods and order of retrieval of parameter from the database is not defined. Using a relational database provides the flexibility of use of the data. Data does not need be stored in tedious files. Retrieval of data in any format needed could be done as the need arises for usage. The user is not controlled by conditions that has been imposed by the original programmer.

Another benefit of the use of a relational database is that data can be retrieved for the use of any model. Whether it is a hydrological model or other models. The hydrological parameters can be used in models that are trying to model the environment.

### 6.5.2 Description of the tables of the database.

A relational database as explained earlier is a collection of related tables. The table created in this project are two. One table for the storage of parameters derived from remote sensing data, called in this project RS_DBASE. The other table is for the storage of parameters collected from conventional sources. This data was supplied by Yorkshire Water Authority, before privatisation one hastens to add.

Each table has a primer key in order to maintain the data in an identifiable fashion. This key is the day number. The other columns contain Physical characteristics of the basin and the hydrological parameters. The SQL command to retrieve the names of the columns is DESCRIBE *name-of-table*. (See Figure 6.5)

SQL> DESCRIBE RS_DBASE

| Name | Null? | Type |
|---|---|---|
| DAY | | NUMBER(6) |
| XNGRN | | NUMBER(7) |
| YNGRN | | NUMBER(7) |
| ZONE | | NUMBER(1) |
| ELEV | | NUMBER(4) |
| PRECIPITATION | | NUMBER(5,2) |
| TEMPERATURE | | NUMBER(5,2) |
| EVAPORATION | | NUMBER(5,2) |
| TMIN | | NUMBER(5,2) |
| TMAX | | NUMBER(5,2) |
| CLASSES | | NUMBER(2) |
| SNOWCLASS | | NUMBER(2) |

SQL> DESCRIBE CON_DBASE

| Name | Null? | Type |
|---|---|---|
| DAY | | NUMBER(6) |
| ZONE | | NUMBER(1) |
| ELEV | | NUMBER(5) |
| GPREC | | NUMBER(4,1) |
| GTMAX | | NUMBER(3,1) |
| GTMIN | | NUMBER(3,1) |
| GTMEAN | | NUMBER(3,1) |
| GEVAP | | NUMBER(3,1) |
| ACTUAL_DISCHARGE | | NUMBER(7,3) |

Figure 6.5 Description of the two tables of the database.

### 6.5.3 Description of Columns in RS_DBASE.

The primer key in Table RS_DBASE is column DAY. All data referring to that day is stored in the rest of the columns.

Every value of the parameters refer to a point on the grid of the box inclosing the basin map. For each of these points the national grid coordinates are stored in columns XNGRN (Easting) and YNGRN (Northing).

The points fall into prescribed zones. The zone of each point on the grid is stored in column ZONE. Four zones are used in our project labelled as 0 1 2 3. Zones 1 2 3 are three zones of the basin, while zone 0 refer to the points in the table that fall outside the basin boundary but within the box inclosing it. Table 6.1 shows the scheme of zone numbering. These zones were determined according to the requirements of SRM.

| ZONE | Elevation Range |
|---|---|
| 1 | 800 -1000 |
| 2 | 1000-1200 |
| 3 | 1200-1700 |

Table 6.1 Zone numbers and their corresponding elevation range.

Although this scheme has been adopted in this project this will not tie future users from customising their use of the database by using the elevation information of the points stored in column ELEV. The existence of column zone is only needed to distinguish between points in the basin area and those enclosed in the box.

PRECIPITATION, TEMPERATURE and EVAPORATION, are self explanatory columns. They store the relevant information.

TMIN and TMAX are two columns for storing minimum and maximum temperatures respectively. They were not used in this project. Their use depend on the availability of a remote sensing devise that provide constant coverage of the basin. Those two columns are provisional.

The last two classes in this table are CLASSES and SNOWCLASS. Every pixel was classified in order to detect the existence of snow or not. CLASSES store the result of this processing. The snow classes were identified manually as explained in the last chapter. Those classes are stored in SNOWCLASS column. The point that is thought to be a snow class retain the value of the class. Other points not classified as snow are assigned a value of zero. Although this project only need to identify snow classes the rest of the classes are stored as future conditions may arise and these classes will be use.

### 6.5.4 Description of columns in table CON_DBASE.

The parameters stored in this table are measurements from ground Gauges.

The primer key of this table is also the Column DAY. ZONE and ELEV also store zone and elevation information of the gauging station. GPREC, GTMAX, GTMIN, GTMEAN and GEVAP, store the following parameters respectively, precipitation maximum temperature, minimum temperature, mean temperature, and evaporation.

The last column ACTUAL_DISCHARGE store the amount of water discharged from the basin.

## 6.6 Loading data from system files to database.

### 6.6.1 Introduction.

This section will deal with the loading of the hydrological parameters, derived in the last chapter, unto the tables of the database.

The loading of RS_DBASE table was done through the use of computer programs and the data loader, ODL facility, of ORACLE. The data in CON_DBASE was loaded using the INSERT command of the SQL language. The ODL facility was not used for this table because the gauged data was not large enough to go through the complication of writing programs and then the use of ODL to load the data.

### 6.6.2 Preparation of data for Loading.

The remote sensing derived parameters were extracted and stored in different files. (See section 5.2) The physical information about the basin was also loaded. This information, elevation, zone, and national grid coordinates, was derived from the map of the basin. The map was supplied by the Institute of Hydrology. The information was manually extracted and written to a file. This is so because the Institute has not introduced the facility of providing information in digital form rather than the hard copy format. The elevation and zone information were written manually to a computer file. The manual writing of elevation and zone information results in a free format file PHYS.DAT. This is not compatible with the requirements of ODL. (SEE next section) A program was written, PHYS, to read this file and generate the values of the National Grid Coordinates. The product of this program is a file containing formatted elevation, zone, and national grid coordinates.

The hydrological parameters in different files need no further processing except the snow mapping derived files. These files contain all the classes classified using the clustering technique.

(SEE section 3.3.5) A program was written to to read the classes and output a file that contain the snow classes while pixels not covered with snow are given the value zero. The program produce a file containing all the classes and snow classes.

The different parameters derived in the in last chapter were stored in the different files. In order to load the different parameters in one operation and avoid having to load each parameter on its own a program, PHYS, was written. The program reads the different parameters from different files, for each day, and write them to a file that satisfies the conditions of ODL. The different files comprise of PHYS.DAT, precipitation, temperature, snow classes and evaporation. In case precipitation existed, i.e. cloud covering the basin temperature, snow classes and evaporation are not read. The out put of the program PHYS is a formatted file of the physical information and the Hydrological parameters. For each record a value for the day of the year is also written in the following format YYMMDD where YY stand for the year, MM for the month, and DD for the day. For example 24 January 1986 is entered as 860124.

### 6.6.3 ORACLE data loader, ODL.

The ODL is the ORACLE data loader. It loads data records from external files into the ORACLE database. This facility have some requirements to execute the loading. These requirements are as follows

1- Files may be in any format defined by the operating system.

2- Records must be of fixed length except for the last record.

3- Not all columns of the table need be loaded.

In the last section the data for each day was organised in one file to be loaded to the RS_DBASE. This is done through the use of a control file. Figure 6.6-a shows a listing of an ODL control file.

Invoking ODL to execute the control file is done through entering the following command on DCL level:

ODL *filename.ODL* Username/password *filename1.bad*

In case ODL failed to load any record it will write to the file labelled .BAD. A report on the execution of the loading procedure is reported in a file labelled .LOG. Figure 6.6-B contain a listing of a log file. This process is carried on for each day of the processed data.

```
DEFINE RECORD GRI AS
        DAY (CHAR (6)),
        Z  (CHAR (1),LOC(+2)),
        EV (CHAR (4),LOC(+2)),
        Y  (CHAR (6),LOC(+2)),
        X  (CHAR (6),LOC(+2)),
        P  (CHAR (5),LOC(+2)),
        T  (CHAR (5),LOC(+2)),
        S1  (CHAR (2),LOC(+2)),
        S2  (CHAR (2),LOC(+2));
DEFINE SOURCE FILE
        FROM Z26.DAT
        LENGTH 53
        CONTAINING GRI;
FOR EACH RECORD
INSERT INTO RS_DBASE
        (DAY,ZONE,ELEV,YNGRN,XNGRN,PRECIPITATION,
         TEMPERATR,CLASSES,SNOWCLASS)
VALUES (DAY,Z,EV,Y,X,P,T,S1,S2)
NEXT RECORD
```

Figure 6.6 - a. A listing of an ODL file.

```
ORACLE DATA LOADER: Version 5.1.22 - Production on Tue Dec 12
13:12:53 1989

Copyright (c) 1987, Oracle Corporation, California, USA. All
rights reserved.

LOGGED INTO ORACLE V5.1.22 - Production
 16384 TOTAL BIND SPACE
   151 MAXIMUM BIND ARRAY DIMENSION
  8359 MAXIMUM BIND ARRAY SIZE IN BYTES
   151 ACTUAL BIND ARRAY DIMENSION LIMITED BY MEMORY
LOGGED OUT FROM ORACLE

STATISTICS
  1205 BYTES ALLOCATED
     0 RECORDS SKIPPED
   540 RECORDS READ
     0 RECORDS REJECTED
   540 ROWS LOADED
     0 ERRORS
END ORACLE DATA LOADER Tue Dec 12 13:13:13 1989
```

Figure 6.6 -b A listing of the log file of an ODL file.

In case data stored in the database was not needed any more for every day use, by the programmer, and storage capacity is needed the database information could be down loaded to external files through the use of the Import/Export facility of ORACLE.

## 6.7 Extraction of data from the database.

Extracting data from the database could be done in two ways. The first, is by issuing SQL commands after logging to ORACLE database. This command is a SELECT statement, known as query, where the user select the records she/he wishes to inspect from a certain table criterion for selected records could be issued to limit the retrieved records to the user choice. Other facilities are available for using command SELECT. For specialist details see Working with ORACLE by Hursch [1987]. The use of this command in our project will be illustrated later on. (See Appendix 3 for examples on the results of querying of the database)

The second way of retrieving data from database is done through the writing of a computer program with embedded SQL statements. A program, ASSEMBLE, was written to read from the database and output a file with the required data in a format that is compatible with SRM hydrology model.

ProFORTRAN is the language program ASSEMBLE was written in. This language is made up of embedded SQL statement in FORTRAN statements. SQL statements in the program are preceded by EXEC SQL to identify them. A precompiler translate the SQL statements to ordinary FORTRAN calls. The program is then linked using a special link command that call on the appropriate libraries. This process was done using a command file PROFORKIT.COM.

### 6.8 Description of program ASSEMBLE.

Program ASSEMBLE is a ProFORTRAN program. It prompts the user to enter the date of the simulation period or the period desired. The program gives the choice of reading data through the keyboard, system files or the database. The program logs to the database as it is called. If database was the option for reading data it will retrieve the data desired for the period prescribed. The program is defaulted to read from RS_DBASE. In case the values desired are not available in that table the program will use CON_DBASE.

The program is equipped with error detection facility that will report to the user the error message that occurred accessing the database and where the error occurred.

The program process the retrieved data and to fit the data format of SRM. The information stored in the database, table RS_DBASE, gives an areal description of the hydrological parameters while SRM use lumped values of the parameters. The program averages the values that fall in a certain zone for each parameter to produce a lumped value. Other information could also be extracted such as the area of each zone and mean elevation for each zone. The extent of snow coverage is calculated by counting the pixels classified to be covered with snow in each zone. SQL queries, and their results, used in the program are listed in Appendix 3. These queries illustrate the power available for the user of SQL.

### 6.9 Protocol for retrieving data from database.

The retrieval of hydrological parameters from the database was done according to a set of rules which when gathered together amount to a protocol. This protocol is needed because of the existing differences between the available data and the requirements of SRM.

SRM requires data for the different elevation zones to be input separately, if the data is not available in that form data could be given as one reading of the base station. Remotely sensed parameters on the other hand provide a detailed description of the basin with parameter estimates for every $km^2$. The availability of these data is dependent on cloud cover. Precipitation information will always be available while temperature, snow, and evaporation will not be available for cloud covered days.

The data retrieved from the database was done according to the following protocol:

1- All parameters retrieved on a zonal basis are averaged over the zone.

2- Parameters are retrieved from data derived from remote sensing sources. If the parameter is not available from this source conventional data are used.

The application of the above protocol varies for the different parameters. It is full applicable for precipitation and snow. Precipitation is always available from remote sensing while snow is only available from remote sensing sources, hence, retrieval of conventional data is not needed. Data for snow mapping for cloud cover days should be interpolated between these days. Temperature data is needed for every day, while it is not available from remote sensing sources for cloudy days. Conventional data need to be used.

This is done in ASSEMBLE by extracting conventional data starting from the first day the remote sensing data is not available to the last day of the modelling period. A strenuous effort was done to make the program extract data from CON_DBASE for the day the data was not available and then go back to extract data for the following day from RS_DBASE. This was not possible as the nesting of the SQL queries caused the program to give an SQL error.

A SQL query was executed without the use of the program assemble resulted in the correct return of the information desired. This query was not accepted when incorporated in the proFORTRAN program. Several ways for getting round this problem were tested without yielding any satisfactory results. A very experienced user of SQL sub-language was consulted to no avail. This state of affairs could be attributed to the inadequacy of proFORTRAN as a host language for SQL or to the deficiency of the user's manual. The retrieval of data was then done as described above. This way of retrieving remote sensing data is impaired as it will only be retrieved for the first days where remote sensing data is available. As soon as remote sensing data is not available the rest of the data will be from conventional sources regardless of the availability of remote sensing data.

The data of this project are of cloud free days followed by rainy days with no cloud free days afterwards. Thus the retrieval of the remote sensing data was not impaired as the case of needing remote sensing data after conventional data was not relevant.

## 6.10 Comments on the use of ORACLE database in this project.

The use of a database in this project was necessary for the following reasons:

1- A system for the management of the derived data was needed. A simple system organising the different files containing the various hydrological estimates would have not been adequate. For each day there is either a file for precipitation, or three files for the rest of the parameters, two for temperature, one for Snow or one for evaporation. In the case of this project this would have been tolerable but if the derivation of remote sensing estimates was to be on operational level the amount of files would grow to an unsustainable level.

2- The retrieval of the remote sensing parameter estimates from individual files for use by the hydrological model would have presented a daunting prospect for any user. The use of a database simplifies the process. The use of a preset program for achieving this function reduces this big task to a recurrent function.

3- The use of databases provides the user with a facility of viewing and studying the stored data in a way that was not available before. The combination of the different data sets through the retrieval process presents new insights into the data and may create new data from the already stored data. This will be manifested in Chapter 8. where the process of analysing and presenting the analysis of the different parameters stored in the database was greatly enhanced by the use of SQL commands.

Despite the obvious benefits of using a relational database the use of it in this project could be questioned. As the requirements of the SRM model are modest with respect to the excessive powers of ORACLE.

Remote sensing produces estimates of the hydrological parameters in bulk in comparison with gauging stations. If this areal description of the parameters is not to be used it is not logical to incur all the trouble and expense of storing huge amounts of data in a database. Lumped values will be stored efficiently in small system files, they still could be stored in a database.

The use of the relational database must be viewed with respect to future uses of the data. Models utilising areal hydrological information are becoming more fashionable. Integrating hydrological models with Geographical Information Systems is a new interest of the hydrological scientific community. Database medium is ideal for this future use.

The storage of hydrological parameters will also facilitate their use in other models such as climatological models and environmental modelling programs.

# Chapter Seven.

## Description of HyRSIS.

### 7.1 Introduction.

The system envisaged earlier in chapter two used the concept of a ''total work station''. The idea is, in this age of increasing computer dependency, to provide a system that deals with all the necessary data, provides a programming facility for processing and managing satellite information and gauged hydrological parameters, in an electronic medium. This system should provide multiple functions for the user. It should be simple and provide guidance for the user with the following features:

1- A help system to provide an on the spot directions on the usage of the system.

2- The ability of the user to 'get out' of the program to issue commands on DCL level.

3- An error handling facility to identify likely sources of errors during run time.

These features and others such as the format of the building blocks of the system will be discussed in this chapter.

The data files used for the different processing operations carried on within this system are initially composed of the image of the basin as explained in Chapter Four, and the subsequent files generated throughout the different processes.

All the processes needed for performing the functions of HyRSIS are provided for in the system. Some of the processes are better carried out outside the immediate domain of HyRSIS. Although these functions can be catered for in the system, they are executed quicker before the activation of HyRSIS. Some processes are provided in HyRSIS through the creation of a sub-process when running the main driver of HyRSIS. Sub-processes are inherently slow and have a high demand on the computer resources, hence it is more efficient to carry big processes without going through HyRSIS.

## 7.2 Building Blocks of the System.

The system is composed of a main module and a set of submodules. The main module provides the interface between the programmer and the different modules. The submodules are Precipitation, Temperature, Evaporation, Snow mapping, Hydrology and Database. Each submodule is composed of a set of different programs with each set of programs providing a procedure in which the data is processed, from the raw imagery to the hydrological parameters, in stages. The first program processes the raw image and outputs a file which is used as an input for the next program in line. The compatibility of data files passing between two programs is insured.

The system as a whole is built up using a set of individual programs. These programs were assembled in a library of object files. A list of these programs is available in Table 7.1. This list was created by the VAX-II librarian. It indicates the date of creation of the library and the date of insertion or updating of the different programs in the library.

```
Directory of OBJECT library LSL$SITE_ROOT:[KITMITTO.FILES]MAINLIB.OLB;1
on 19-MAR-1990 16:35:32
Creation date:    27-JUL-1989 10:36:36  Creator:   VAX-11 Librarian V04-00
Revision date:     7-MAR-1990 19:08:24        Library format:   3.0
Number of modules:          36    Max. key length:  31
Other entries:       43   Preallocated index blocks:        49
Recoverable deleted blocks:     47    Total index blocks used:   4
Max. Number history records:   20    Library history records:   20

1SRM$DATA    Ident 01      Inserted  7-MAR-1990 13:58:19 0 symbols
1SRM$MAIN    Ident 01      Inserted  7-MAR-1990 13:58:19 1 symbol
ADD          Ident 01      Inserted  7-MAR-1990 14:20:12 1 symbol
ASSEMBLE     Ident 01      Inserted  7-MAR-1990 18:56:35 1 symbol
ATC          Ident 01      Inserted  7-MAR-1990 14:20:27 1 symbol
AVHCALIB     Ident 01      Inserted 27-JUL-1989 10:36:37 1 symbol
CALIB        Ident 01      Inserted 27-JUL-1989 10:36:37 1 symbol
DAY          Ident 01      Inserted  7-MAR-1990 14:20:44 1 symbol
DAY1         Ident 01      Inserted 27-JUL-1989 10:36:36 1 symbol
DISP         Ident 01      Inserted 15-SEP-1989 16:14:25 1 symbol
DISPUIS      Ident 01      Inserted 15-SEP-1989 16:14:15 1 symbol
EVAPGRID     Ident 01      Inserted  7-MAR-1990 15:26:52 1 symbol
EVAPO        Ident 01      Inserted  7-MAR-1990 14:21:57 1 symbol
GET_BYTES    Ident V1.0    Inserted 15-SEP-1989 16:13:42 2 symbols
GOOD         Ident 01      Inserted  7-MAR-1990 19:08:23 1 symbol
HISTOS       Ident V1.0    Inserted 15-SEP-1989 16:13:57 5 symbols
INPUT        Ident V1.0    Inserted 15-SEP-1989 16:16:19 5 symbols
IOUT         Ident 01      Inserted  7-MAR-1990 19:08:23 1 symbol
LAPSE        Ident 01      Inserted  7-MAR-1990 19:08:23 1 symbol
MULT         Ident 01      Inserted  7-MAR-1990 14:22:18 1 symbol
PHYS         Ident 01      Inserted  7-MAR-1990 18:53:12 1 symbol
PRECGRID     Ident 01      Inserted  7-MAR-1990 14:22:36 1 symbol
PRESNO       Ident 01      Inserted  7-MAR-1990 19:08:23 1 symbol
RATION       Ident 01      Inserted 15-SEP-1989 15:42:11 1 symbol
RATION1      Ident 01      Inserted 15-SEP-1989 15:49:58 1 symbol
READIN       Ident 01      Inserted  7-MAR-1990 19:08:21 1 symbol
RUNOFF       Ident 01      Inserted  7-MAR-1990 19:08:23 1 symbol
SNWCLS       Ident 01      Inserted  7-MAR-1990 15:14:40 1 symbol
SRM$DATA     Ident 01      Inserted  7-MAR-1990 19:08:20 0 symbols
SRM$MAIN     Ident 01      Inserted  7-MAR-1990 19:08:24 1 symbol
SUBSAMPLE    Ident 01      Inserted 15-SEP-1989 16:14:25 1 symbol
TEMP         Ident 01      Inserted 27-JUL-1989 10:36:38 1 symbol
TEMPERATURE Ident 01       Inserted 27-JUL-1989 10:36:38 1 symbol
TEMPR        Ident 01      Inserted  7-MAR-1990 14:28:24 1 symbol
TMPGRD       Ident 01      Inserted  7-MAR-1990 14:28:04 1 symbol
TSRTEL       Ident 01      Inserted 15-SEP-1989 15:42:49 1 symbol
```

Table 7.1 List of the programs included in the object library, MAINLIB.OLB, of HyRSIS.

Each of the individual programs were built and tested on data individually. The individual programs were written and tested on the relevant data, the desired features were incorporated in the different programs. Each program is run, before insertion in the program library, on it's respective data input and examined, sources of errors are identified and catered for. When the performance, error handling and interface conformity, of a program is judge satisfactory and the processing of data is carried correctly the program is included in the program library.. A program, MAIN, was then written to provide an interface facility with the different programs. MAIN introduces the user and provides a guided interface to the different modules of HyRSIS. All programs relating to a certain process, such as precipitation or temperature, are provided for the user in a module. Other utilities are also available through MAIN. It utilises the available functions of the operating system to provide facilities for the user. These facilities include a help system, access to DCL level and error handling facility.

**7.3 System operating levels.**

The system has four level of interaction.

1- Machine operating level.
2- Main module level.
3- Individual Modules level.
4- Processing submodules level.

The numbering of the above level does not indicate the different interactive levels of HyRSIS. The four levels are accessed through the main module. (See Figure 7.1)

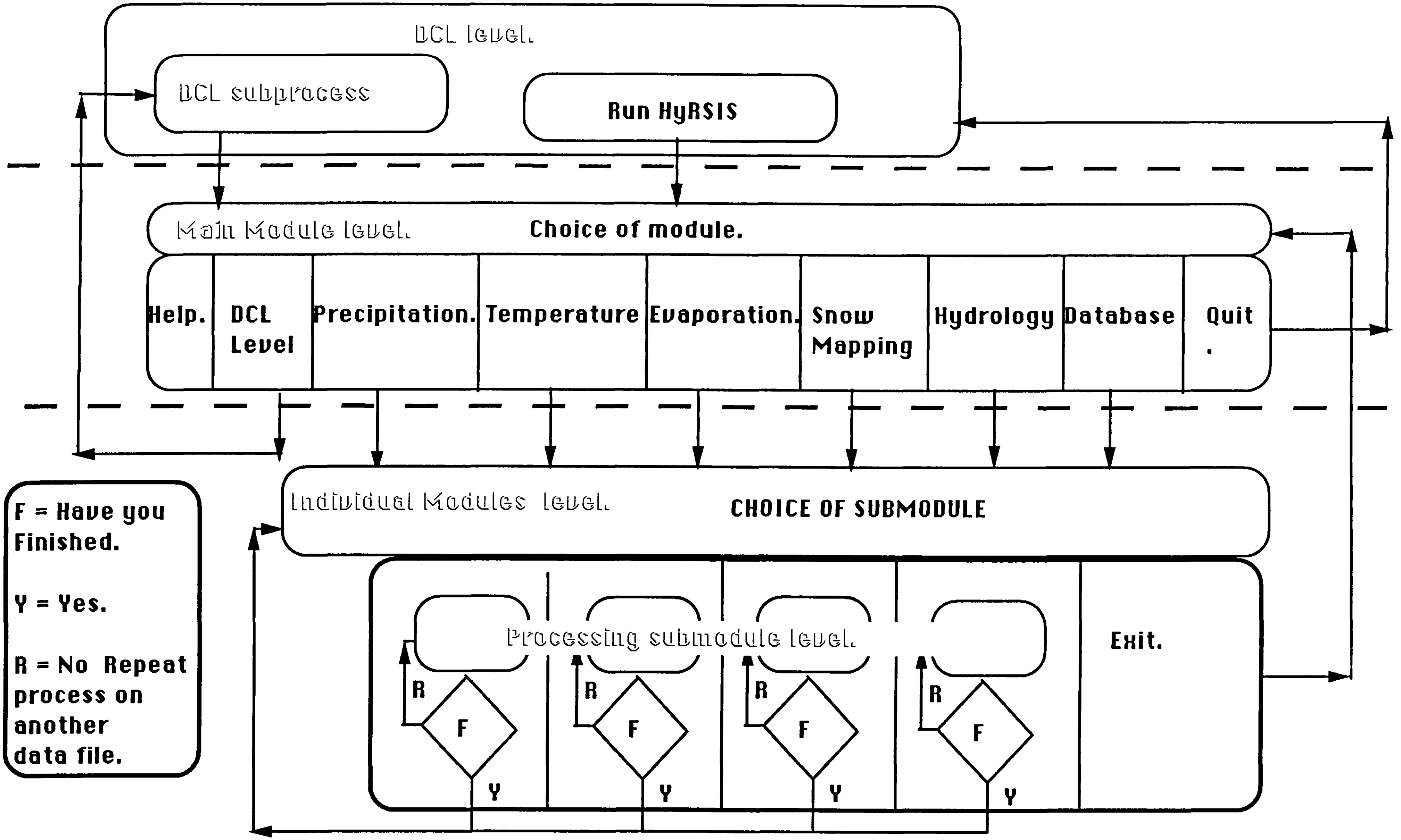



Figure 7.1 System operating level, and the different components of the Main module.

When a user starts to run HyRSIS entry is made at the main module command level, from this level the user can access machine operating level and the modules level. If the user accessed the machine operating level the only other level that can be accessed from here is to the main module level.

The modules level has two access routes, the main module level and the processing submodules level.

The processing submodule level is the level at which programs are run and data is processed. At the end of processing each individual data file the user has the choice to process another data file using the same program. If this action was not selected the user is a returned to the individual module level.

As an example suppose the user wants to process some cloud images to estimate precipitation for one day. The actual succession of commands as run interactively is presented in Table 7.2. Letters in **BOLD** are the users commands.

**Run HyRSIS**

```
WELCOME TO THE MAIN MODULE

PLEASE CHANGE TO UPPERCASE
CHOOSE THE MODULE YOU WANT TO WORK WITH
PRINT THE FIRST UPPER CASE LETTER(S) OF THE FOLOWING
MODULE, Precipitation, Temperature,HYdrology,
Evaporation, Snow mapping,Help, Database, Quit

Type DCL for creating a subproccess to enter dcl commands.

P


IN THIS MODULE THE REMOTE SENSING IMAGES OF THE BASIN
ARE PROCESSED TO PRODUCE PRECIPITATION ESTIMATES
```

```
ENTER CHOICE OF THE PROGRAM YOU WANT TO WORK WITH
PRINT THE FIRST UPPER CASE LETTER(S) OF THE FOLOWING
PROGRAMS  Day, Add, Multiply,Precigrid,Help,EXit,DISplay


D
PROGRAM TO AGGREGATE IMAGES OF A DAY TO ONE IMAGE


 Enter dayno...
2 8
 Enter Number of Samples.
2 0
 Enter Number of Records.
2 7
THE OUTPUT IMAGE IS     28day.dat


DO YOU WANT TO PROCESS ANOTHER IMAGE USING PROGRAM DAY?   ANSWER Yes or No
N
ENTER CHOICE OF THE PROGRAM YOU WANT TO WORK WITH
PRINT THE FIRST UPPER CASE LETTER(S) OF THE FOLOWING
PROGRAMS  Day, Add, Multiply,Precigrid,Help,EXit,DISplay

EXIT
YOUR ENTRY IS NOT VALID

PLEASE ADHERE TO THE CODE GIVEN


IN THIS MODULE THE REMOTE SENSING IMAGES OF THE BASIN
ARE PROCESSED TO PRODUCE PRECIPITATION ESTIMATES


ENTER CHOICE OF THE PROGRAM YOU WANT TO WORK WITH
PRINT THE FIRST UPPER CASE LETTER(S) OF THE FOLOWING
PROGRAMS  Day, Add, Multiply,Precigrid,Help,EXit,DISplay


EX
CHOOSE THE MODULE YOU WANT TO WORK WITH
PRINT THE FIRST UPPER CASE LETTER(S) OF THE FOLOWING
MODULE, Precipitation, Temperature,HYdrology,
Evaporation, Snow mapping,Help, Database, Quit

Type DCL for creating a subproccess to enter dcl commands.

Q

Fortran  stop.
```

Table 7.2 A listing of the flow of commands for a day's precipitation estimates session.

## 7.4 Error Handling Facility.

All the available programs brought within this project were modified. One of the features incorporated in them was an error handling facility.

The features of this facility differ, during run time, from one program to another. This is due to varying sources of errors that could be encountered during run time. The features were customised for each of the individual programs.

The error handler defines the source of error encountered during the run of each of the programs. Two kinds of messages are issued when errors are encountered. The first is an explicit message defining the error by number, VAX FORTRAN error , and text. The second kind of errors is that identified only by the VAX FORTRAN error number. The VAX FORTRAN Manual should be consulted for the complete identification of that error.

The error number/text identification facility is provided for the most likely sources of errors that are encountered where immediate remedial actions are possible. The error number identification is for errors that are not expected and no immediate remedial action could be performed.

After the identification of the error the user is returned to the last level of command encountered. In the main module the user is then returned to the last operating level used. In the individual programs the control is returned to the first input functions of the program.

Program ASSEMBLE has two error identification facilities, the FORTRAN error handling facility, and the ORACLE error handling facility. If an error was encountered during the execution of one of the SQL statements Two values are returned to the user. The first identify the number of the ORACLE error, the second identifies the SQL statement at which the error occurred.

### 7.5 The Main Module.

Obtaining the interactive level of the main module is done through running HyRSIS at the system operating level. The main module provides access to two other operating levels, the DCL level and the choice of submodules level. If the user wants to transfer from one operating level to another the user has to 'go' through the main module level. In the main module most of the facilities and features are available for use. The user can access any of the following options: (See Figure 7.1)

1- Obtain help on any of the modules or submodules in HyRSIS.
2- Transfer to DCL level for issuing operating system commands.
3- Enter Precipitation module.
4- Enter Temperature module.
5- Enter Evaporation module.
6- Enter Snow Mapping module.
7- Enter Hydrology module.
8- Enter Database module.
9- Quit.
10- Display images on screen.

Help is needed for any electronic processing system. The paper documentation associated with any system should be corroborated with an electronic medium documentation. This electronic documentation provides the user with tips on the working of the available functions and commands used in that system. HyRSIS provides help on two systems, itself and the operating system of the host computer. Help on the functions and programs of the HyRSIS was compiled in this project. While help on the host operating system is provided through accessing the VAX/VMS help system. Help on some VMS functions that are relevant to HyRSIS is not available on the operating system help. HyRSIS provide some help on these functions and direct the user to the relevant printed documentation.

The HyRSIS help is available on two of levels the Main module level and the Submodule level. No help is provided during the processing level.

The operating system help is obtainable through the DCL level. (See section 7.7)

## 7.6 Displaying images on screen.

The visual representation of the image files might be of interest to the user. A special set of utility programs has been included in HyRSIS for displaying image files on the GPX screen. The GPX screen is a graphics screen attached to the VAX Minicomputer in the Department of Photogrammetry and Surveying. Option Display is only available on this screen. This option is available on all operating levels. To activate the display utility on the main module level and the individual modules level option the user should select option Display. While at the DCL level the user need to type DISplay in order to activate this utility

This facility is provided thorough the use of many programs. These programs were written by J. Pearson, system manager of the department, to establish an image viewing facility for images incorporated in system files. In contrast with files that are designated as images by different brands of software. These files usually contain a header that explains and identifies the file as a file of certain properties and calls upon the software and hardware resources of the system they use for displaying the image on the screen. These programs were incorporated in HyRSIS by inclusion in the systems object library. The different programs incorporated in this library are shown in Table 7.1

### 7.7 Access to DCL level.

Access to DCL level is needed during the running of the HyRSIS for several purposes: (See figure 7.2)

1- The management of files generated by the user.

2- Management of input data files.

3- Acquisition of some information about certain data file through the use of operating system functions.

4- The issuing of some HyRSIS commands on the operating level.

DCL command level is accessed through the main module level. This is done through the creation of a sub-process in the main module. The usage of a sub-process results in a relative slowing of the retrieval and execution of the different processes of the system. All commands and functions issued at this level can be done before the activation of HyRSIS. The provision of accessing DCL level is basically for the management of the data files. All other operations are better executed before running HyRSIS.

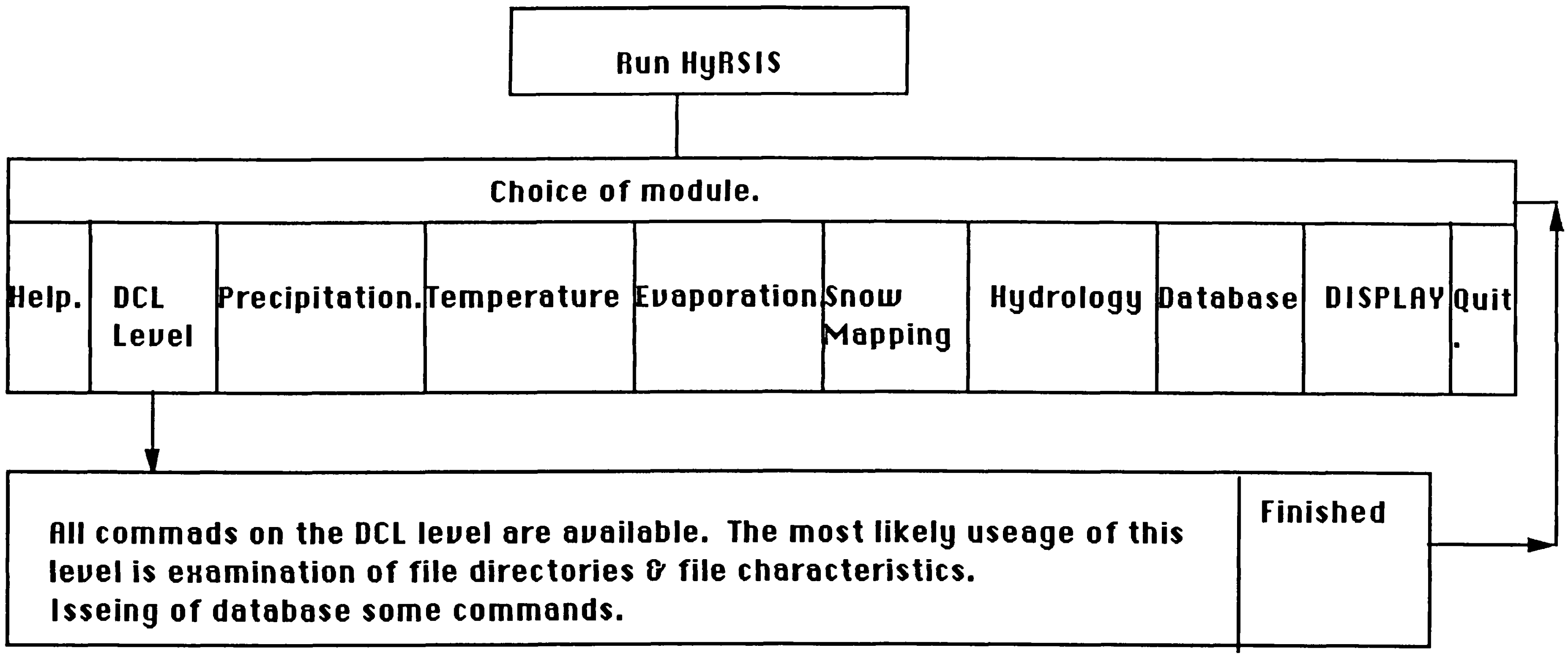



Figure 7.2 Digital Command Language functions and utilities availabel through HyRSIS.

## 7.8 Preview of the common features of the different modules.

The different modules of the system were built using the same philosophy. This philosophy suggests the need for the availability of certain features in the individual modules. The individual modules should contain, alongside the different program for processing the remote sensing data to hydrological parameters, a set of features that are common to all modules. These modules are as follows:

1- A program for extracting the numeric data from image files. These programs are named in the following fashion ***grid where *** stand for, Preci for Precipitation, Temp for Temperature, Evapo for evaporation, and Snow For snow mapping.
2- Display utility reviewed in Section 7.6.
3- Help utility see section 7.5.
4- Exit facility to transfer control from the individual module to the main module level.

Each of the individual modules will be reviewed in the following sections providing a list of the available programs in each module. The flow of processing files of image data to the different hydrological parameters is the same for each of precipitation, temperature, evaporation and snow modules.

## 7.9 Precipitation module.

This module provides all the programs needed for the processing of image data to precipitation estimates. It is composed of several programs DAY, ADD, MULTI, DISP, and PRECIGRID, as well as the two facilities HELP and EXIT.

Programs DAY, ADD, and MULTI are the image processing programs for the derivation of the precipitation estimates. A detailed description of these programs was provided in Chapter Four. The image data is processed first using program DAY. The resultant of that process is then processed using program ADD. The last stage of predicting the precipitation estimate is done by processing the file product of program ADD using program MULTI. The file products of each of the above programs are in image format which can be displayed on screen. Option display provides the facility to display the different image data on screen. Precipitation estimates are extracted from the image file using program PRECIGRID. For each of the above processes the user has the choice of running the application on more than one file. As HyRSIS gives the user a choice of either rerunning the application or exiting to the level of the individual modules.

The HELP option accesses the user to the HyRSIS help system. While EXIT transfers the user from the Precipitation module interactive level to the main module command level. The different functions of the precipitation module are explained in the flow chart supplied in Figure 7.3.

The input data for the module are the image data of the basin. (See Chapter V) Another file used by the module is the historical precipitation data used by program MULTI. This file is compiled before the use of HyRSIS. A file for each of the months of the year, for each basin, should be compiled.

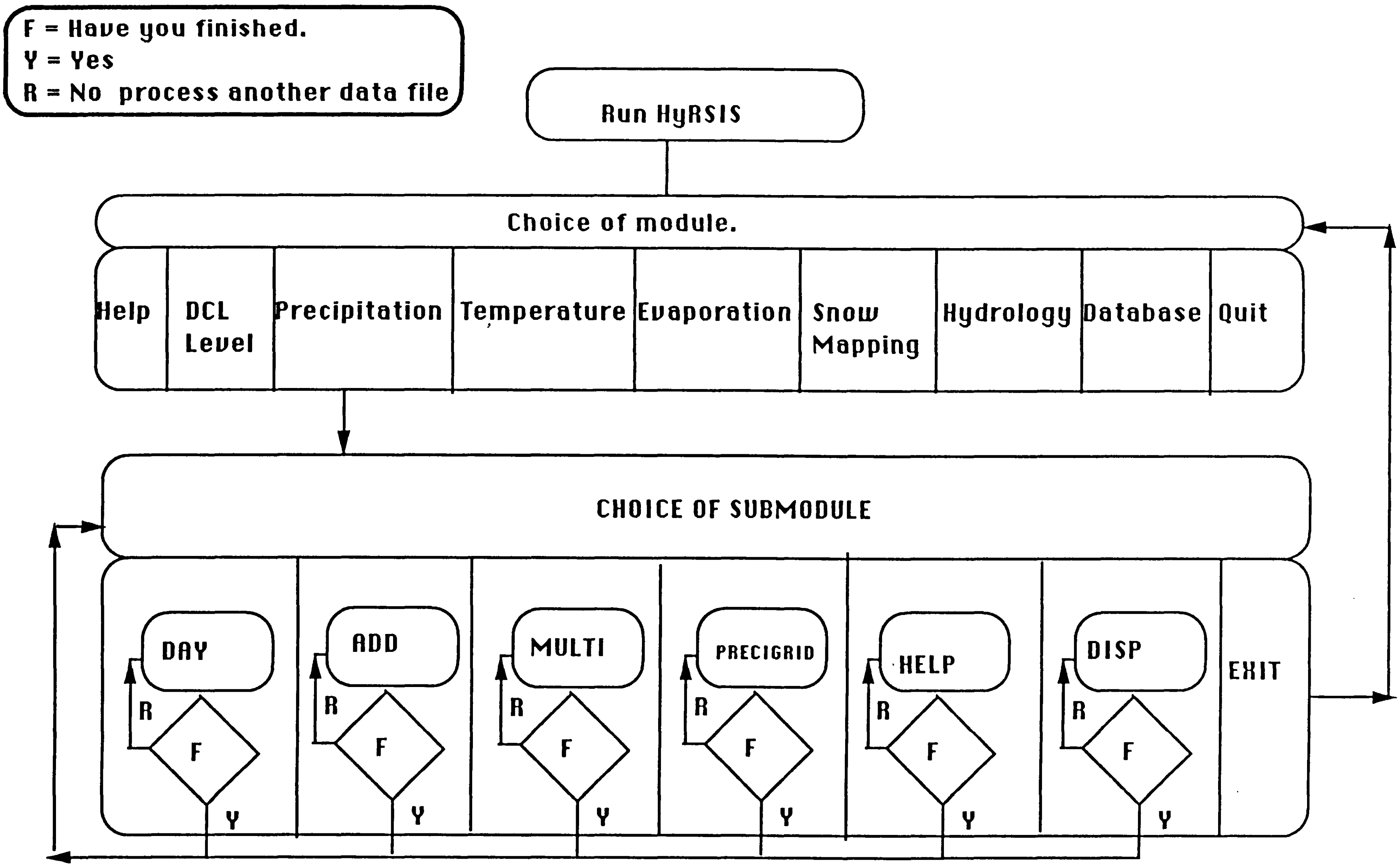



Figure 7.3 Flow of commands for Programs included in the Precipitation module

## 7.10 Temperature module.

The different components of the temperature module are as follows TSRTEL, TEMPR, ATC, TEMPGRID, DISP, HELP and EXIT. TSRTEL is the calibration extraction program. TEMPR and ATC are the image processing programs and TEMPGRID is the program for extracting the image data. The order of use of these programs is the same as of the precipitation module. The Calibration data are first extracted. Although program TSRTEL is available when using TSRTEL the extraction of calibration data, for this case, is done outside HyRSIS. As files of AVHRR imagery are too big and a tape drive is needed to read the calibration data directly from tape. A tape drive was not available on the VAX of Dept. of photogrammetry.

The calibration data extracted using TSRTEL are used by program TEMPR to produce temperature estimates. TEMPR is used on image data of channels four and five of the AVHRR imagery. The two files product of this process are used by program ATC to implement an ATmospheric Correction on the temperature estimates. Program TEMPGRID is then used for extracting these estimates. The processing of more than one file is also available in this modules. Options DISP, HELP and EXIT are used in the same way as explained in the preceding sections. A graphical interpretation of the different processes of the temperature module are presented in Figure 7.4.

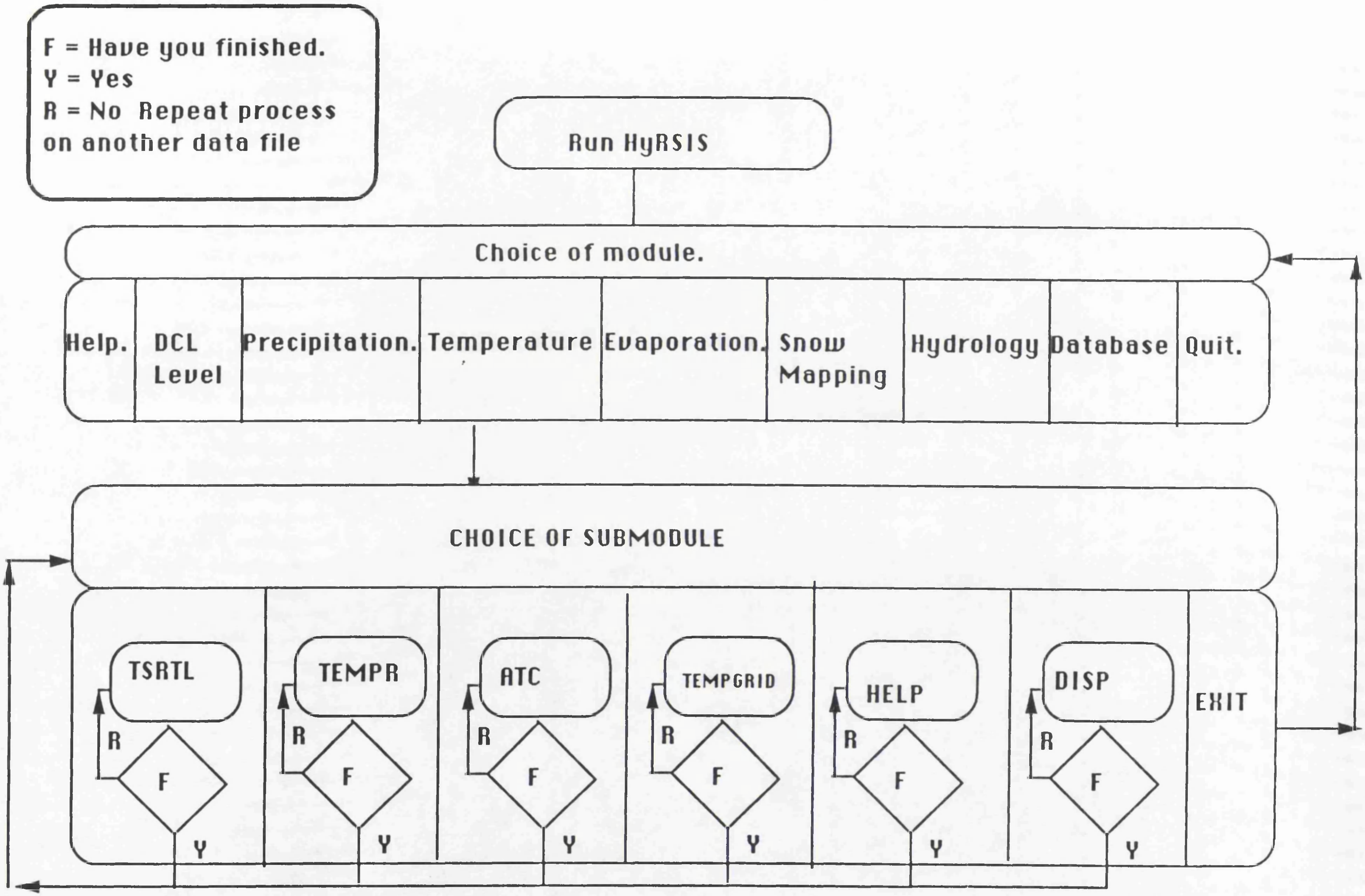



Figure 7.4 Programs and features available at Temperature module.

## 7.11 Evaporation.

The evaporation module contains one processing program, EVAPO, and the rest of the, by now, usual features as EVAPOGRID, DISP, HELP, and EXIT.

Program EVAPO process the image data produced by the temperature module to produce an estimate of the evaporation occurring in the basin. The estimates are then extracted using EVAPOGRID. As with the past two modules the user has the option of rerunning the application programs at the end of each run. DISP, HELP and EXIT provide the usual features. Figure 7.5 presents a graphical interpretation of the evaporation module.

## 7.12 Snow Module.

The snow module is composed of the following programs SNWCLS, DISP, HELP and EXIT.

The classification and mapping of snow classes was done on the $I^2S$. The different processes were depicted in chapter four. The image of the basin used as an input to this module is a classified image of basin. The snow classes has been predetermined on the I2S.

Program SNWCLS extracts the different classes in the image file, and produces a file that contains the different classes including those classes identified as snow classes. DISP, HELP, and EXIT provide the same features as in the rest of the modules. The snow module is graphically presented in Figure 7.6.

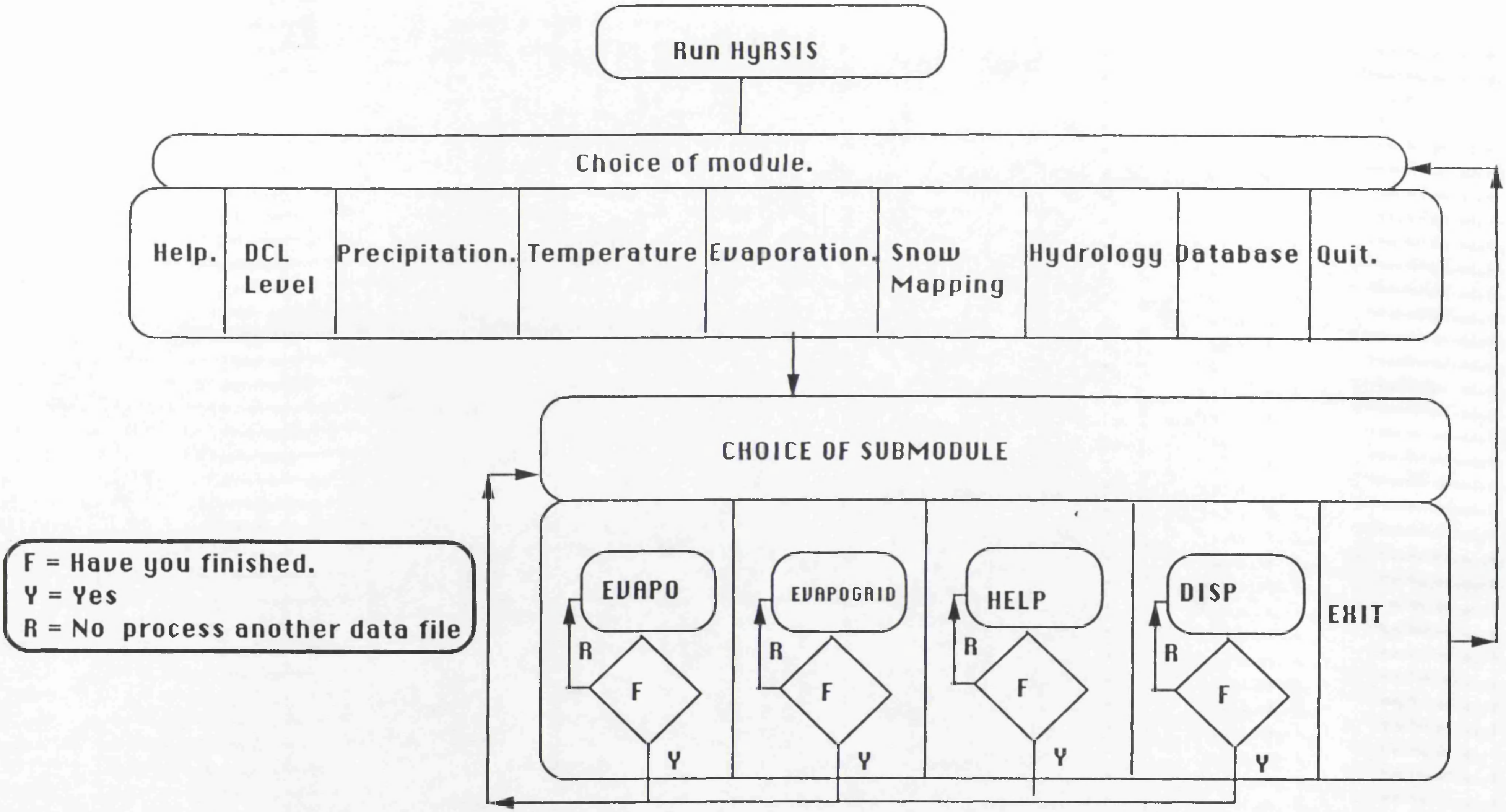



Figure 7.5 Flow of commands for programs included in the Evaporation module.

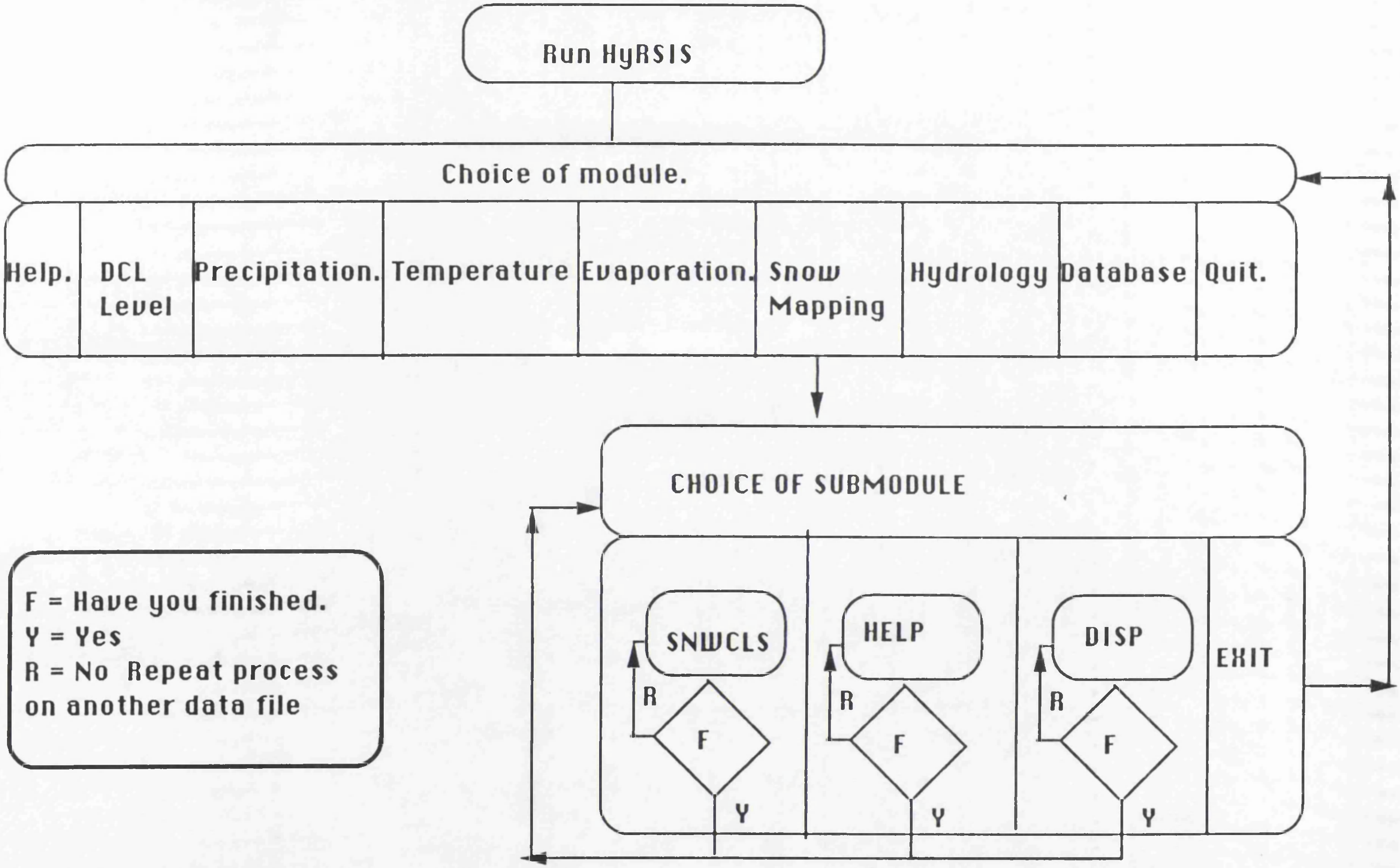



Figure 7.6 Programs and features of snow mapping module.

## 7.13 Database Module.

The data base module contains the following programs PHYS, RS_DBASE.ODL, ASSEMBLE, HELP and EXIT. No processing of image data is done in this module. This is the data management module. Data produced from the image processing modules are arranged and loaded into the database.

Program PHYS reads data of the different parameters, all parameter files generated for a certain date, and outputs a file. This file contains the different parameters with other information, elevation, zone, and national grid coordinates, for each pixel.(See Section 6.6)

The data, after being organised by PHYS, is loaded to the database through the use of the ODL facility. (See Section 6.6.3) The ODL facility is only available at DCL level. The retrieval of information from the database is done through the use of program ASSEMBLE. Data Access ORACLE for the querying of the database can also be done through the DCL level.

The ORACLE database is not available for the different users of the VAX minicomputer. Access to use ORACLE facilities is restricted to one account on the VAX II. ORACLE could be available to any of the VAX II users if the Database Administrator DBA grants access to them. The use of ORACLE in this project has been through the use of the DBA account on the VAX.

ASSEMBLE was written and tested in the DBA account. It was then installed in the object library of HyRSIS. This will allow the use of ASSEMBLE from an account other than the DBA's. Thus ODL is not

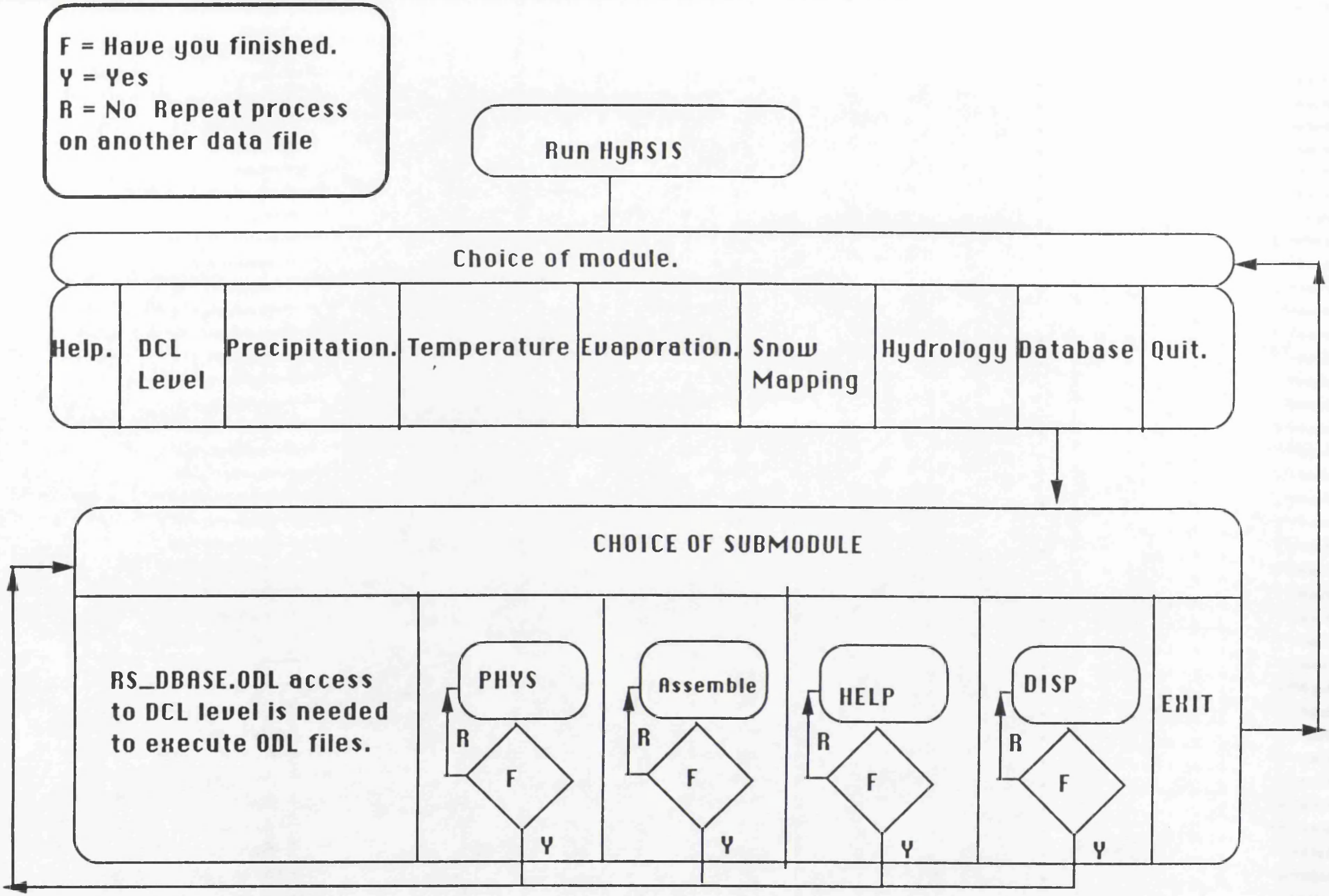



Figure 7.7 Programs and dunctions available in the Database module.

available for use other than from the DBA's account.

The other features of the database module such as HELP and EXIT provide the same facilities as explained at the beginning of this chapter. Presented in Figure 7.7 is the graphical representation of the Database module.

### 7.14 Hydrology Module.

The Hydrology module is composed of SRM, HELP, DCL and EXIT. The SRM program is the basic utility of this module. It provides the hydrologic modelling of the river basin. The input data to this module is provided by the Database module. Program ASSEMBLE retrieves the data from the database and writes it to a system file.

This file, containing the hydrologic information stored in the database, needs editing in preparation for use by the Hydrology model. The accesses of the user to the editing of the file is secured through the DCL level. The DCL level is accessed from the choice of the DCL option in this module or choosing the DCL option from the main module, or by using the DCL operating level before running HyRSIS. (See Figure 7.8)

### 7.15 Over view of the system.

HyRSIS is composed, basically, of a compilation of programs, a database, and program which acts as a main driver. The details of this process has be presented throughout this chapter.

The flow of data, from raw imagery to hydrological modelling, in this system passes through different stages. These stages can be summarised as follows:

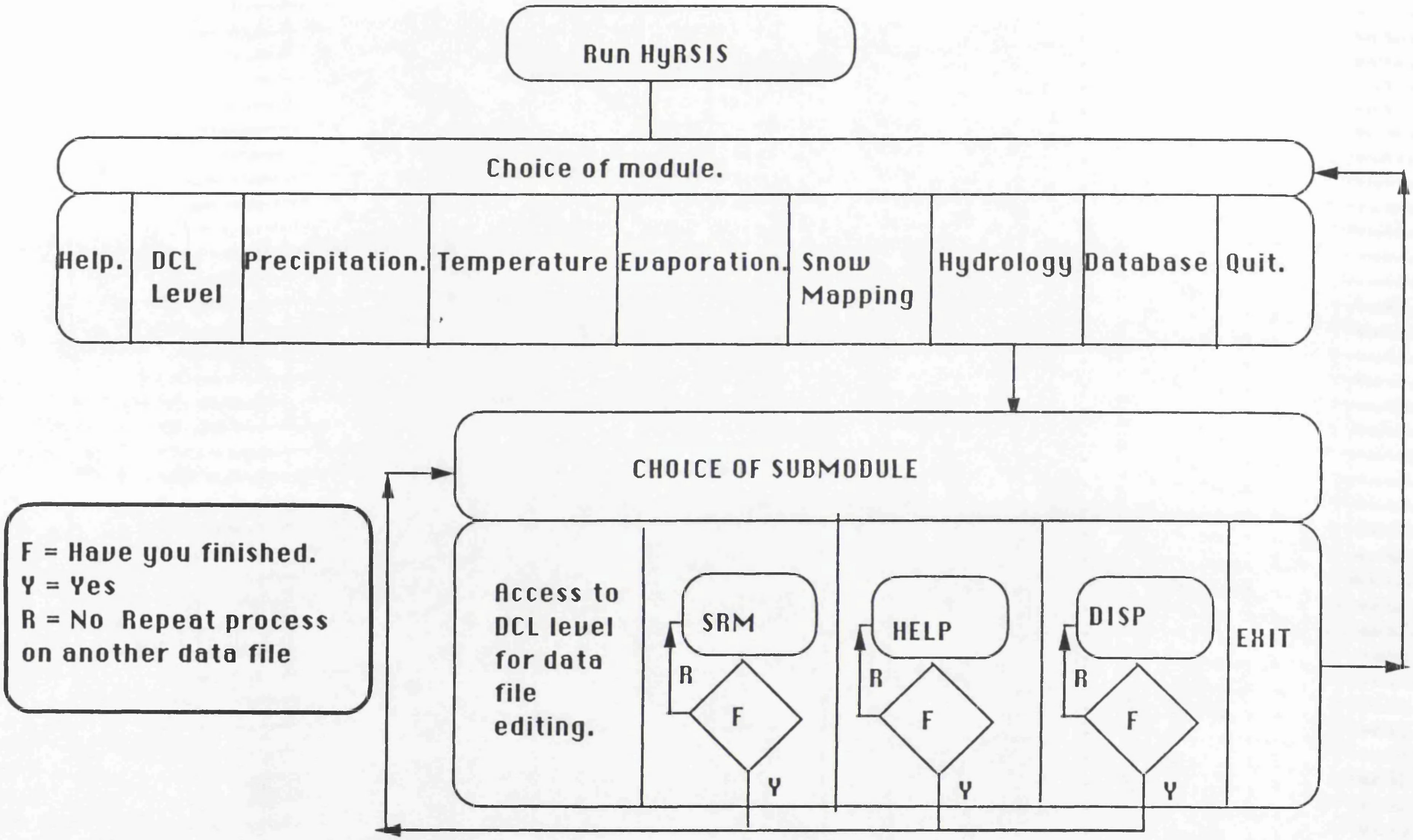



Figure 7.8 Programs and features vailable in the Hydrology module.

1- Processing of raw imagery, which include extraction of telemetry data and the image of the basin map.

2- Processing of image data into various hydrological parameters.

3- Organisation of this data and loading into the database.

4- Reading this data for hydrological modelling.

The flow of these functions is illustrated in Figure 7.9.

The raw imagery passes in different processes before the production of hydrological parameters and ultimately the performance of hydrological modelling on this data. Figure 7.10 provides an overview of the different processes the raw imagery passes through before the delivery to the hydrological model.

The different functions carried on the data throughout the different stages is done through the usage of the programs available in the library of this system. The updating of the system can be done through the replacement of outdated programs from the library without the need to change the main driver.

The expansion of this system to include a bigger variety of programs can be done through the inclusion of these programs in the systems library. This will call for the expansion of the main driver program. The data generated by these programs could be catered for by the introduction of new tables in the database, or the expansion of the old tables. Both options are available within the ORACLE database system.

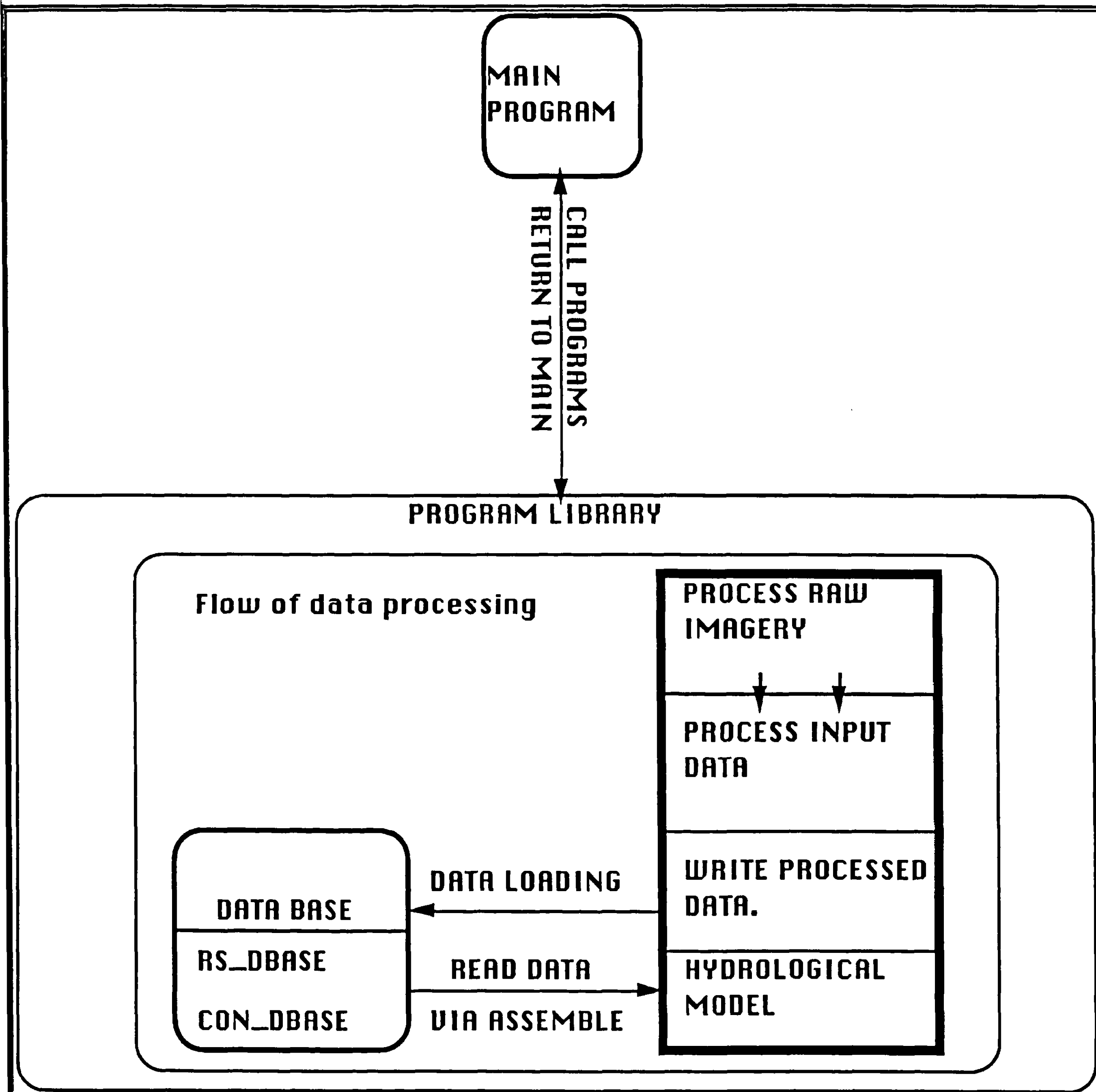



**Figure 7.9 Flow of processes on the data files from imagery to hydrological modelling**

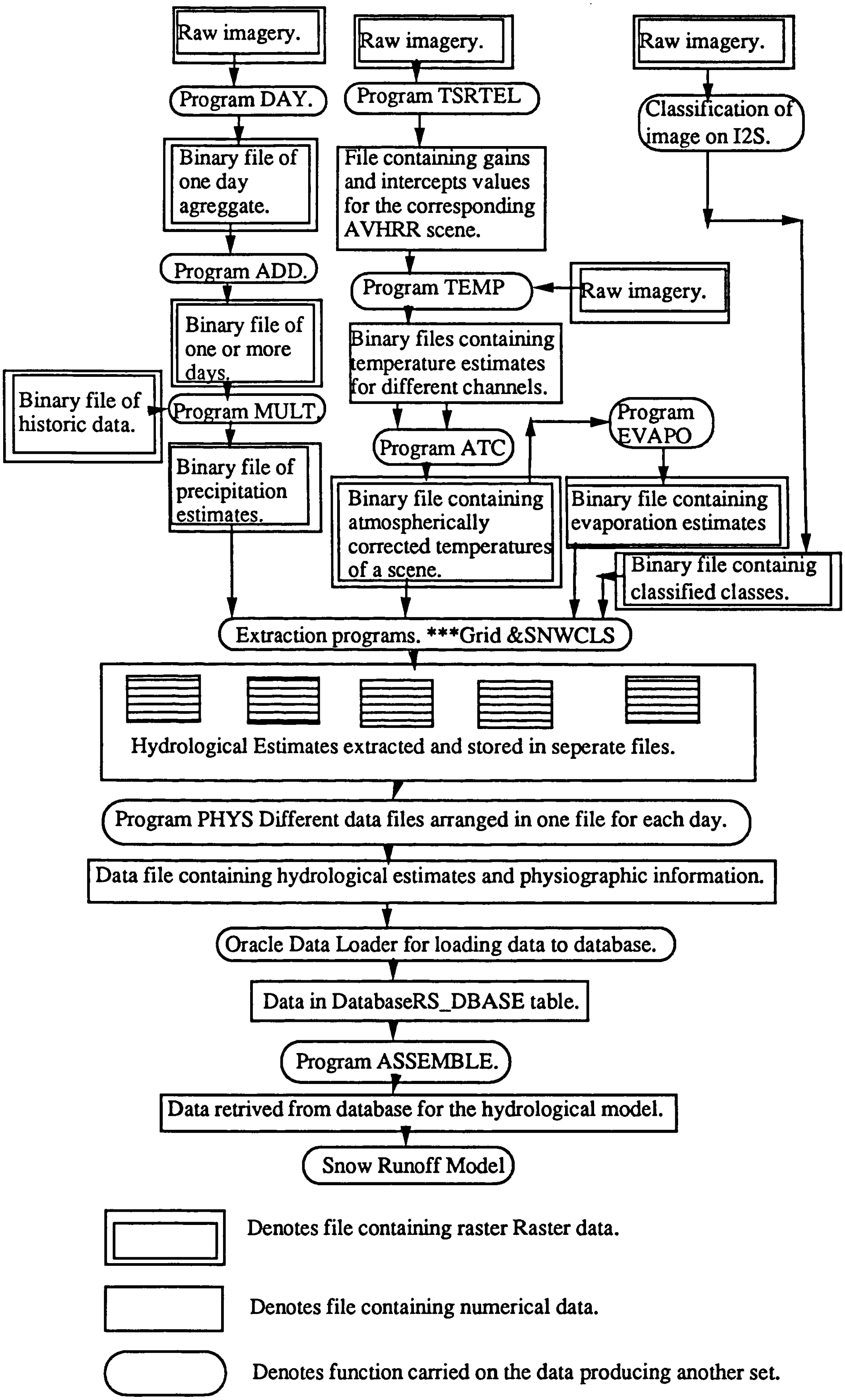



Figure 7.10 An overview representation of the different processes carried to produce hydrological parameters from raw imagery until dilivery to the hydrological model.

# Chapter Eight.

## Results and Discussion of Results.

### 8.1 Introduction.

The preceding chapters have described the different techniques for deriving and estimating various hydrological parameters. This was coupled with the integration of these different techniques into a compatible package. The need for a study case was discussed in Chapter Five. The conditions of selecting a study area and a modelling period were also reviewed.

The basin of the Aire to Kildwick Bridge was selected as a study area for a period of a week in January 1986. This week, 24th to 29th of January, included days in which precipitation was estimated and days where the clear weather conditions facilitated the mapping of snow and the estimation of ground temperatures.

This Chapter will concentrate on reviewing the results of the estimates of the different processes. The different processes will be discussed separately. Although the accuracy of the results will be reviewed, showing good results, it should be clear that at the start of this study the criteria of accuracy was considered of secondary importance, at the initial stages of the process of building HyRSIS. The primary role of this study was the establishment of an understanding of the interaction of the different methods and to arrive at a mechanism which will allow the integration of the different data sources into a compatible data set.

This decision was taken on the assumption that such line of interest is better left to the individual developers of the different techniques used in this study. An attempt to improve the results would have been futile as the different researchers work exclusively on their techniques. The time, effort and scope of this study does not permit this kind of indulgence. However, the accuracy and the performance of the different hydrological estimates will be examined, elaborated upon, and pushed to the limit in this Chapter.

The Chapter will start by discussing the accuracy of the geometric corrections carried on the different images, then each of the parameters derived in the case study will be reviewed individually. Estimates will be listed. Accuracy will be assessed. Relevance of estimates will be noted.

## 8.2 Geometric correction.

### 8.2.1 Introduction.

The swath width of an AVHRR image is 2400 kilometres while the basin's dimensions were 27 X 20 kilometres. The pixels referring to the basin were extracted by geometrically correcting the image using the warping function on the $I^2S$ (See Section 4.3). The degree of accuracy in extracting the remote sensing information has a direct effect on the relevance of the derived parameters. If the error is marginally big the parameters may be estimated for an area other than the area of interest. Errors as big as one pixel correspond to around 5% errors on the basin level. However in judging the acceptable level of accuracy two factors should be considered.

1- The accuracy attainable by the remote sensing technique.

2- The effect of the positioning accuracy on the relevance of the remote sensing data in comparison to gauged data.

This section will present the accuracy attained for the different days. This will be done by dividing the week into two groups. The first group is clear weather, 24th, 25th, and 26th, days. The second is the rainy, 27th, 28th, and 29th, days.

### 8.2.2 Clear days.

The extraction of the basin subimage from the image of the whole swath is done in two steps. The first step is the extraction of an image, of 512 pixels by 512 records or 660 records for some of the cloud cover slots., of the British Isles. The second step is the extraction of the basin subimage by the use of the warping function of the $I^2S$. Table 8.1 provides a list of the average errors as calculated by the warping function. (See section 4.3.3.2) These errors are measured in multiple of pixels.

| Clear days. | | Precipitation days. | |
|---|---|---|---|
| Day | Average Error (pixels) | Day | Average Error (pixels) |
| 24 | 0.5 | 27 | 0.655 |
| 25 | 0.76 | 28* | 0.7, 0.9, 0.58 |
| 26 | 0.15 | 29* | 2.6, 1.9, 3.9 |

Table 8.1 Average errors as calculated by the warping function for corresponding days. * The multiple values are for different slots in the same day.

The average errors depicted by the warping function for clear days are of subpixel values. These are small margins of error leading to a high degree of confidence in taking the extracted information as a direct representation of the basin. Image 8.1 is a

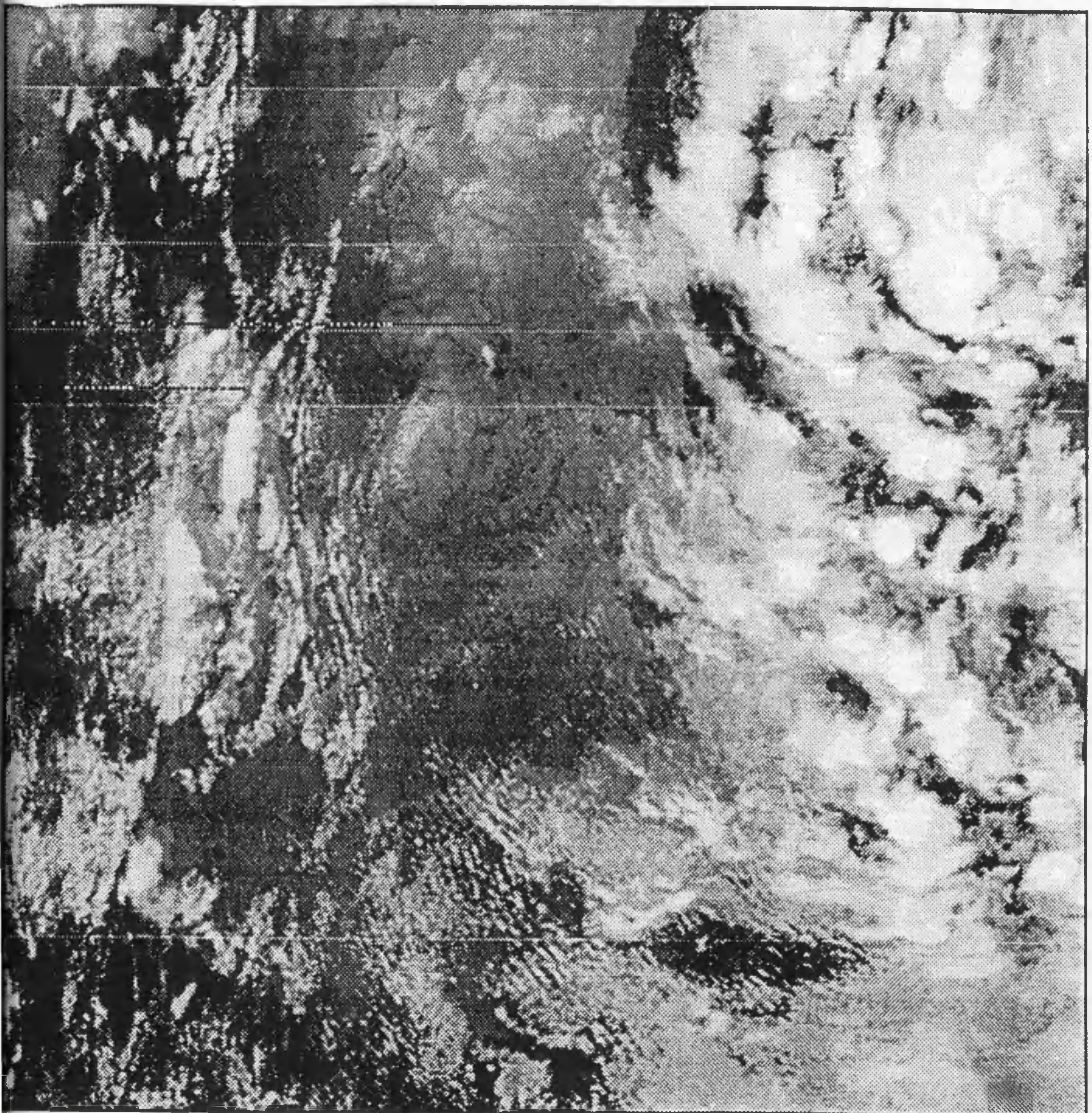


Image 8.1 AVHRR band 4 image of Britain for day 24 before warping.

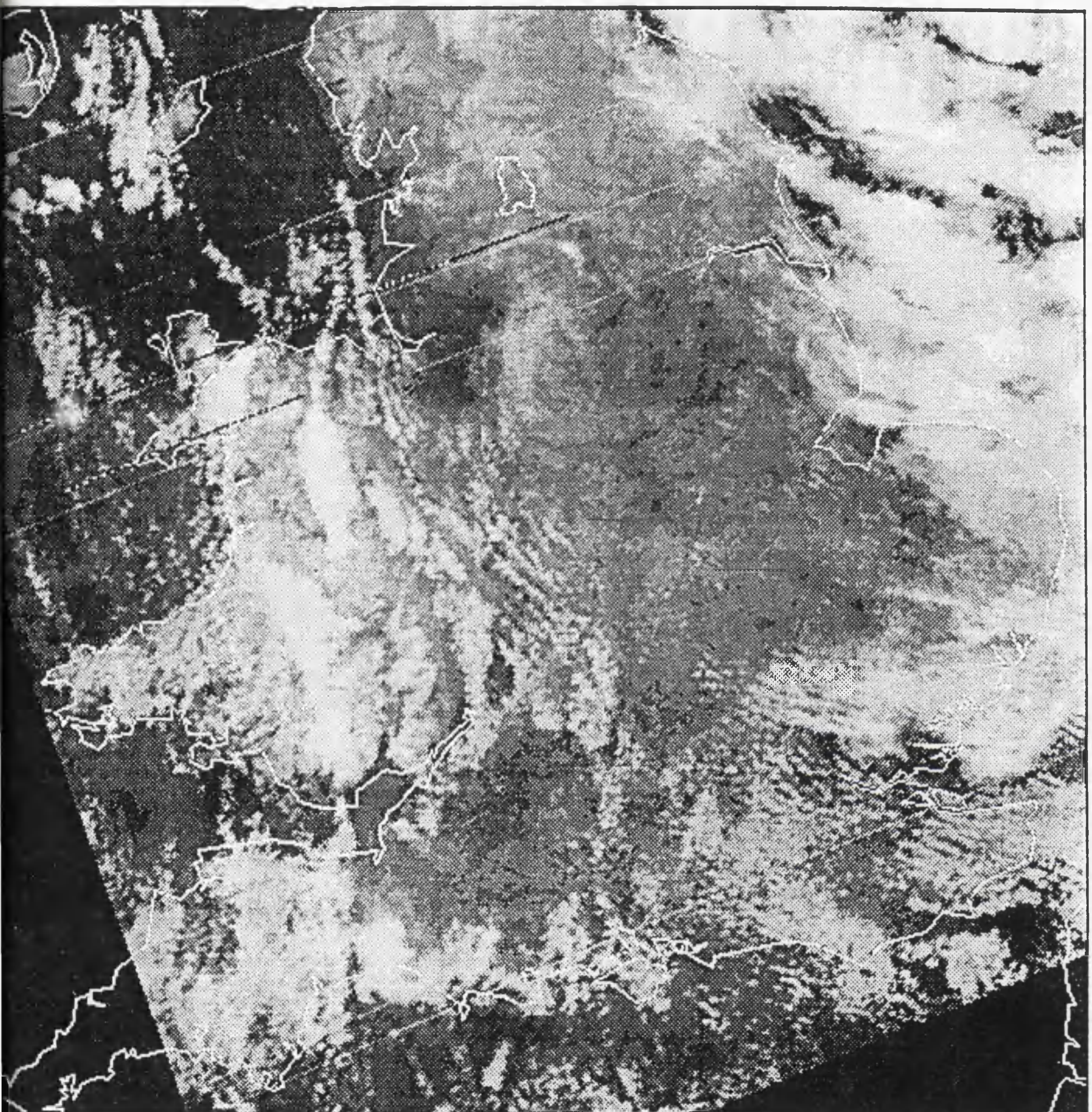


Image 8.2 AVHRR image for day 24 after applying geometric correction.

512 X 512 image of Britain as extracted from the original complete 2400 km swath. Image 8.2 is the same image after applying the geometric correction. In Image 8.2 the coast line of England and Wales was added in order to make the coast line more distinguishable. The location of the basin of the river Aire is also outlined. The superimposed coast line is the control image used for the geometric correction procedure. Parts of the control image have no corresponding pixels in Image 8.1 These pixels will be filled with black pixels, value equal zero denoting no information. The parts of Image 8.1 which have not corresponding pixels in the control image are warped. They do not appear in Image 8.2 as their location is outside the frame of the control image. These part were truncated, on the wish of the user of the warping function, as there was no interest in them.

In Image 8.1 variations in the intensity of reflection in parts of the Irish sea off the coast of the Lake District are clearly depicted. These borders of these variations follow the coast line, this effect is even more identifiable in Image 8.2. These variations are pointed out to prevent confusion with the coast line.

### 8.2.3 Precipitation days.

The precipitation days posed a special problem. The image extracted from the whole AVHRR scene was not limited to a 512 pixels X 512 lines image as parts of the coast not covered with clouds were different from one day to another. Some of the images of a 512 pixels X 660 lines dimension were needed to be extracted before the geometric correction procedure could be performed. The inclusion of the extra 148 lines was in order to provide as much as possible exposed coast line i.e not covered with cloud. The slots which were of 512 X 660 dimension are for day 27, the three slots of day 28, and two slots of day 29. For each of the images a control image as extracted from the control image derived in Section 4.3.

The average errors for day 27 and 28 are acceptable as they are of subpixel values. The errors indicated for day 29 are exceptionally high. The clouds covered most of the coast line. The points generated by the control_points function were few. The warping function performed a linear transformation resulting in relatively big errors. (See Section 4.3.3.3) The effect of these errors will be discussed in Section 8.3.

Image 8.3 provides a good example of the problems, and the source of the relatively large errors for cloud covered days. It is an image of the Cornwall coast, the Irish Republic coast and a cloud covered England and Wales. The recognisable coast was used to generate the control file. The resultant warped image is shown in Image 8.4. Control points were not generated for the right hand part of the image because of cloud cover. They were generated for the Cornwall coast and the east coast of Ireland. The average error of 2.9, depicted in Table 8.1 refer to these two areas, the errors around the basin area will be of that order although with a lesser degree of certainty.

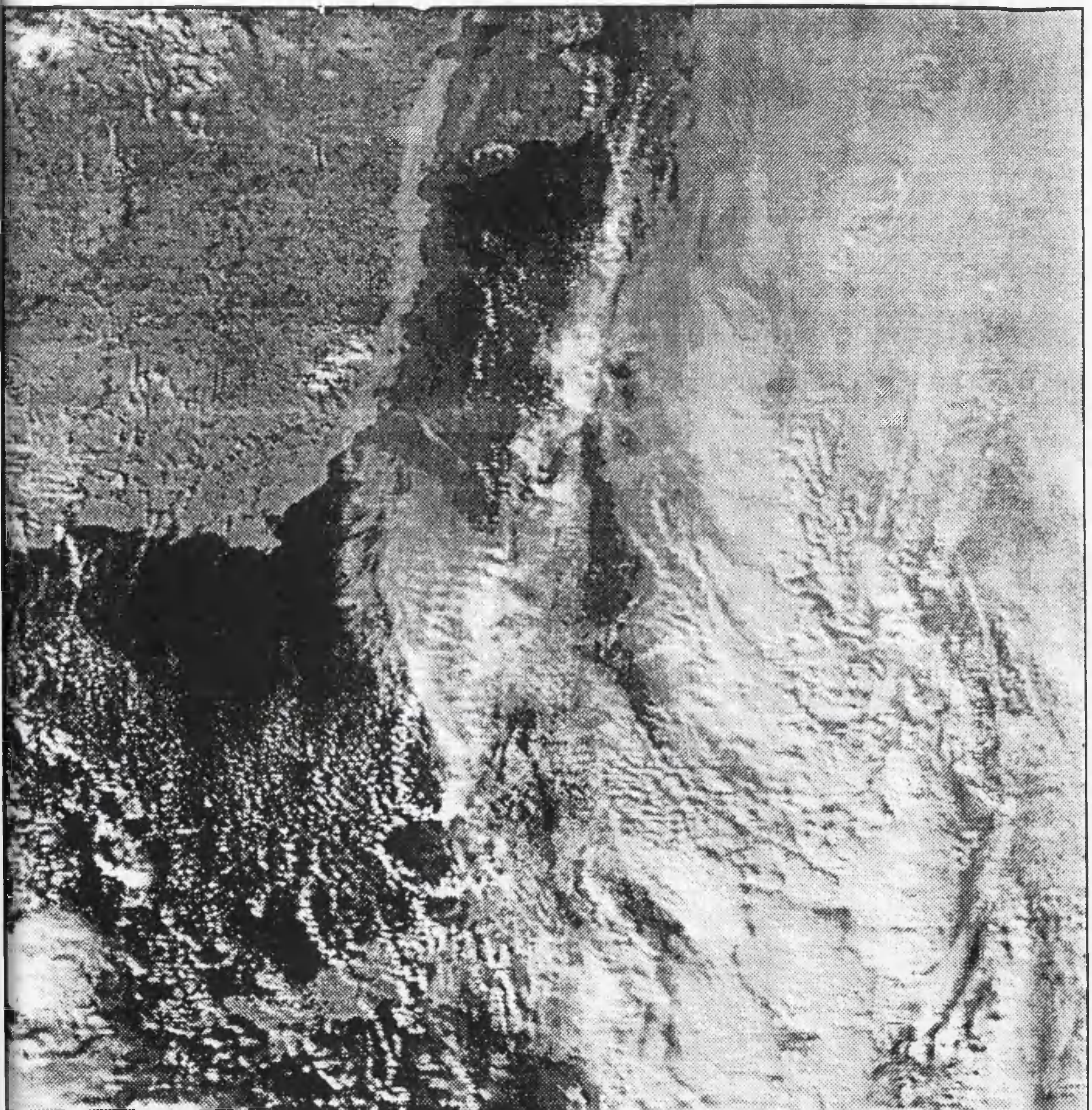


Image 8.3 AVHRR band 4 image of cloud covered England and Wales with the cloud free coast of Cornwall and Ireland for day 29.

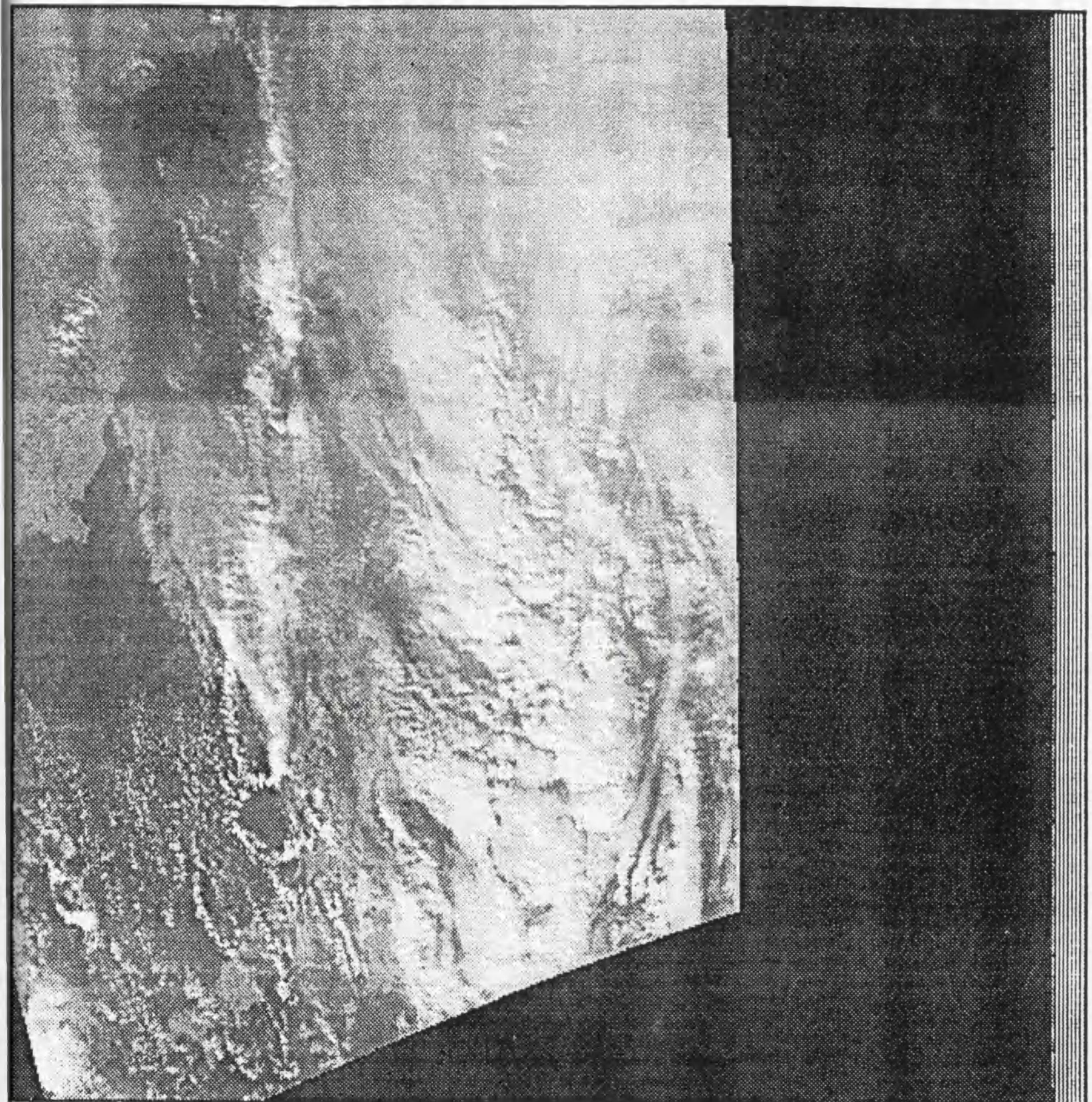


Image 8.4 The result of warping of Image 8.3.

### 8.2.4 AVHRR Pixel size of the River Aire basin.

The size of AVHRR pixels varies along the scan line. The further the pixel is from the nadir the larger the area of land it represents. Figure 8.1 was derived from a report by Eales, [1988]. It represents the width of AVHRR pixel along the scan line, moving away from nadir, assuming that earth is spherical and the effect of satellite motion is negligible. The deterioration of the pixel value is plotted against scan angle.

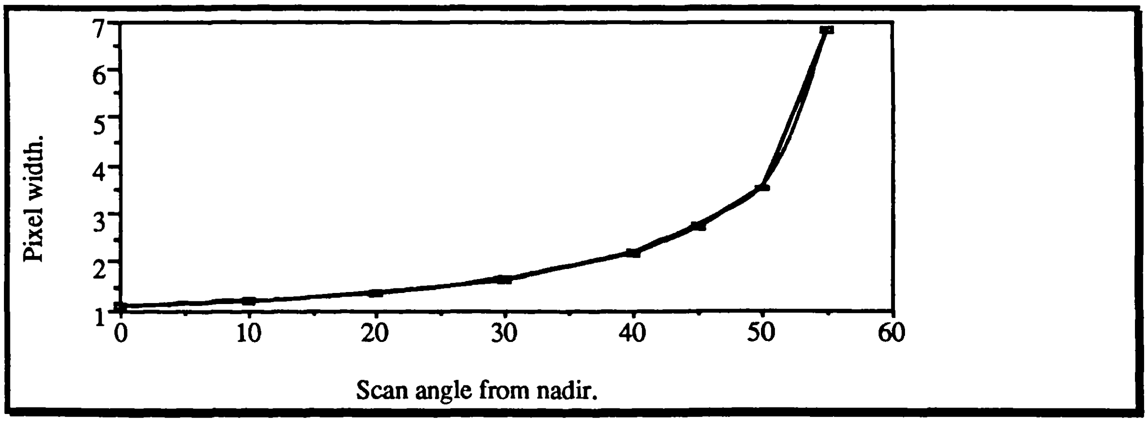



Figure 8.1 The variation of pixel width plotted against the scan angle from nadir. (Source: Eales, 1988)

The scan angle encompassing Britain is 27$^{o}$, i.e. for a 512 pixel wide frame encompassing Britain. The different images used in this report are positioned between a minimum and a maximum angle away from nadir of 13$^{o}$ and 21$^{o}$. (See Figure 8.2) Although these figures were compiled and calculated from the positions of the frame containing Britain on the scan line for all the images used in this project, they could be used a general guide for the positioning of the Aire basin on the scan line. The scan angles calculated here are for eight orbits, while the repeat orbit is every 4-5 days suggesting the general application of these figures.

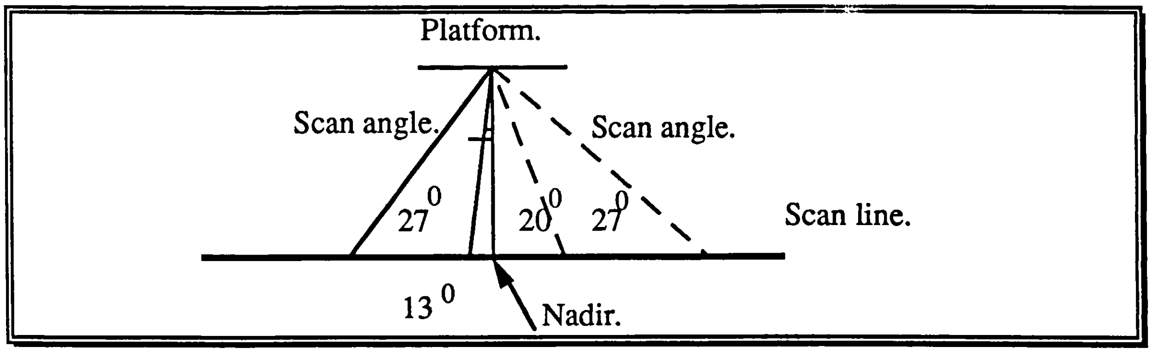



Figure 8.2 The position of Britain along the scan line. The plain lines represent the lowest value of scan angle used while imaging Britain while the dashed lines represent the highest scan angle.

The Aire basin is approximately in the middle of the frame containing the image of Britain, a subset of the whole swath width of AVHRR, for which the scan angle is between $26^{o}$ and $37^{o}$. The pixel size will be less than 2 km for the worst position of a scan angle of $40^{o}$. The geometrical correction of the image will lead to the transformation of a pixel of 2 km width into two pixels on the the geometrically corrected image. These two pixels, on the geometrically correct image, carry the same information which is the spectral response of two kilometres on the surface of the ground. Thus the amount of detail extracted for a certain image is directly related to the position of the basin on the scan line. Thus for some cases the actual information provided by the sensor is for every two kilometres rather than for every 1.1 km.

The position of the basin on the scan line varies from one day to another. The implications of this variation are not completely understood. Although this effect has been realised early when using AVHRR, [Duggin *et. al.* 1982], studies are still being proposed and carried on this subject.

The understanding of the above physical constraint of the sensor should help in putting the results obtained by remote sensing into perspective.

## 8.3 Precipitation Estimates Results.

Precipitation estimates were derived using the PERMIT technique of the Bristol method. This method uses a thresholding technique on the remotely sensed images of the cloud. (See Chapters 3 & 4) This method had been tested for the tropical region. This is the first time it has been used for a region this high in latitude.
The data available for the rainy days were three slots for days 28 and 29 and one slot for day 27.

The threshold used for aggregating cloud images in the tropical region has proved low for the British Isles. The cloud images were processed using the different programs of PERMIT incorporating the threshold used for the tropics. The method indicated no rain present on the three days on which the rain occurred. The threshold was lowered from 197 to 187. This indicated rain occurring for day 28 and 29, while it indicated that no rain occurred on day 27. One slot was used for day 27. This means that clouds imaged in that slot were not cold enough to produce rain. Three slots were used for the days 28 and 29. The different slots of these days have indicated rain.

This is the first time PERMIT is being applied to estimate precipitation for such a high latitude. PERMIT has usually been used utilising GOES images. It was envisaged that it can use AVHRR images. This is also the first time AVHRR images are used. The GOES images used to utilise eight slots per day, while AVHRR can only provide four slots per day. The number of slots and days, and the size of the samples it has been applied to, do not give clear indications of the effectiveness of this method for high latitudes. Resolving the value of the threshold at 187 will require a larger sample and a more extensive experimentation with the value of the threshold. However, it has been established here that the method

1- produces precipitation estimates using AVHRR imagery even at high latitudes for as low number of slots as three.
2- the value of the threshold needs to be lowered from that of equatorial regions. This could mean that clouds produce rain at high latitudes at higher temperatures then the temperatures of clouds in low latitudes. The reduction in the value of the threshold is almost certain while the implications of this deduction can not be established on the evidence of just the data presented here.

Table 8.2 shows the average precipitation estimated for each day, for each zone, according to PERMIT. The average precipitation was calculated by dividing all the occurrences of precipitation for each zone.

| DAY | ZONE | AVERAGE PRECIPITATION in mm |
|---|---|---|
| 24 | 0,1,2,3 | 0 |
| 25 | 0,1,2,3 | 0 |
| 26 | 0,1,2,3 | 0 |
| 27 | 0,1,2,3 | 0 |
| 28 | 0 | 1.935 |
| 28 | 1 | 1.393 |
| 28 | 2 | 1.208 |
| 28 | 3 | 1.297 |
| 29 | 0 | 4.99 |
| 29 | 1 | 4.79 |
| 29 | 2 | 5 |
| 29 | 3 | 4.351 |

Table 8.2 Average precipitation occurring on the different elevation zones on the basin image..

On the other hand Table 8.3 provides a list of the different remote sensing estimates of rain occurring over the basin for days 28, and 29, the days on which PERMIT indicated rain. The count represents the number of pixels that had the same value of precipitation occurring on them. The sum of the count for each day should be 540, i.e. the number of pixels for the rectangle containing the basin.

| DAY | PRECIPITATION in mm | COUNT |
|---|---|---|
| 28 | 0 | 367 |
| 28 | 4 | 61 |
| 28 | 5 | 66 |
| 28 | 6 | 24 |
| 28 | 7 | 21 |
| 28 | 8 | 1 |
| 29 | 0 | 7 |
| 29 | 4 | 203 |
| 29 | 5 | 187 |
| 29 | 6 | 83 |
| 29 | 7 | 54 |
| 29 | 8 | 6 |

Table 8.3 Occurrence of the different values of precipitation values for days 28 and 29.

The value of average precipitation is affected by the presence of zero precipitation values for pixels. It could be argued that for a relatively small area like the Aire basin the zero occurrences should be ignored as it is unlikely that discrepancies will occur on the scale of 20 X 27 $km^2$. However, the calculation of the average of precipitation was done using the zero values. The most important feature of remote sensing, in comparison with gauged parameters, is the ability of describing the areal variation of a parameter.

The high number of zero precipitation pixels may be contributed to the loss of one slot for that day or that the value of the threshold is not adequate and it should be lowered further or finally a combination of both. This can only be established with a much bigger sample of data and much more number of days. Along side with a study on the cloud top temperatures indicated by pixel values and comparing the results with the readings of cloud temperatures from the meteorological office.

The values of precipitation predicted by PERMIT are close to the those gauged by conventional means. Table 8.4 provides the value of gauged rains and the average rain precipitation as estimated by PERMIT.

| | Precipitation. | |
|---|---|---|
| Day | Gauged | PERMIT |
| 28 | 2.5 | 1.46 |
| 29 | 5.4 | 4.78 |

Table 8.4 List of Average precipitation, gauged, and averaged estimates of remote sensing.

Comparing the results of gauged and remote sensing estimates of precipitation of Table 8.4. one might deduce that PERMIT has a great potential. However, this judgement can not be passed on the evidence of two observed days of precipitation.

The PERMIT method will not produce values of precipitation estimates for any day more than those estimated for day 29. The PERMIT technique does not take into consideration occurrence of precipitation in more than one slot per day as explained in Section 4.5. The maximum estimates per day is going to be the average precipitation depicted in the historical data this was the case for day 29.

At the end of this section it should be noted that the writers of the Bristol method do advise caution on the use of PERMIT for day to day estimates and emphasise its use as an inventory technique rather than a highly accurate daily estimates producer.

## 8.4 Temperature Estimates Results.

Temperature estimates were derived for cloud free days using the algorithms described by NESS. Temperature estimates were derived for both channels four and five. The derivation of the temperature estimates was done in a process that started with the extraction of the calibration data. The calibration data were used for the estimation of temperature values for both channel four and five of the AVHRR image. It was suggested in Section 4.6 that an empirical formulae should be used for applying an atmospheric correction using the derived temperature estimates of channel four and five. The different empirical formulas for atmospheric correction were tested on the data available. They proved to produce temperature estimates that were very far from those registered by conventional gauges. The range of "atmospherically corrected" temperatures was, typically, -7 to +7 $C^{o}$, very large compared with those not corrected 0.7 to 2.8 $C^{o}$. The non corrected range was more in line with the conventional data range as its was between -3 and +4 $C^{o}$. Hence it was decided to use the non-corrected data as source data for the database. However, this does not imply that Atmospheric correction should be written off and not used any more. Rather a more cautious approach in accepting the estimates resulting from remote sensing methods will be appropriate.

| DAY | MAX TEMPERATURE C°. | MIN TEMPERATURE C°. |
|---|---|---|
| 24 | 0.7 | -3.2 |
| 25 | 1.3 | -5.6 |
| 26 | 2.8 | -6.7 |

Table 8.5 Maximum and Minimum temperatures registered by conventional means for the three days at the Aire on Kildwick Bridge Station.

| DAY | TEMPERATURE | Count Channel 4 | Count Channel 5 |
|---|---|---|---|
| 24 | -3 | * | 13 |
| 24 | -2 | * | 39 |
| 24 | -1 | 3 | 46 |
| 24 | 0 | 125 | 149 |
| 24 | 1 | 102 | 202 |
| 24 | 2 | 211 | 87 |
| 24 | 3 | 99 | 4 |
| 25 | -2 | 13 | * |
| 25 | -1 | 17 | * |
| 25 | 0 | 99 | * |
| 25 | 1 | 45 | * |
| 25 | 2 | 149 | * |
| 25 | 3 | 213 | * |
| 25 | 4 | 4 | * |
| 26 | -2 | * | 17 |
| 26 | -1 | * | 46 |
| 26 | 0 | * | 439 |
| 26 | 1 | 29 | 6 |
| 26 | 2 | 167 | * |
| 26 | 3 | 324 | * |
| 26 | 4 | 20 | * |

Table 8.6 Temperature estimates, channels four and five assorted in categories for every day. The count denotes the number of occurrences of a certain temperature category for the corresponding day and AVHRR channel.

* Denotes Non existence data or category.

Presented in Table 8.5 is a list of the maximum and minimum temperatures registered by conventional means. While Table 8.6 provides a list of the derived temperature estimates for both channels four and five for each day. Temperature estimates for day 25 utilising channel five data are not available as the file containing these data was corrupted.

The images used for producing temperature estimates were registered during the afternoon pass of the satellite. This time is usually the time when temperatures are at a maximum. Hence, the temperature estimates from remote sensing sources are compared with the maximum temperatures recorded with conventional means.

Comparing the categorise of temperature estimates of channel four and channel five it could be seen that channel five estimates temperatures to be lower than those registered by channel four. When comparing the estimates of the two channels with those of conventional data it could be seen that:

1- Estimates from channel five tend to estimate temperatures to the cooler side of those registered conventionally.

2- Estimates from channel four are closer to the Maximum gauged temperature.

3- The temperature estimates are close to the registered maximum.

These deductions are based on two of the days temperature estimates days, 24 and 26. The above deductions will be more convincing as the data is viewed by other means. Figures 8.3..........to 8.7 present the data in the following manner for any of the figures:

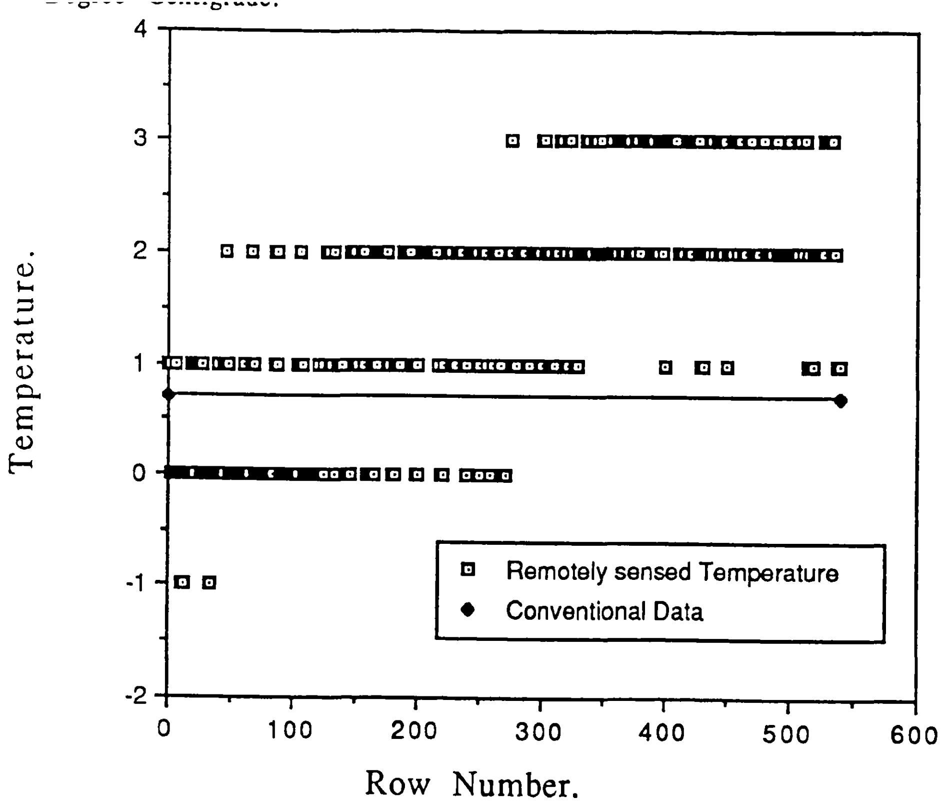



Figure 8.3 Temperature estimates for the different pixels in the basin image for day 24 band 4.

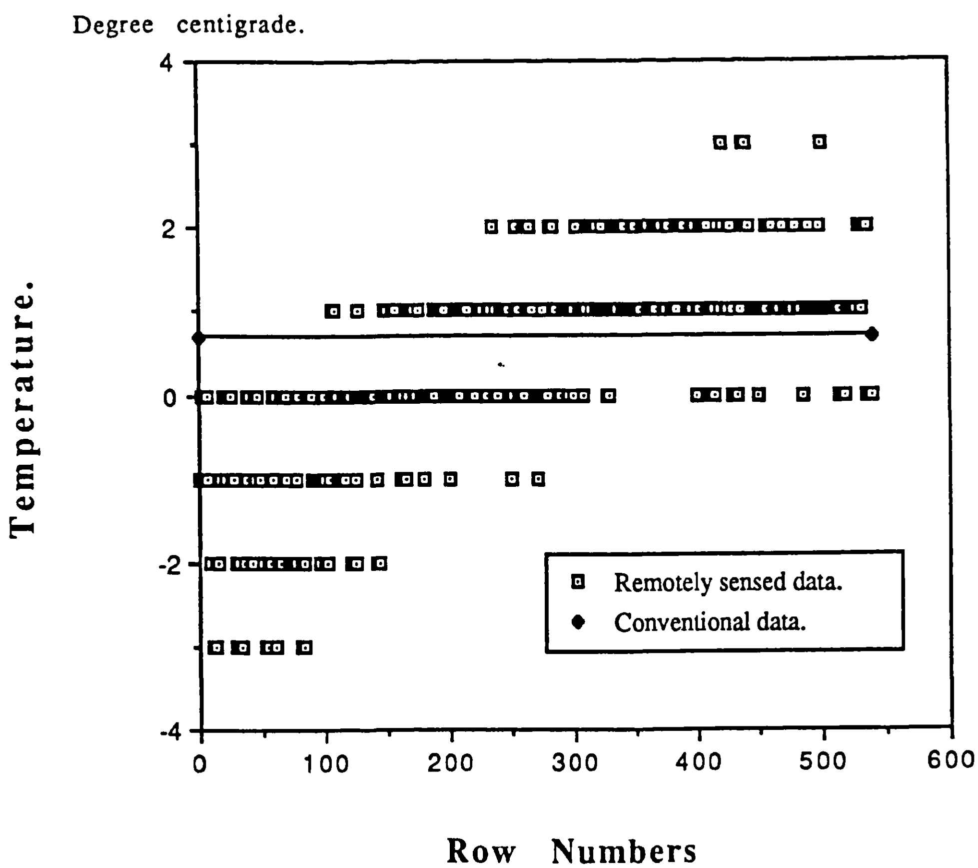



Figure 8.4 Temperature estimates for the different pixels in the basin image for day 24 band 5.

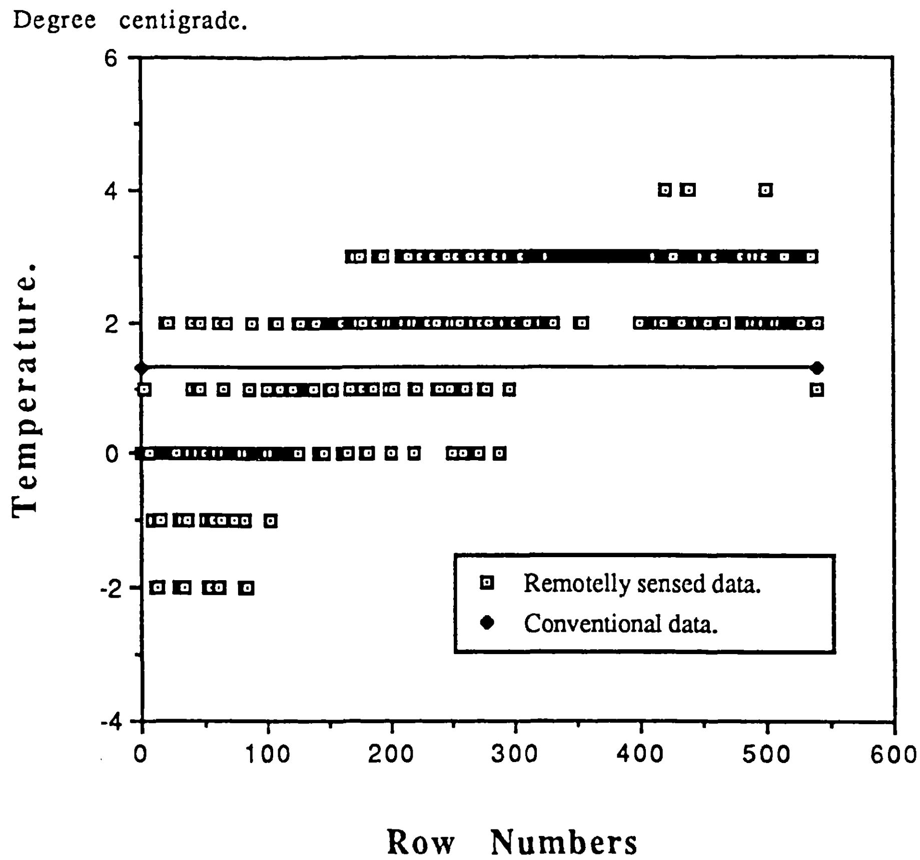



Figure 8.5 Temperature estimates for the different pixels in the basin image for day 25 band 4.

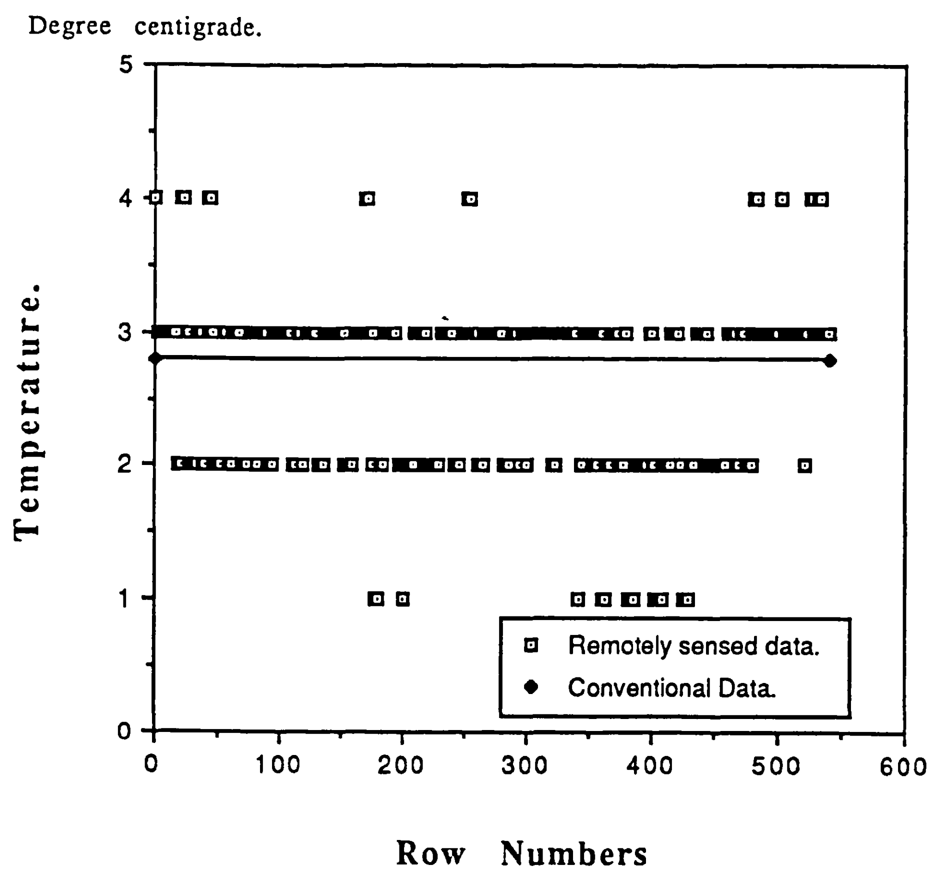



Figure 8.6 Temperature estimates for the different pixels in the basin image for day 26 band 4.

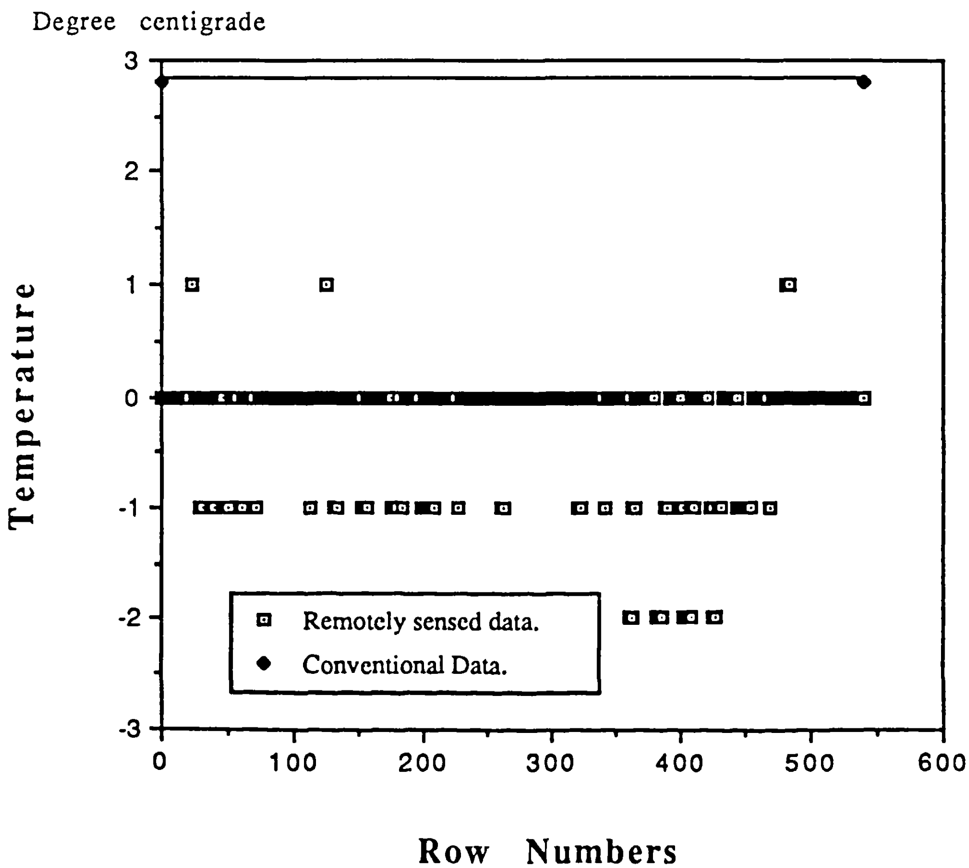



Figure 8.7 Temperature estimates for the different pixels in the basin image for day 26 band 5.

-The data plotted in each figure are the temperatures registered in the basin versus row numbers. Each of the figures represent the temperature registered by one of the channels for a day.

-The vertical axis represent the temperature categories registered for each day in each channel.

-Conventional data provides two readings for each days for the whole of the basin. The reading used here is the maximum reading for each of the days. (See beginning of this section.) The conventional data are represented in a line to indicate that it applies for the whole of the basin as all the temperatures registered are to be compared with it.

-The plotted temperature data was arranged in a methodical way in which the row number corresponding to each point represent the position of a pixel on the rectangle encompassing the basin. Thus, the horizontal axis is the position of each pixel with reference to the uppermost left pixel of the basin image. The first 20 numbers are the first line of this rectangle, the 21st pixel is the left pixel on the second line 22nd is the one after and so on.

The variation of temperatures in the basin is conceivable over an area as big as the Aire basin (282 $km^2$). The heavy lines in the different graphs indicate a large number of pixels in that category of temperature estimates. Channel four estimates have the gauged maximum temperature line in a central position near heavy lines indicating strong correlation with the registered conventional data. The number of pixels in extreme categories, i.e. away from conventional data, is small for channel four estimates. However, the above sample is not very conclusive as it is restricted in size. The empirical equations of the atmospheric corrections have channel four as the main contributor to the resultant estimate. (See section 4.6) Accordingly channel four estimates were used as the source data.

| DAY | ELEV-ATION in feet | AVERAGE TEMPE-RATURE |
|---|---|---|
| 24 | 800 | 2 |
| 24 | 900 | 2.3506 |
| 24 | 1000 | 1.7758 |
| 24 | 1100 | 1.8787 |
| 24 | 1200 | 1.0740 |
| 24 | 1300 | 0.5 |
| 24 | 1400 | 0.2413 |
| 24 | 1500 | 0.2380 |
| 24 | 1600 | 0.1428 |
| 25 | 800 | 3 |
| 25 | 900 | 2.8051 |
| 25 | 1000 | 2.3189 |
| 25 | 1100 | 2.2424 |
| 25 | 1200 | 1.1728 |
| 25 | 1300 | 0.6944 |
| 25 | 1400 | -0.1379 |
| 25 | 1500 | -0.5238 |
| 25 | 1600 | -0.5714 |
| 26 | 800 | 3 |
| 26 | 900 | 2.597 |
| 26 | 1000 | 2.586 |
| 26 | 1100 | 2.545 |
| 26 | 1200 | 2.7407 |
| 26 | 1300 | 2.583 |
| 26 | 1400 | 2.5517 |
| 26 | 1500 | 2.857 |
| 26 | 1600 | 3.0714 |

Table 8.7 Average of remotely sensed temperatures (channel four) for the different elevations of basin.

Table 8.7 presents the average temperature estimates at the different elevations of the basin. The most important observation is the variation of the average temperature with elevation above sea level for days 24 and 25. In these two days the average temperature decreases in a regular manner as the height increases. This meteorological phenomenon is very well known. As a general rough guide temperatures decrease with elevation by the ratio of one degree centigrade for every one hundred metres elevation above sea level. This is approximately replicated for day 25 while estimates for day 24 also decrease with elevation but with a lesser rate. The estimates for elevation 800 ft are anomalous with regard to the rest of results. This could be explained with the fact that only one pixel in the whole image has this elevation. The estimate for this pixel was not balanced with other estimates for the same elevation.

Temperature estimates for the basin for day 26 do not conform to this rule. The variation of average temperature does not correspond to elevation. This variation is around 0.5 degrees throughout the different elevations suggesting a uniform distribution of temperatures over the basin.

It should be noted that the temperature estimates are derived from the same image as that used for the mapping of snow. Thus the temperature of every pixel in the snow pack is defined as the mapping is done.

## 8.5 Snow mapping.

Snow mapping was performed using the unsupervised cluster classification technique of Harrison-Lucas. The processing was done on the 512 X 512 image of England and Wales. The result of the image classification can be seen in Images 8.5 .... to 8.13. These nine images are for the three clear days where snow mapping was available. Each of the days has three images. The first image is

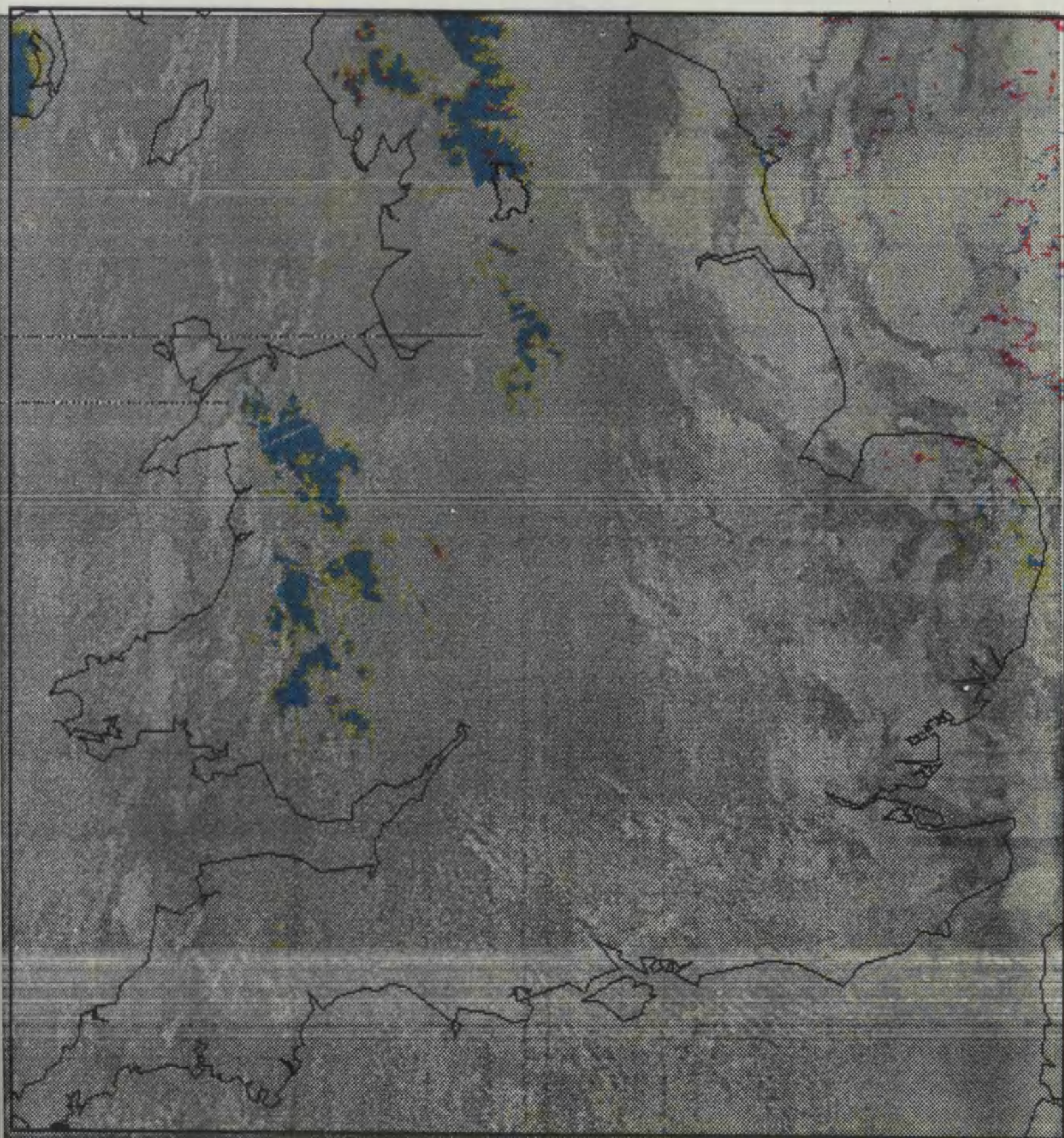


Image 8.6 Mapped snow classes for day 24.

Image 8.5 Image of Britain for day 24 on a transparency.

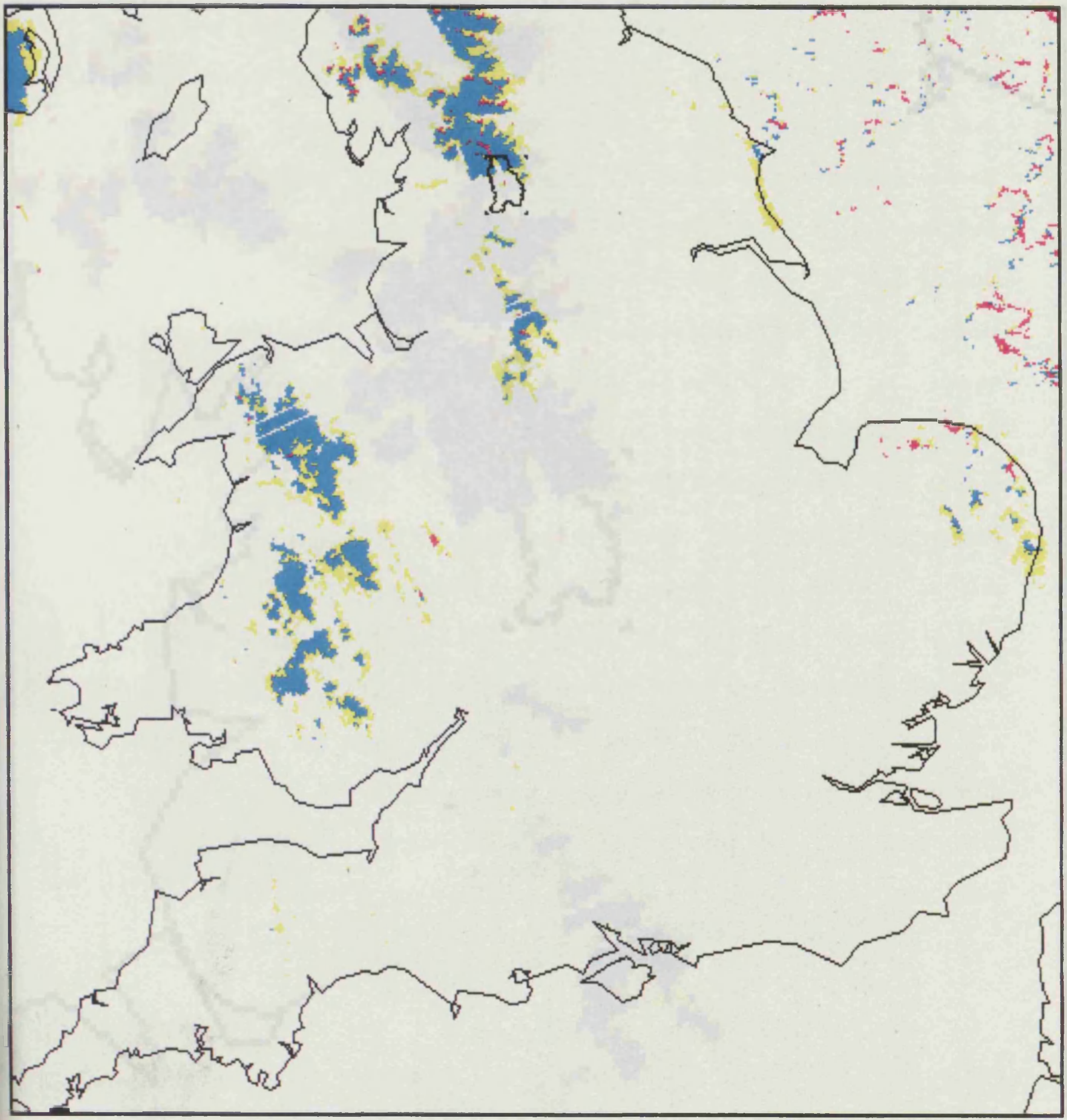


Image 8.6 Mapped snow classes for day 24.

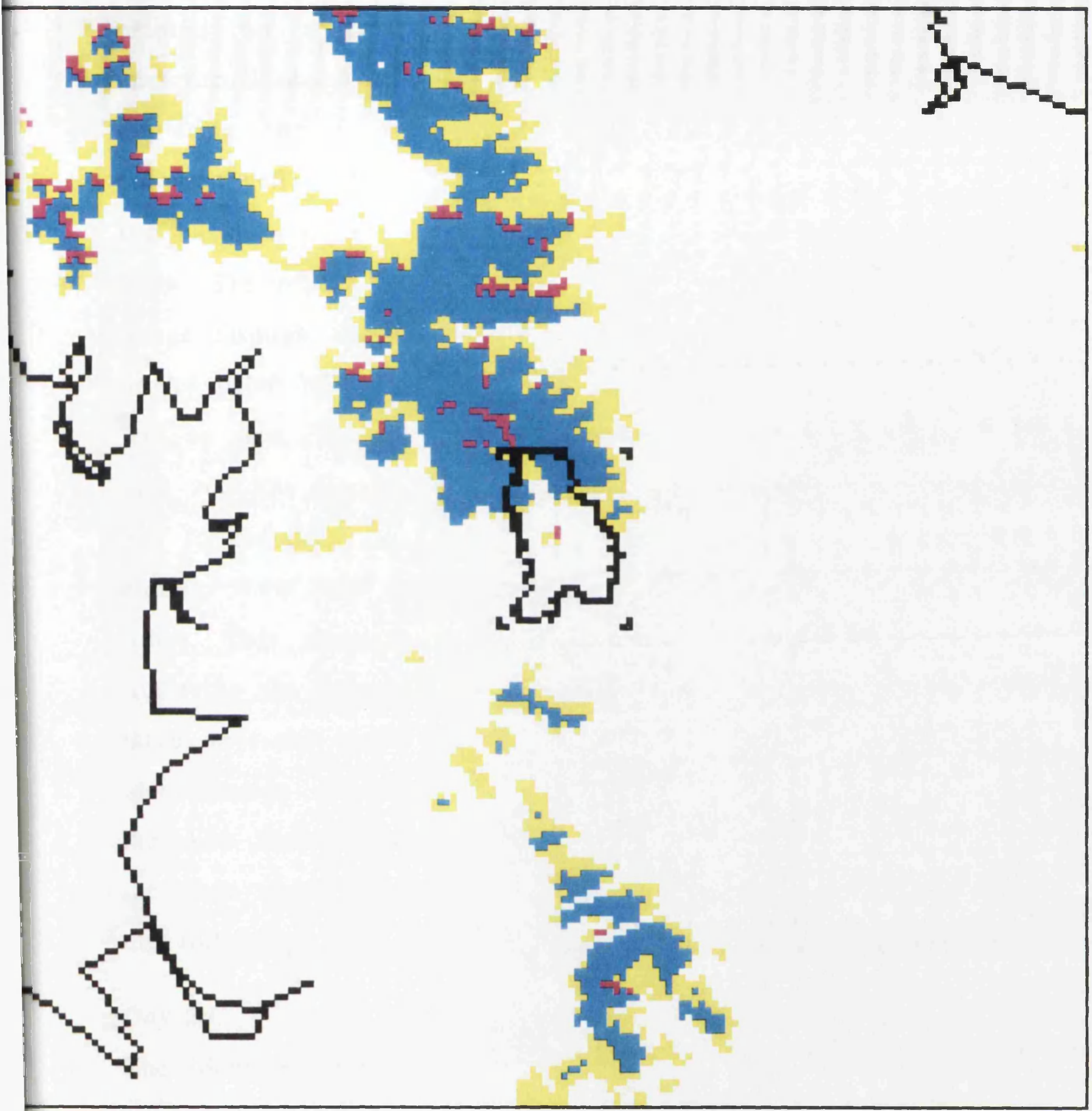


Image 8.7 A zoomed image on the north of England for day 24.

printed on a transparency, this image is the geometrical uncorrected image of that day. The second image is a colour image depicting the different snow classes. The snow classes are coloured yellow, blue and magenta. The third image is a zoom on the basin area in order to bring out the details of the mapped snow. The reader is able to see the mapped snow of the second image through the transparency. If the reader used a white sheet of A4 paper to separate the two images, details of the first image will be seen. The important features to notice are the clouds, both high and low clouds. Now remove the white sheet, this will enable you to correlate the mapped snow classes with ground snow and clouds. You will probably need to repeat this process several times. This procedure was applied for the three days, in the following the images for each of the days are analysed. For the three days the north of England was free from cloud cover. The identification of snow classes was done in the area surrounding the Aire basin. These identified classes are also correlated with the some cloud signatures. The analysis of the different days yield the following:

*Day 24.*

The identified classes as snow have strong correlation with cloud cover. The detailed scanning of the Image 8.5 and 8.6 reveals that clouds pixels identified as snow are on the edges of high clouds. On these edges low clouds are revealed. Low clouds have an overlapping spectral signature with that of snow.

*Day 25.*

In Images 8.8 and 8.9 the correlation between snow classes and cloud cover is concentrated in two regions, over Wales and the

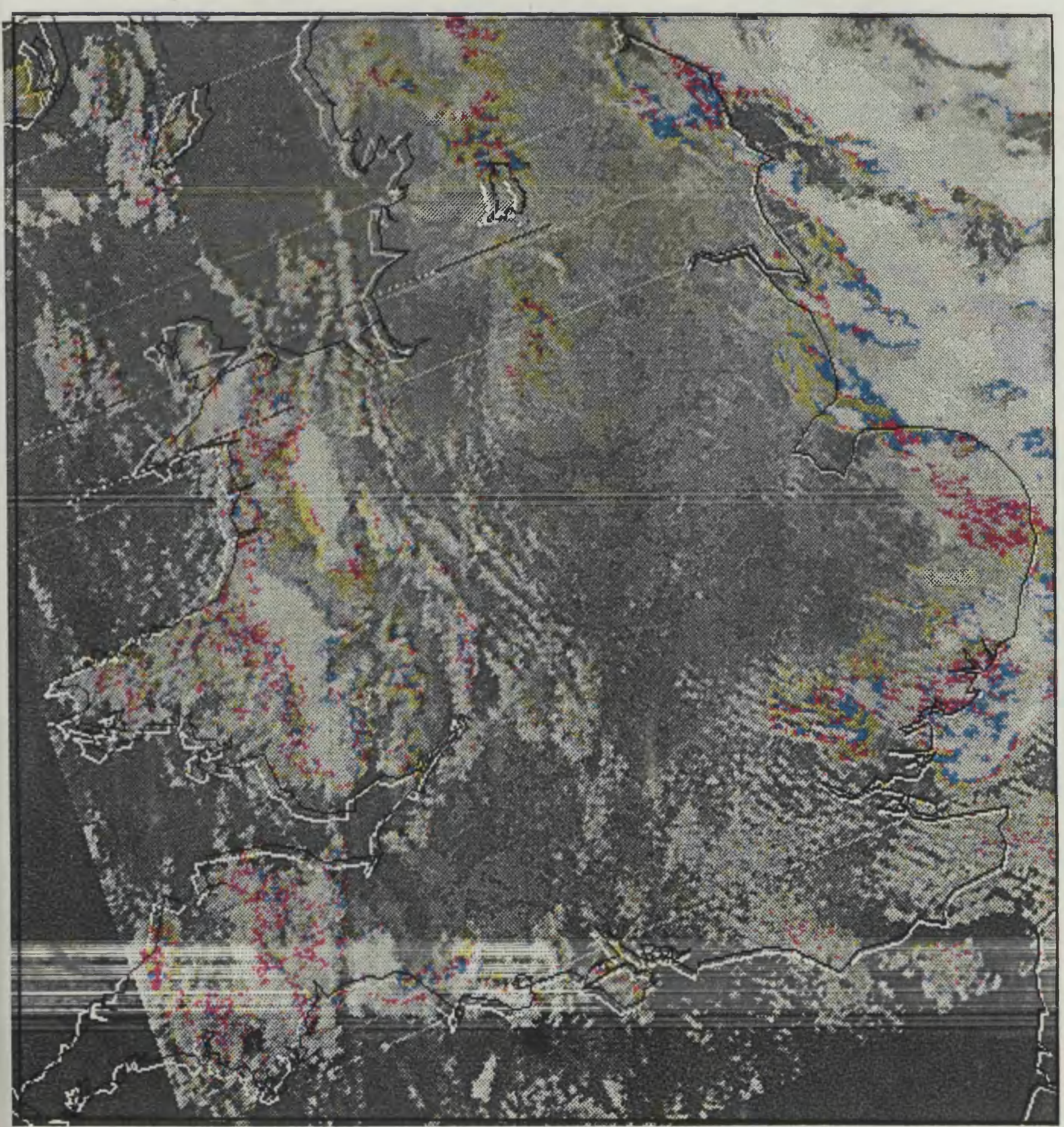


Image 8.9 Mapped snow classes for day 25.
Image 8.8 Image of Britain for day 25 on a transparency.

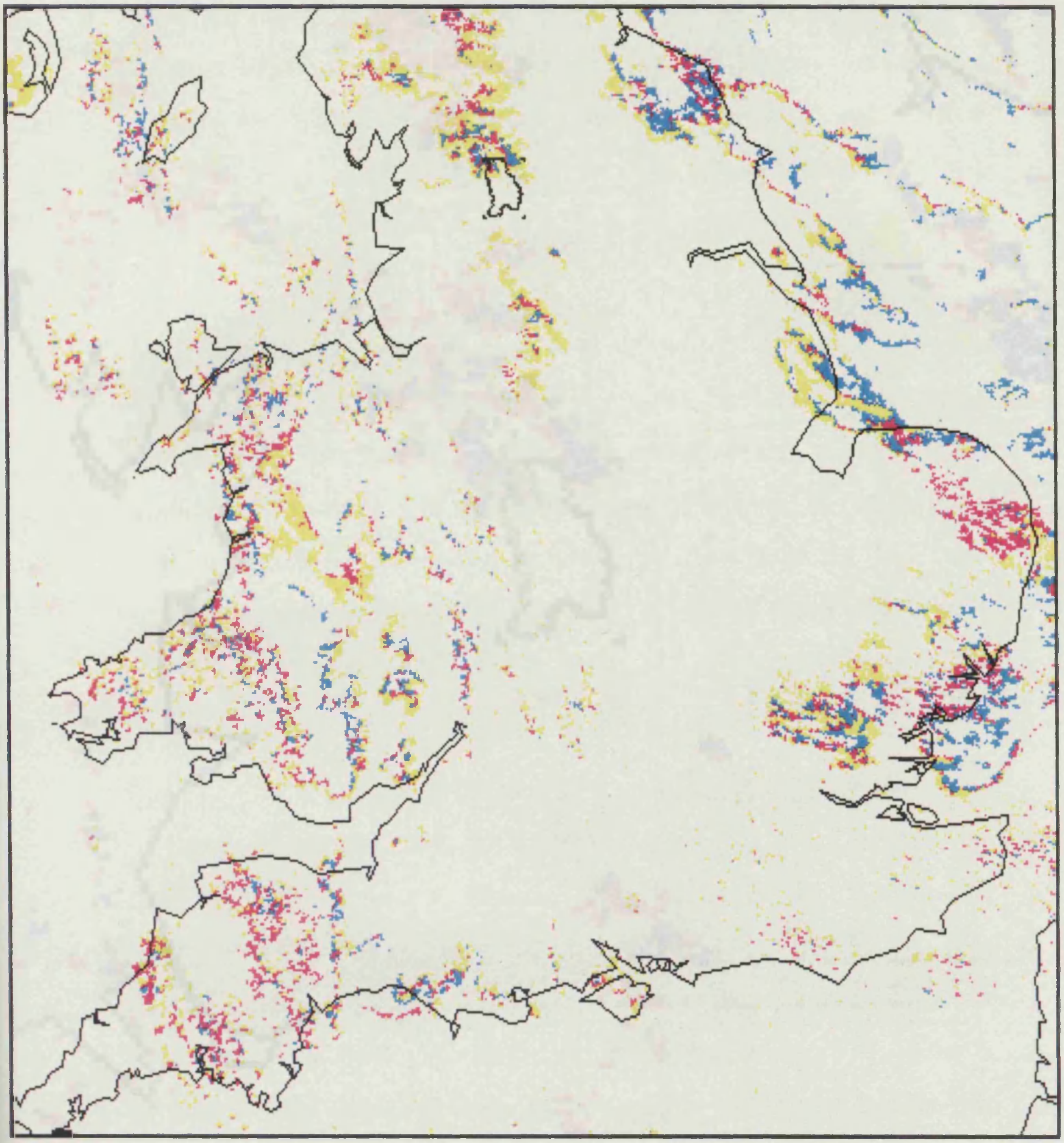


Image 8.9 Mapped snow classes for day 25.

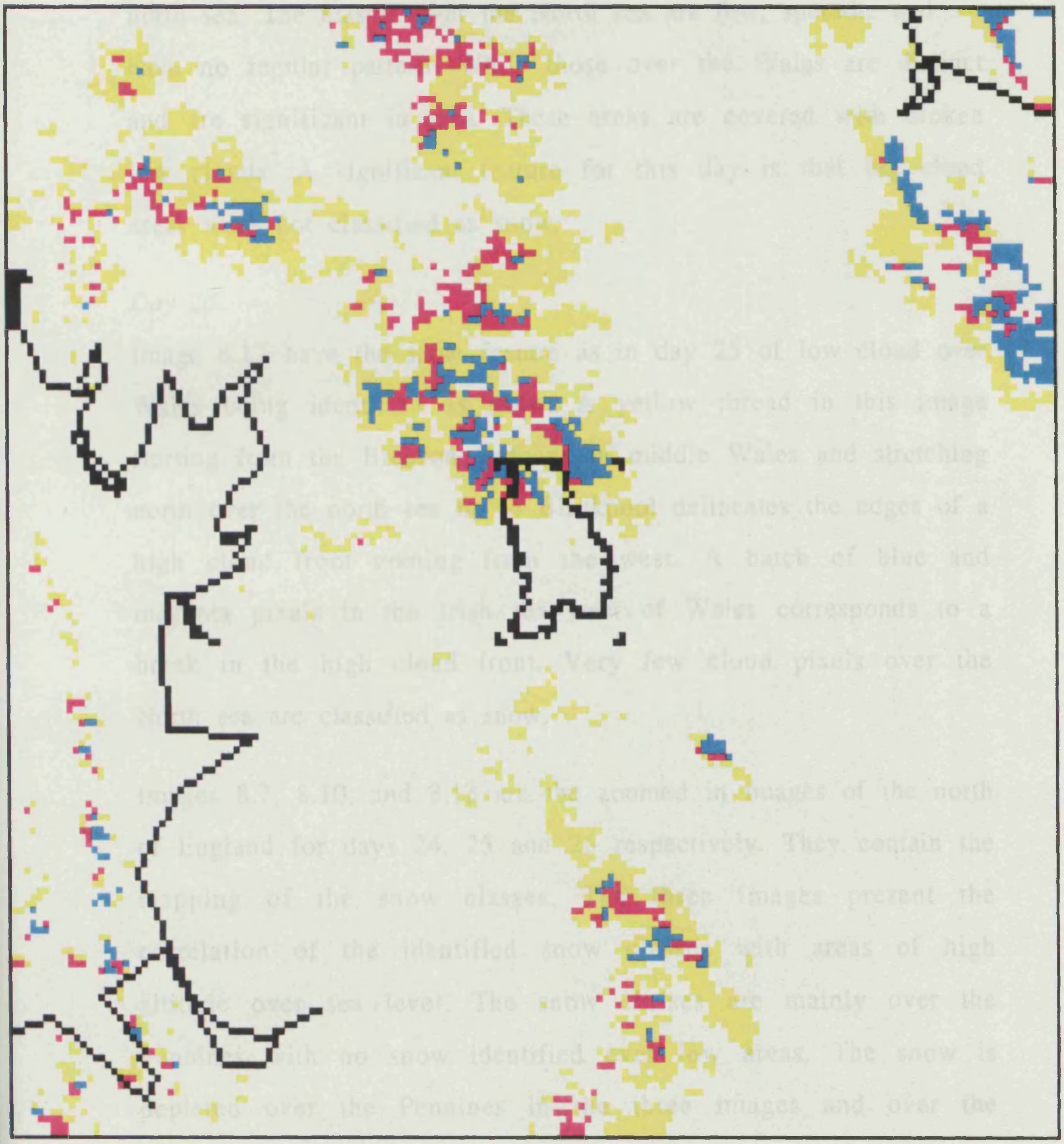


Image 8.10 A zoomed image on the north of England for day 25

north sea. The classes over the North sea are few, sporadic and have no regular pattern. While those over the Wales are distinct and are significant in area. These areas are covered with broken low clouds. A significant feature for this day is that big cloud areas were not classified as snow.

*Day 26.*

Image 8.12 have the same feature as in day 25 of low cloud over Wales being identified as snow. A yellow thread in this image starting from the Breacon Beacons in middle Wales and stretching north over the north sea up to Blackpool delineates the edges of a high cloud front coming from the west. A batch of blue and magenta pixels in the Irish sea west of Wales corresponds to a break in the high cloud front. Very few cloud pixels over the North sea are classified as snow.

Images 8.7, 8.10, and 8.13 are the zoomed in images of the north of England for days 24, 25 and 26 respectively. They contain the mapping of the snow classes. The three images present the correlation of the identified snow classes with areas of high altitude over sea level. The snow classes are mainly over the Pennines with no snow identified over low areas. The snow is depicted over the Pennines in the three images and over the North York Moors in Image 8.7 to the upper right of this image.

Individual snow classes, identified by the different colours, appear to have a pattern of clustering together. The yellow class appear on the out skirts of the snow pack while the blue areas are sandwiched between the yellow class and the red class which appear to be always surrounded by the other two classes. This

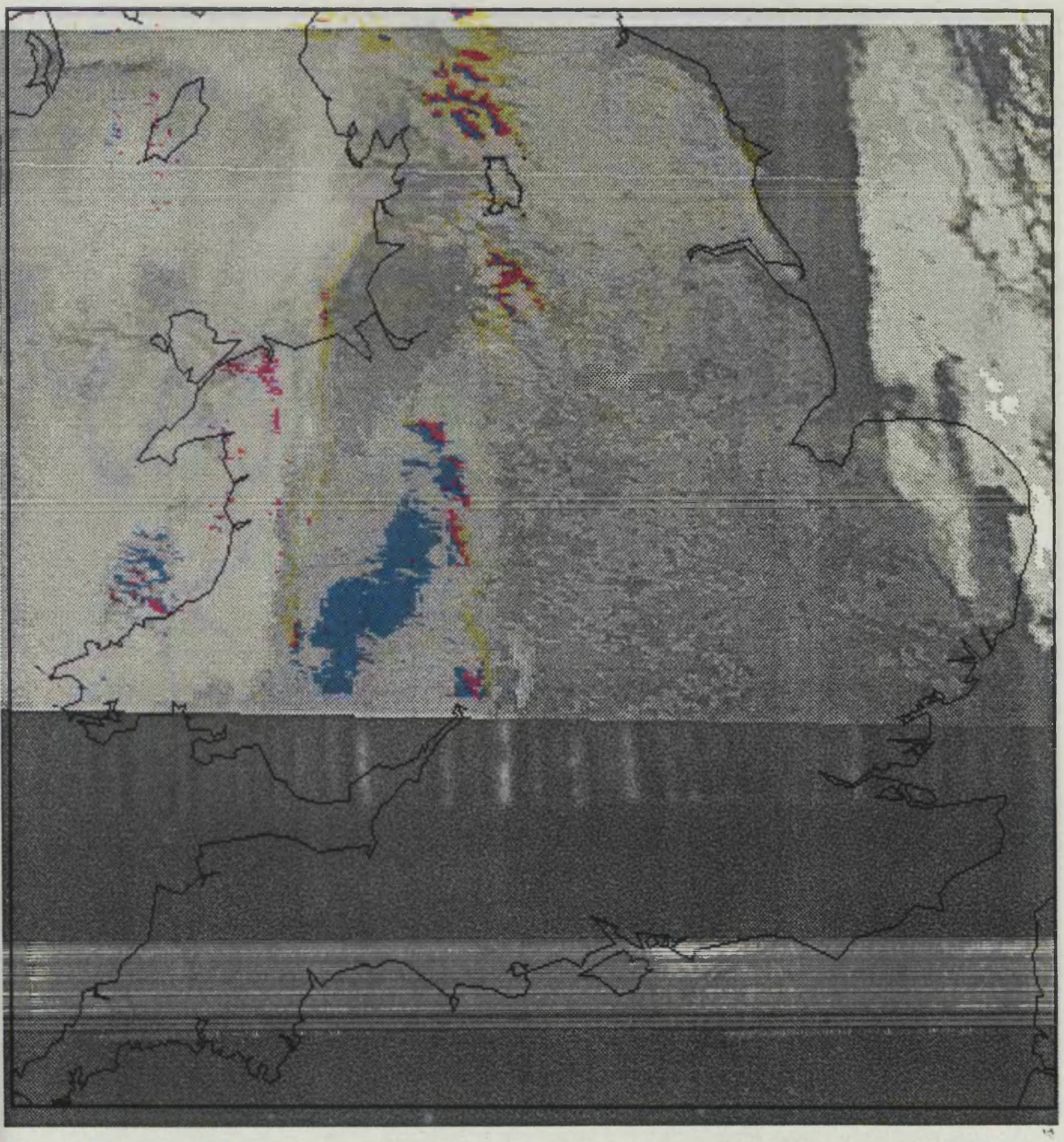


Image 8.12 Mapped ·snow classes for day 26.
Image 8.11 Image of Britain for day 26 on a transparency.

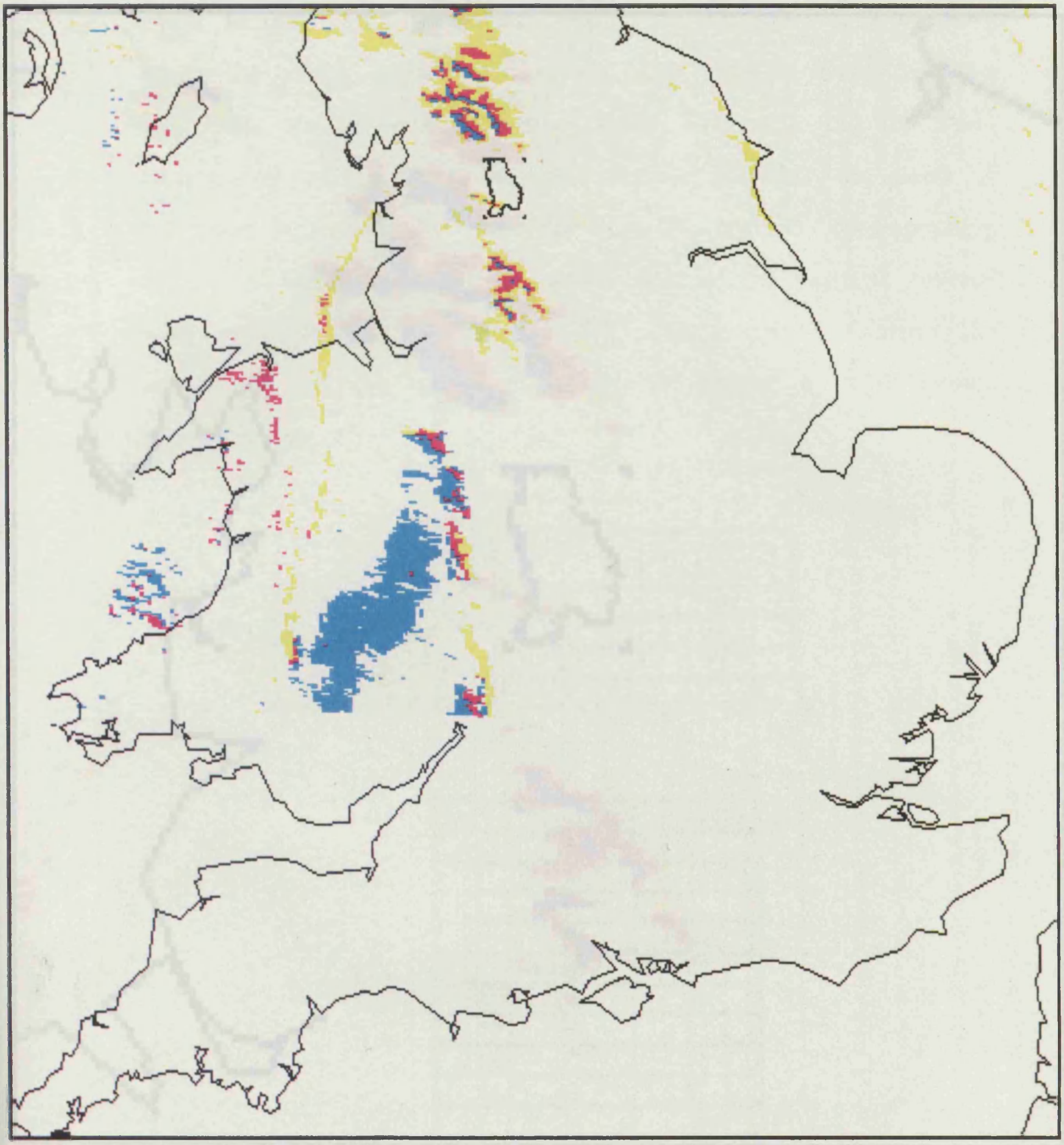


Image 8.12 Mapped snow classes for day 26.

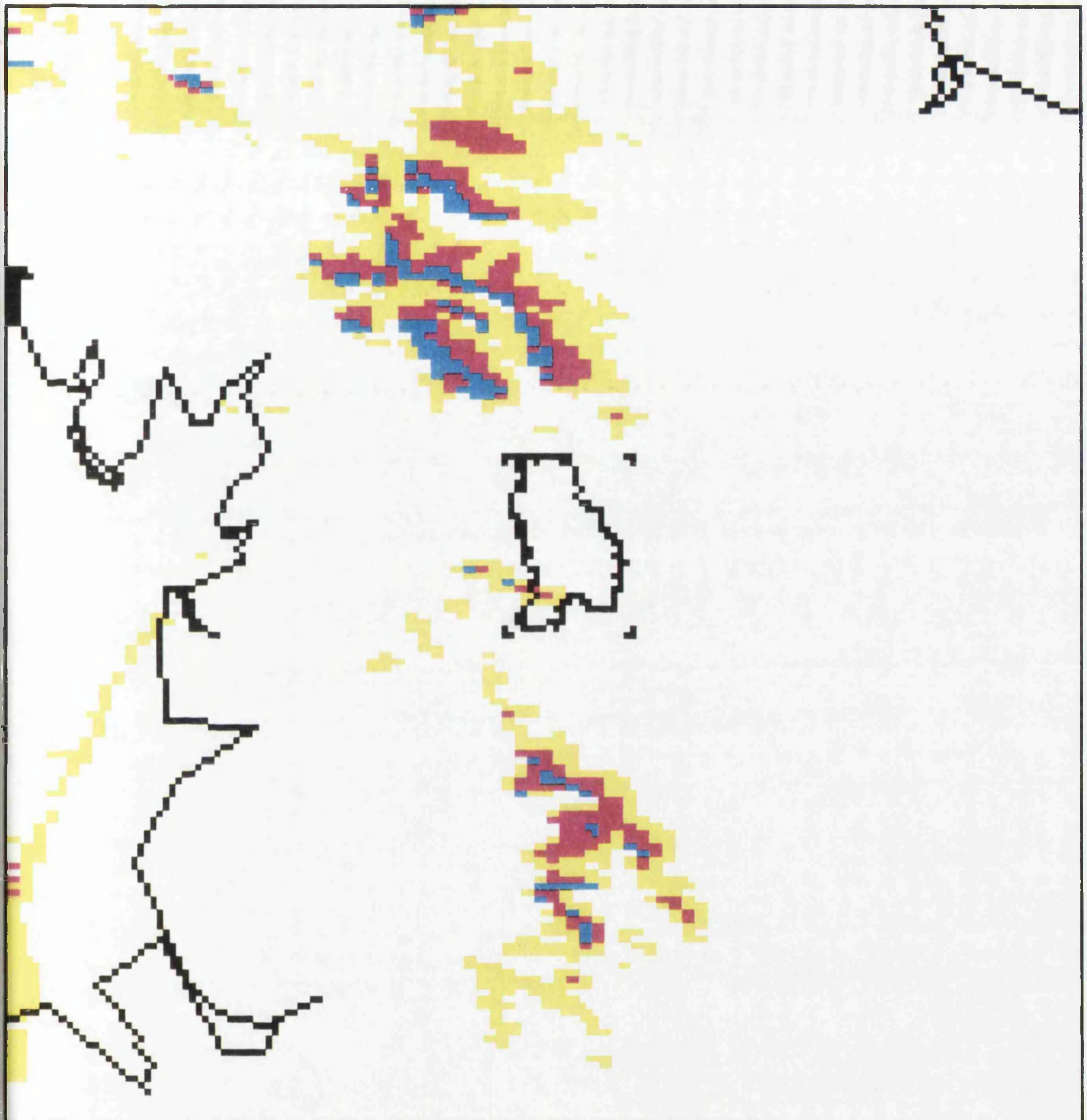


Image 8.13 A zoomed image on the north of England for day 26.

could be an indication of the degree of hardness of the snow, where the yellow class is the softest class, blue is harder and the red pixels are of those hardest of them. The north and the south west corner of the basin have the highest altitudes. the north of the basin is covered by snow for days 24, and 25, corresponding images 8.7 and 8.10, while the south west of the basin is covered with snow for day 26, Image 8.13. These result confirm the correlation of the snow classes with height a well known phenomenon.

| DAY | Number of classes |
|---|---|
| 24 | 29 |
| 25 | 49 |
| 26 | 28 |

Table 8.8 Number of classes for each day.

| DAY | CLASSES | COUNT |
|---|---|---|
| 24 | 6 | 5 |
| 24 | 8 | 78 |
| 24 | 12 | 8 |
| 24 | 13 | 19 |
| 24 | 20 | 37 |
| 24 | 28 | 361 |
| 24 | 29 | 32 |
| 25 | 13 | 55 |
| 25 | 14 | 72 |
| 25 | 21 | 2 |
| 25 | 22 | 64 |
| 25 | 23 | 49 |
| 25 | 30 | 228 |
| 25 | 32 | 27 |
| 25 | 47 | 1 |
| 25 | 49 | 42 |
| 26 | 3 | 6 |
| 26 | 5 | 83 |
| 26 | 6 | 418 |
| 26 | 15 | 24 |
| 26 | 18 | 7 |

| | | |
|---|---|---|
| 26 | 24 | 2 |

Table 8.9 Classes occurring the the basin image.

Table 8.8 present the number of classes for each of the days. The classes occurring in the 20 X 27 subimage of the basin are presented in Table 8.9. This Table also provides an account of the occurrence of each of the classes in the basin image.

The snow classes occurring in the basin image are presented in Table 8.10.

| DAY | SNOW-CLASSES | COUNT |
|---|---|---|
| 24 | 0 | 406 |
| 24 | 8 | 78 |
| 24 | 13 | 19 |
| 24 | 20 | 37 |
| 25 | 0 | 353 |
| 25 | 14 | 72 |
| 25 | 21 | 2 |
| 25 | 22 | 64 |
| 25 | 23 | 49 |
| 26 | 0 | 507 |
| 26 | 15 | 24 |
| 26 | 18 | 7 |
| 26 | 24 | 2 |

Table 8.10 Snow classes occurring in the basin image.
The Zero values refer to non snow classes.

The snow mapping for the Aire basin was done independently, but following the same procedure of classifications, by two researchers. The first one performed by Mr. Richard Lucas of the Department of Geography in Bristol University (BU), the second was undertaken in this thesis. The results of the BU mapping are presented in Table 8.11 while the mapping done in this thesis research work, at University College London (UCL), are presented in Table 8.12.

| DAY | ELEVATION ZONE | AREA OF ELEVATION ZONE | SNOW AREA | TOTAL SNOW AREA |
|---|---|---|---|---|
| 24 | <600 | 146 | 0 | |
| 24 | 600-800 | 49 | 1 | |
| 24 | 800-1000 | 40 | 6 | |
| 24 | 1000-1400 | 35 | 32 | |
| 24 | 1400-2000 | 16 | 13 | 52 |
| 25 | <600 | 146 | 0 | |
| 25 | 600-800 | 49 | 12 | |
| 25 | 800-1000 | 40 | 14 | |
| 25 | 1000-1400 | 35 | 33 | |
| 25 | 1000-2000 | 16 | 16 | 76 |
| 26 | <600 | 146 | 0 | |
| 26 | 600-800 | 49 | 13 | |
| 26 | 800-1000 | 40 | 17 | |
| 26 | 1000-1400 | 35 | 22 | |
| 26 | 1400-2000 | 16 | 8 | 61 |

Table 8.11 Snow mapping results, for the basin of the river Aire, as processed in Bristol University.

| DAY | ELEVATION ZONE | TOTAL AREA | SNOW AREA | TOTAL SNOW AREA |
|---|---|---|---|---|
| 24 | 900-1000 | 155 | 1 | |
| 24 | 1000-1400 | 122 | 41 | |
| 24 | 1400-1600 | 11 | 9 | 51 |
| 25 | 900-1000 | 155 | 6 | |
| 25 | 1000-1400 | 122 | 57 | |
| 25 | 1400-1600 | 11 | 11 | 74 |
| 26 | 900-1000 | 155 | 11 | |
| 26 | 1000-1400 | 122 | 9 | |
| 26 | 1000-1600 | 11 | 0 | 20 |

Table 8.12 Snow mapping results as processed in University College London.

The two tables have different elevation zones and areas. This resulted from the different tools used by the two researchers. The

BU researcher used an elevation map of England when calculating the elevation zones which resulted in a the inclusion of zone areas not found in the Basin. His map has coarse elevation zones which are not very accurate. Whereas the research carried at UCL was done using the detailed elevation map of the Aire basin.

Discrepancies might occur between individual researchers using even the same tools. This is due to three factors:

1- The warping of the 512 X 512 is dependent on the generated control file which might vary between different users.

2- The options used in the classification function on the I2S are up to the individual user. Any differences in the options will produce differences in the number of classes and what they represent.

3- The identification of the snow classes is left to the individual user. If a researcher identified a class as a snow class while the other did not the two results will vary considerably.

The results of the BU and UCL mapping agree remarkably well for day 24 and day 25. For day 26 they differ considerably. A most likely cause suspected is the misinterpretation of a class. This possibility has been explored here and found that the initial interpretation was correct as it was not possible to identify any other class as a snow class.

A check on the classes in the Aire basin image was done. The result is in Table 8.13. This Table presents the different classes and their corresponding temperatures as measured by the satellite. Table 8.14 is a derivative of Table 8.11. In this Table the non snow classes are labelled ZERO in order to reduce the over flow of information and facilitate the identification of the snow classes and their corresponding temperatures.

| DAY | CLASSES | TEMPER-ATURE | COUNT |
|---|---|---|---|
| 24 | 6 | 0 | 3 |
| 24 | 6 | 1 | 1 |
| 24 | 6 | 2 | 1 |
| 24 | 8 | -1 | 1 |
| 24 | 8 | 0 | 53 |
| 24 | 8 | 1 | 12 |
| 24 | 8 | 2 | 12 |
| 24 | 12 | 0 | 3 |
| 24 | 12 | 1 | 2 |
| 24 | 12 | 2 | 3 |
| 24 | 13 | 0 | 15 |
| 24 | 13 | 1 | 4 |
| 24 | 20 | -1 | 2 |
| 24 | 20 | 0 | 22 |
| 24 | 20 | 1 | 9 |
| 24 | 20 | 2 | 4 |
| 24 | 28 | 0 | 26 |
| 24 | 28 | 1 | 67 |
| 24 | 28 | 2 | 171 |
| 24 | 28 | 3 | 97 |
| 24 | 29 | 0 | 3 |
| 24 | 29 | 1 | 7 |
| 24 | 29 | 2 | 20 |
| 24 | 29 | 3 | 2 |
| 25 | 13 | 3 | 52 |
| 25 | 13 | 4 | 3 |
| 25 | 14 | 0 | 20 |
| 25 | 14 | 1 | 32 |
| 25 | 14 | 2 | 20 |
| 25 | 21 | 0 | 2 |
| 25 | 22 | -2 | 7 |
| 25 | 22 | -1 | 6 |
| 25 | 22 | 0 | 43 |
| 25 | 22 | 1 | 8 |
| 25 | 23 | -2 | 6 |
| 25 | 23 | -1 | 11 |
| 25 | 23 | 0 | 32 |
| 25 | 30 | 0 | 2 |
| 25 | 30 | 1 | 5 |
| 25 | 30 | 2 | 108 |
| 25 | 30 | 3 | 113 |
| 25 | 32 | 2 | 18 |
| 25 | 32 | 3 | 9 |
| 25 | 47 | 4 | 1 |
| 25 | 49 | 2 | 3 |
| 25 | 49 | 3 | 39 |

| | | | |
|---|---|---|---|
| 26 | 3 | 4 | 6 |
| 26 | 5 | 3 | 71 |
| 26 | 5 | 4 | 12 |
| 26 | 6 | 1 | 6 |
| 26 | 6 | 2 | 157 |
| 26 | 6 | 3 | 253 |
| 26 | 6 | 4 | 2 |
| 26 | 15 | 1 | 14 |
| 26 | 15 | 2 | 10 |
| 26 | 18 | 1 | 7 |
| 26 | 24 | 1 | 2 |

Table 8.13 Classes occurring in the image basin and their corresponding temperatures.

Table 8.14 indicate that the non snow classes, for the three days have temperatures of Zero and above. The pixels classed as non snow and having a temperature of zero are small in number and only occur for day 24 and day 25. For day 25 just two pixels are non snow and of temperature zero. For day 24 this category was comprised of 35 pixels. These mainly occur in the lower elevation indicating non snow status.

For day 26 any of the classes that might not have been identified as snow have temperature values greater than zero reaffirming the results of the research carried in UCL.

| DAY | SNOW-CLASS | TEMPER-ATURE | COUNT |
|---|---|---|---|
| 24 | 0 | 0 | 35 |
| 24 | 0 | 1 | 77 |
| 24 | 0 | 2 | 195 |
| 24 | 0 | 3 | 99 |
| 24 | 8 | -1 | 1 |
| 24 | 8 | 0 | 53 |
| 24 | 8 | 1 | 12 |
| 24 | 8 | 2 | 12 |
| 24 | 13 | 0 | 15 |
| 24 | 13 | 1 | 4 |
| 24 | 20 | -1 | 2 |
| 24 | 20 | 0 | 22 |
| 24 | 20 | 1 | 9 |
| 24 | 20 | 2 | 4 |
| 25 | 0 | 0 | 2 |
| 25 | 0 | 1 | 5 |
| 25 | 0 | 2 | 129 |
| 25 | 0 | 3 | 213 |
| 25 | 0 | 4 | 4 |
| 25 | 14 | 0 | 20 |
| 25 | 14 | 1 | 32 |
| 25 | 14 | 2 | 20 |
| 25 | 21 | 0 | 2 |
| 25 | 22 | -2 | 7 |
| 25 | 22 | -1 | 6 |
| 25 | 22 | 0 | 43 |
| 25 | 22 | 1 | 8 |
| 25 | 23 | -2 | 6 |
| 25 | 23 | -1 | 11 |
| 25 | 23 | 0 | 32 |
| 26 | 0 | 1 | 6 |
| 26 | 0 | 2 | 157 |
| 26 | 0 | 3 | 324 |
| 26 | 0 | 4 | 20 |
| 26 | 15 | 1 | 14 |
| 26 | 15 | 2 | 10 |
| 26 | 18 | 1 | 7 |
| 26 | 24 | 1 | 2 |

Table 8.14 Snow classes and non snow classes and their corresponding temperatures.

## 8.6 Hydrologic Modelling.

The hydrologic modelling was carried on using SRM. The modelling period was for the days where data was available i.e. between day 24 and day 29 of January. The program was run using the output of the program ASSEMBLE, the file was named SRMORA.DAT. The data incorporated in this file are mainly from remote sensing sources if remote sensing data was not available for a certain day conventional data was used (See Section 6.9). This file needed a small amount of editing to prepare before use by SRM. The editing involved the insertion of information, not included in the database, needed for running SRM and not accrued by ASSEMBLE. These data were the basin data and operational data as defined by SRM (See Chapter Five). The available data was used. Some data was assumed using the recommendations of the SRM manual. These data are in particular the following :

1 - the runoff coefficient of snow.
2 - the runoff coefficient of rain.
3 - the degree days factors.
4 - the adjustment for temperature lapse rate.

Little editing was needed for SRMORA.DAT. However, great care should be exercised when performing this function. The omission of one back slash symbol from the data, omitted from edited data, in the data file resulted in the crashing of the SRM program run. One day was spent in debugging the run of the program before the error was located.

Having prepared the data file, where the data was primarily from remote sensing sources and complemented with conventional data, for SRM it was run.

The manual of SRM states that the model can be run, in forecasting mode, for periods of duration ranging between one day and several weeks. It was assumed that this is also the case for the simulation mode, as this point was not very clear in the documentation of the manual. However, running the program for a period of six days it was apparent that the minimum running period for SRM in simulation mode is one month. This resulted in the computed flow being assigned to the beginning of the month rather than the first day of the actual data, day 24. The results of this run are represented in Table 8.15 denoted by @1.

The program was run again on the same data file which was edited to present the data as starting in the beginning of the month of January. The results of this run are presented in Table 8.15 denoted @2. Comparing the flows of @1 and @2 result in deducing that @1 produced approximately the same results of @2. The only difference between the two runs is the location of the actual data.

SRM was run using conventional data without information from remote sensing data except for the data of snow mapping (snow mapping is not available from any other means). The resultant flow is presented in Table 8.15 denoted @ 3.

The complete results, out of each run of SRM, of these runs are presented in Appendix 4. While the computed and the actual flow volumes are presented in Table 8.15.

It is clearly seen in this Table that the computed flow is very similar to that of actual volumes of flow for the three runs.

| | RUNOFF REFFERING TO ACTUAL DAY REMOTE SENSING DATA & CONVENTIONAL @1 | | RUNOFF USED AT START OF MONTH REMOTE SENSING & CONVENTIONAL DATA @2 | | RUNOFF USED AT START OF MONTH ONLY CONVENTIONAL DATA USED @3 | |
|---|---|---|---|---|---|---|
| JAN-UARY | COMPU-TED | ACTUAL | COMPU-TED | ACTUAL | COMPU-TED | ACTUAL |
| 1 | 14.154 | 0.000 | 14.154 | 15.070 | 14.154 | 15.070 |
| 2 | 10.457 | 0.000 | 10.457 | 9.430 | 10.457 | 9.430 |
| 3 | 7.886 | 0.000 | 7.889 | 7.692 | 7.886 | 7.692 |
| 4 | 6.062 | 0.000 | 6.073 | 7.335 | 6.062 | 7.335 |
| 5 | 4.743 | 0.000 | 4.751 | 6.613 | 4.743 | 6.613 |
| 6 | 3.773 | 0.000 | 3.779 | 8.603 | 3.773 | 8.603 |
| 7 | 3.049 | 0.000 | 3.053 | 0.000 | 3.049 | 0.000 |
| 8 | 2.499 | 0.000 | 2.503 | 0.000 | 2.499 | 0.000 |
| 9 | 2.077 | 0.000 | 2.079 | 0.000 | 2.077 | 0.000 |
| 10 | 1.747 | 0.000 | 1.749 | 0.000 | 1.747 | 0.000 |
| 11 | 1.487 | 0.000 | 1.489 | 0.000 | 1.487 | 0.000 |
| 12 | 1.280 | 0.000 | 1.281 | 0.000 | 1.280 | 0.000 |
| 13 | 1.113 | 0.000 | 1.114 | 0.000 | 1.113 | 0.000 |
| 14 | 0.976 | 0.000 | 0.977 | 0.000 | 0.976 | 0.000 |
| 15 | 0.865 | 0.000 | 0.865 | 0.000 | 0.865 | 0.000 |
| 16 | 0.772 | 0.000 | 0.772 | 0.000 | 0.772 | 0.000 |
| 17 | 0.694 | 0.000 | 0.695 | 0.000 | 0.694 | 0.000 |
| 18 | 0.629 | 0.000 | 0.630 | 0.000 | 0.629 | 0.000 |
| 19 | 0.574 | 0.000 | 0.574 | 0.000 | 0.574 | 0.000 |
| 20 | 0.527 | 0.000 | 0.527 | 0.000 | 0.527 | 0.000 |
| 21 | 0.486 | 0.000 | 0.487 | 0.000 | 0.486 | 0.000 |
| 22 | 0.451 | 0.000 | 0.452 | 0.000 | 0.451 | 0.000 |
| 23 | 0.421 | 0.000 | 0.421 | 0.000 | 0.421 | 0.000 |
| 24 | 0.395 | 15.070 | 0.395 | 0.000 | 0.395 | 0.000 |
| 25 | 0.372 | 9.430 | 0.372 | 0.000 | 0.372 | 0.000 |
| 26 | 0.351 | 7.692 | 0.351 | 0.000 | 0.351 | 0.000 |
| 27 | 0.334 | 7.335 | 0.333 | 0.000 | 0.333 | 0.000 |
| 28 | 0.318 | 6.613 | 0.318 | 0.000 | 0.317 | 0.000 |
| 29 | 0.304 | 8.603 | 0.303 | 0.000 | 0.303 | 0.000 |
| 30 | 0.291 | 0.000 | 0.291 | 0.000 | 0.291 | 0.000 |
| 31 | 0.280 | 0.000 | 0.279 | 0.000 | 0.279 | 0.000 |

Table 8.15 Computed and actual flow volumes for the simulation period. Three cases of modelling incorporated.

SRM calculates, for each run, the Nash-Sutcliffe coefficient $R^2$. This is a non-dimensional value, a goodness-of-fit measure, that is a direct measure of the performance of the simulation. A listing of the calculations of this coefficient for the three runs are presented in Table 8.16. Along side the total and mean volume flows for both computed and actual flows.

| | TOTAL ACTUAL VOLUME | MEAN ACTUAL VOLUME | TOTAL COMPUTED VOLUME | MEAN COMPUTED VOLUME | GOODNESS OF FIT MEASURE |
|---|---|---|---|---|---|
| RUNOFF REFFERING TO ACTUAL DAY REMOTE SENSING & CONVENTIONAL DATA @1 | 54.743 | 7.8204 | 69.3662 | 9.9095 | 0.3768 |
| RUNOFF USED AT START OF MONTH REMOTE SENSING & CONVENTIONAL DATA @2 | 54.7430 | 7.8204 | 69.4141 | 9.9163 | 0.9599 |
| RUNOFF USED AT START OF MONTH ONLY CONVENTIONAL DATA USED @3 | 54.7430 | 7.8204 | 69.3641 | 9.9092 | 0.9599 |

Table 8.16 Total and mean of both Computed and Actual flow volumes and Goodness of fit measure for the three cases.

The goodness of fit for the first run is greatly affected by the shift, in the days, between the actual and computed flows. It is, i.e. the goodness of fit measure, improved when the data is run with the date synchronised between the computed and the actual data. The Nash-Sutcliffe coefficient measures the daily variance of the recorded flows. The shift between actual and computed flow in @1 results in a large daily difference hence the adverse effect on the goodness of fit measure.

Although the computed flow varies for @2 and @3 the Nash-Sutcliffe coefficient is the same for the last two runs at 0.9599. These results are extremely good and were totally unexpected as the data was run for just six days and not for the whole month. The results of simulation provided by the SRM manual provide a goodness of fit measure of 0.902. This simulation was run for six months in which variations are more likely.

Baumgartner *et. al.* [1986] reported the use of SRM for the simulation of snow runoff for an alpine basin, the paper did not present the goodness of fit measure as the measured runoff is distorted by the presence of hydroelectric generation plants controlling the flow from the reservoir. The paper presented the percent seasonal difference, which is the percentage difference between computed and actual flows. It stood at 5.6 % while it was 4.1 % in the SRM manual. The percent seasonal difference of this project stood at 26 % for the three simulations. This is due to the fact that SRM produces estimates for the whole of the month of the simulation in accordance with natural processes where basins yield flow even without the existence of precipitation or snow. If the percent seasonal difference was compared with the six days of the simulation it is reduced to 14 %. This in turn is not a very good result, but is attributed to the shortness of the period.

## 8.7 Summary.

This chapter has presented the results of the different processes carried in this project. The results of the geometric correction carried for each of the images established the relevance of the derived parameter to the study area. The clear days were satisfactory while the results for cloudy days leaves something to be desired. Improvement in the process of correcting AVHRR imagery for cloud cover days is vital. This could be provided by the inclusion of automated methods geometric correction.

The precipitation method results were good in comparison with the actual precipitation occurring for the days of the project. The performance of this method over longer periods is viewed with apprehension.

The temperature estimates were good in general. The use of channel 4 as a sole provider of data for temperature estimates should emphasise the importance of careful study of remote sensing estimates.

A qualitative analysis of the accuracy of snow mapping results is hard to present as snow extent for that period is not available. The production of snow maps on daily basis without the help of remote sensing in general and AVHRR in particular is a daunting prospect. No other satellite can provide this utility for the time being. Baumgartner *et. al.* [1986] used Landsat-MSS data for the mapping of snow in their study and concluded that the use of AVHRR imagery should be investigated.

Careful consideration and attention is needed when accepting remote sensing estimations of the hydrological parameters. This statement should be viewed as a general comment on the results presented in this project and the results of any project utilising remote sensing.

The hydrologic modelling in this project relied on some empirical parameters. Some of these estimates may be derived using satellite information. This avenue should be investigated in future studies for incorporation in HyRSIS. The results presented were of dual indications, the goodness of fit measure was good while the variation between the computed and actual flow was high. These results can not be taken with a high degree of confidence without the extension of the modelling period to a complete season. At the end it should be noted that the amalgamation of the above processes and the methods provide for the first time a completely remote sensing approach to hydrological studies.

# Chapter Nine

## Conclusion and Future Implementations.

### 9.1 Introduction.

The proposal of the project set out in Chapter Three comprised of a global proposal and a definitive proposal. The measure of accomplishing the aims set out in for this thesis is established by comparing the result of the work done with the proposed project. The accomplished project has been represented in the last chapters.

The features of the accomplished project can be summarised as follows

1- A system that provides interactive remote sensing image processing facility for the user has been established.

2- This system incorporates all the programs needed, in a compatible set, for the processing of the remote sensing information to the hydrologic parameters according to the desired frequency and the attainable accuracy.

3- A help system was incorporated for the benefit of the users.

4- The system is versatile, allowing the user to move through different operating levels. A feature which allows access to the operating system level from access could be gained to other interactive systems, such as the ORACLE database.

5- The system contains all the necessary processes to operate on remote sensing images. The raw satellite imagery is processed in several stages to hydrological parameters. The processed information is then stored in a database. The last stage of the process is the retrieval of this information for use by the hydrology model.

6- The system caters for remote sensing data information as well as for conventional data.

7- It identifies errors during the different processing tasks reducing the time consumed by the user to identify and remedy his faulty actions.

This chapter will discuss and comment on HyRSIS and compare it with similar research projects. An overview of the possible use of it in operational circumstances will be provided. The potential applications of the system will be considered and recommendations for further development of the system will be provided. Comments on the results achieved in the case study will also be presented.

## 9.2 Realisation of HyRSIS

HyRSIS presents a compatible set of methods and procedures for tackling the problem of hydrological modelling. It sets the core foundation for a system that approaches the problem of integrating the information produced by remote sensing information in water resources studies.

The prospect of the integration of remote sensing data products with hydrologic modelling is not confined to this project. Groves *et al* [1984] reported the development and testing of a remote sensing based hydrological model. They used a geographic information system as a framework for the development of their model. The main source of their satellite data was Landsat which provided information about the physical conditions of the soil cover such as soil texture group, and land cover.

Price & Ragan [1986] reported on the development of a component of NASA's Pilot Land Data System to support hydrologic research in which they stated that a significant challenge resides in the development and implementation of a database system that can ingest, track and provide data in a "friendly", minimal-response-time fashion.

The importance of information systems is realised throughout the scientific community and organisations involved with the management of the resources. This also applies to water resources, Rennick [1986] reported on the implementation of a geographic system in the water resources in the United States Geographical Survey. He reported on the establishment of a distributed information system which connects the different computers of the the Water Resources Division of the geographical survey. The report also reflected on the problems of selecting a database that can integrate and maintain the already existing data sets in the different divisional offices. A database was selected and is under evaluation. No interest of the inclusion of remote sensing information in this system was reported. On the other hand Lemmella & Sucksdorff [1986] reported the introduction of an information system for water resources for the National Board of Waters in Finland. The system contains a central file of all data on water courses and drainage basins. It utilises geographic coordinates and basin numbers as coordinating entities. It also contains a digitised map of Finland along side physiographical factors derived from Landsat and SPOT. The paper envisages the the use of data from weather satellites in the mapping of snow and the derivation of temperature estimates for cloud free days. It could be easily realised that this part of the information system has been accomplished in this project.

A Geographic Information System Toolkit (GIST) for water resources and engineering applications was introduced by Beaumont et al. [1988]. GIST uses various data input sources from satellite imagery, digitised aerial photographs to non-spatial data, as gauging stations. It uses an ORACLE database as a storage medium. This system was also built in a modular format. It communicate with other software packages. The primary usage of this system was for integration and handling of the conventional and remote sensing applications. The system has been used for the land mapping and developing a spatial description of the study areas on a geographic referenced basis. GIST has been used in conjunction with other software packages for geotechnical, highway and water resources applications especially in developing countries where mapping facilities are poor. The water resources applications of GIST concentrates on relating ground water resources to the physiographic characteristics of the region. What is interesting about this system is that is was built on the same design philosophy as the work carried in this project. The similarity of the two systems are shown in the following quotation from the conclusion of this paper describing GIST, "A flexible, modular approach to the design of the software and carefully defined interfaces with specialist hardware make full use of existing facilities and will also allow the system to exploit the potential of current and future development in computer technology.''. GIST and HyRSIS were developed independently, however, they both complement each other. GIST presents a powerful tool for the ground mapping applications while HyRSIS provide the hydrological parameters production aspect which is missing from GIST. When realising that GIST was built with the support of two civil engineering companies Scott Wilson Kirkpatrick & partners, and Wimpey Laboratories Limited the effort that went into the attainment of HyRSIS can be appreciated.

As late as 1989 Flach *et al* [1989] describe and discuss a model for a river basin information system for developing countries. They propose a system for the collection and management of remote sensing data that deals with different aspects of water resources. The details of their proposal strike a great likeness to the global proposal presented in Chapter Three of this thesis with special attention to the case of developing countries.

This project presents a precedence in applying the proposed integration of remote sensing information into hydrological modelling in the context of an information system, i.e. database management and storage of data. The work of this project could be used as a core to build on to achieve the global proposal and to extend it to cater for all aspects of operation of a water resources system. On the other hand it could be amalgamated with another system such as GIST as the two systems provide complementary functions.

Remote sensing information has been used with hydrological parameters. Baumgartner *et. al.*[1986], amongst others reported the use of remotely sensed snow cover in hydrologic modelling, using SRM as the hydrological model, with the rest of the data temperature and precipitation coming from conventional sources. Other applications reported in the literature on the use of remotely sensed precipitation data in hydrologic modelling is only restricted to that parameter with the other hydrological parameters produced by conventional means.

This project, for the first time, presents a hydrological modelling with information constituted, in general, from remote sensing sources with minimal information coming from ground gauges. The project also presents a comparison between the results realised through the exclusive use of remote sensing information supplemented by gauged information and those achieved from conventional data complemented with remote sensing of snow cover.

The incorporation of a database in any system provides a facility to view and study data in a way that was not possible before. The different tables incorporated in Chapter Eight were only possible because of the use of a relational database. As the analysis of the data went under way, new questions arose. Answering these questions would have not been possible without a database. For example when analysing the differences that occurred in snow mapping between the work carried in Bristol University and that carried in this thesis a comparison of the temperatures of the different classes in the basin image would have shed some light on the correlation between the classes and their corresponding temperatures. The huge amount of data, 540 pixels X 29 classified classes X 6 temperature classes per day, would have made answering this question extremely difficult, three days could be managed with difficulty manually, longer periods will be viewed to say the least with discomfort. While all it needed was a good understanding of SQL in order to issue the appropriate commands to retrieve the data in the desired format (consult Table 8.13 and Table 8.14 for the result of this query). The intelligent use of a database, as demonstrate in this thesis, shows relationships that were not easily available before.

## 9.3 Critical assessment of HyRSIS.

The production of this project went through various stages and suffered constraints which restrained the wider application of the project and affected some of the interaction phases of the project. This section will cast a critical look on this study and discuss the aspect of research that is of interest that could be pursued within the scope of a study of this kind.

The main program which acts as a driver for the different programs and provides an interactive interface between HyRSIS and the user is limited in two aspects. The first being the limited use of the communication phrases between the user and the programs. The user has to follow a certain code while accessing programs and moving between different modules of the system. This code is composed of an imposed abbreviation of the names or commands used in the system. This encroachment might impose and reflect an image of an ''unfriendly'' system. However, the restrictions were necessary in order to limit programming effort to a minimum, on non vital features of the system. This could be remedied by a straight forward expansion of the vocabulary of in the programming of the main module.

The second unsatisfactory aspect of this program is the limited application of the main module. The main module is limited in its interaction with the programs and modules incorporated in it. The introduction of the new methods and programs that are not already included in the program necessitates the expansion of the main program by adding new lines of programming. It would be desirable to have a program that can call the modules by identifying them by name as in the $I^2S$ system, where the inclusion of new programs will not require a change in the programming of the main driver. This is especially needed in case the system is to grow to become a large system dedicated for the processing and management of remotely sensed hydrological parameters.

The production of the different hydrological parameters was done through the use of different methods. The acquisition and establishment of these methods in a working order consumed a lot of work and effort that could have been spent on the management of the data collected and stored in the database. The collection of data in a database needs optimisation, an aspect that needs more attention in HyRSIS. The expansion and future use of the database in an efficient way is an important attribute that needs a theoretical and an operational study. The above features need to be investigated along side with the use of Geographic Information Systems (GIS).

## 9.4 Operational use of HyRSIS.

During the process of building HyRSIS the idea of operational use was pondered upon. HyRSIS was built with the specific purpose of using a hydrological model, that is, simulating an hydrological process of a basin. If an organisation was to incorporate such a system, that deals with extensive areas rather than a defined relatively small area, some of the processes would need rearranging. It would be more realistic and cost effective to process a geometrically corrected image, or the raw image which then could be national grid referenced, of the land under their dominion, then load the produced hydrological parameters to a database. The individual modellers, for any basin and any model, will then be able to extract the relevant information from the database.

An organisation which is dedicated for the production of an extensive system dealing with every aspect of the water system might require a much more complicated system. However the research of this project should point the way for the future development of such a system.

## 9.5 The way forward.

The realisation of this project necessitated the incorporation of a wide range of programs. The collection of these programs required a great deal of time and effort. This process underlined the need to compile a library of programs that deal with the processing of remote sensing information which is exclusively dedicated to water resources studies. This project has compiled a good many such programs. The HyRSIS library needs to be complemented with several methods which deal with some aspects of the hydrological process which has not been tackled in this project. These processes include the use of satellite imagery for the classification of land cover and, estimation of runoff coefficients, land saturation, and the incorporation of methods that deal with fast changing conditions, i.e. rain storms for flood warnings.

The incorporation of digital terrain models in the system will be of great advantage for the operational management of water resources authorities. An automated generation of this data such as that carried on in the Department of Photogrammetry and Surveying coupled with animated visualisation of the terrain will introduce a powerful tool, which was not available before, for the study and assessment of the ecological impact of the management decisions on the study area.

Natural disasters and man-made projects produce direct effects on the environment. Water bodies are a major part of the natural environment, lakes, rivers, creeks, marshes, and swamps. These features are directly related to the physiographic conditions of the environment. Changes, whether natural or man made, could be simulated, incorporated and superimposed on the digital terrain model. These could be simulated and then projected in a graphical animated fashion. Thus providing a unique way of investigating future events allowing for the establishment of alternative choices or contingency plans.

HyRSIS was built in a modular format. Any program that became out dated and a new version that had modifications and improvements carried on it could be replaced at will without having to disturb or carry a major change on the whole system. This is due to the fact that the system incorporated a library of programs. The extension of HyRSIS to cater for every aspect of hydrological information should be relatively easy with the use of the relational database. The incorporation of new data can be done through the inclusion of new tables in the database. Relations could be established between the different tables through the use of the national grid reference coordinates.

HyRSIS was built using the available VAX/ VMS operating system features. The help system, programs object library, and error handling facility, all are the product of the features of the VAX/VMS system as provided to FORTRAN 77 programs.

The portability of HyRSIS is thus dependent on the operating system it is working under. The way HyRSIS is built makes it only compatible with VAX/VMS systems, however, this system is widely available in commercial and scientific quarters. Though, the development of HyRSIS to become independent of the operating system would introduce a desirable feature. The UNIX operating system is the most likely candidate to house HyRSIS for such a development as it was envisaged as a system that provided program development independent of the operating system.

Another feature that is desirable in these days is the user friendliness of the system. HyRSIS, as it stands now, is rather restrictive. The formatting of the system to present the user with a working environment of pull down menus and screen-mouse interaction, in a graphical manner, on the lines of the Macintosh philosophy would be convenient. The above recommendations point the finger towards Sun workstations.

A new operating system, the Mach, has been launched in the United States of America, late 1987, and is being launched in the U.K.. This system is being launched with the NeXT workstation, but it could be run on most DEC VAX processors, Sun 3 workstations, some IBM and a range of PCs. [Neesham 1990]

## 9.6 Conclusion.

The system described in this thesis accomplishes the stipulated definitive proposal introduced in Chapter Three. The incorporation of a database as a storage medium for the derived information coupled with the programming of the retrieval process extends the role of the system from catering for the requirements of a particular hydrological model to any model that requires hydrological data input. The only function needed for this extension is the incorporation of the new hydrologic program in the process coupled with a program dedicated for retrieving the required data from the database. Thus it falls short of delivering the global model. On the other hand it is well ahead of the proposed project.

The production of the global proposal was not feasible because, as explained in Chapter Three, of the understandable restrictions imposed on this work such as time, man power, and a supporting organisation dedicated for this type of work.

One aspect of the system, on the negative side, which calls for consideration is the problem of extracting the basin image for rainy days. The process presented in this thesis was conducted and presented on a makeshift basis. While these makeshift foundations are not suitable it should be remembered that the prime purpose of it was the incorporation of the precipitation estimates in the overall process. The incorporation of a system that can extract the pixel data of the intended area was not feasible as funds for the purchase of the program facilitating this process were not available. However if HyRSIS was to be used in an operational condition the incorporation of this program will be of utmost importance.

On the other hand the results produced in processing the remote sensing images and the hydrological modelling were satisfying. The image processing programs produced excellent results. The hydrologic modelling produced results far better than expected with goodness of fit measure nearing 0.9566. The slight improvement in the hydrological modelling results achieved by using remote sensing derived parameters may not justify the trouble introduced by using them. This is attributed to the fact that the hydrologic model could not make use of this information. However, the physical situation of the basin is much more understood and quantified using remote sensing information. This could be clearly seen by comparing the images of the basin in which the snow classes mapped with the information supplied by the individual hydrologists. (See remarks on sheets of accumulated snow measurements supplied by the Yorkshire Water Authority Appendix 3) The combination of the two sources of information provide a complete picture of the snow situation on the ground.

The coupling of temperature estimates with snow mapping, although not fully utilised by SRM, could be of great use in future development of hydrological models.

It remains to be seen if the high quality of the results could be sustained if the image processing, and hydrologic period was to be extended for a long period. Although there is no evidence that could suggest the contrary. The only serious source of errors could be from the use of the PERMIT method for daily precipitation. As this method will not be able to identify heavy rain situations. It is left to the user to identify those days and introduce a compensating function. However, even if this action was not taken, the PERMIT method will average the precipitation estimates over the modelling period limiting the effect of this error.

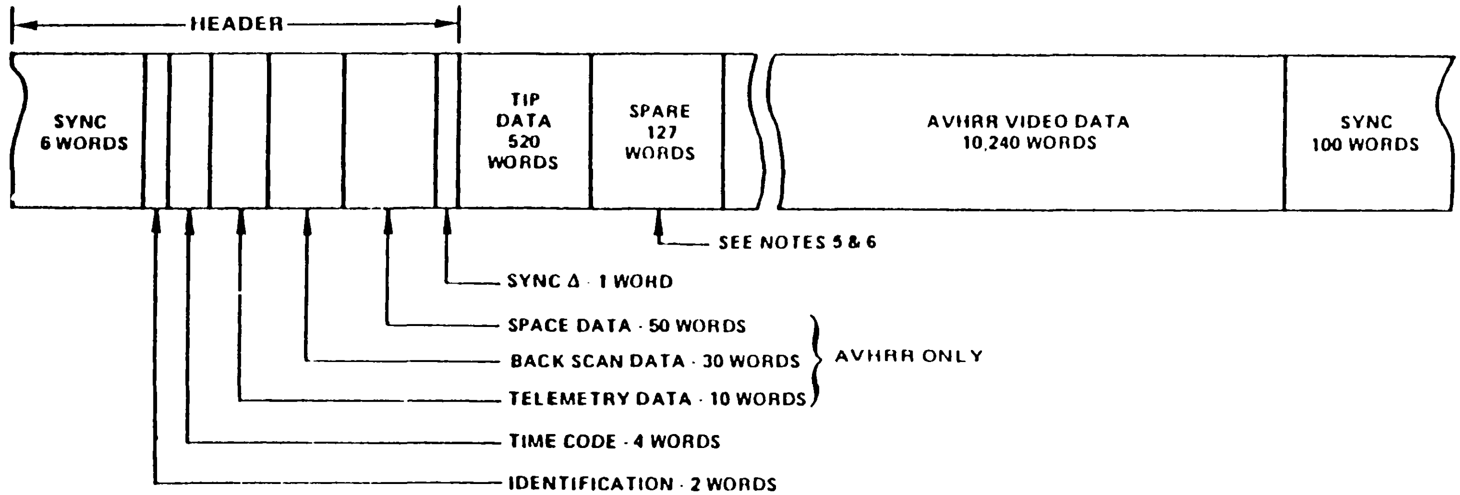
This project fills an important niche in the field of remote sensing of hydrological parameters. It introduces for the first time a much talked about system for the utilisation of remote sensing generated data. A system which generates the data from raw imagery, stores and manage these data, along side conventional data, and finally utilises this data. The usage of the data in an integrated way catering for several parameters derived from remote sensing techniques rather than just one parameter, as has been usual up till now.

As a final conclusion it could be said that the aims of this project have been fully accomplished.

# Appendix 1

This appendix contains the description of an AVHRR image format as send by the receiving station to the different users.The first page presents a general idea of the progression of the registered data on the CCT. A details description of the data then follows.

The data is composed of two sections, a header and the image which is referred to as AVHRR video data. The header is composed of 103 words. The telemetry data are located between word 13 and 22. The Internal target information are positioned between word 23 and 52. Words 53 to 102 contain the space data. The above data is generated by the scanner module for each scan line. The three sets of data are used for calculating the calibration coefficients.




NOTES:

(1) MINOR FRAME LENGTH · 11,090 WORDS
(2) THREE MINOR FRAMES PER MAJOR FRAME
(3) MINOR FRAME RATE · 6 FRAMES/SECOND
(4) WORD LENGTH · 10 BITS/WORD
(5) ALL SPARES ARE 10TH DEGREE P-N CODE (BAR).

| TLM WORD ALLOCATIONS | | ID WORD BIT ALLOCATIONS | | |
|---|---|---|---|---|
| | | 1ST ID WORD | | 2ND ID WORD |
| 1-5 | RAMP CALIBRATION | 1 | SYNC ID | (SPARE) |
| 6 | CHANNEL-3 TARGET TEMP (5 PT SUBCOM) | 2-3 | FRAME ID | |
| 7 | CHANNEL-4 TARGET TEMP (5 PT SUBCOM) | 4-7 | SPACECRAFT ADDRESS | |
| 8 | CHANNEL-5 TARGET TEMP (5 PT SUBCOM) | 8 | RESYNC MARKER | |
| 9 | CHANNEL-3 PATCH TEMP | 9 | DATA 0 | |
| 10 | SPARE | 10 | DATA 1 | |

TIROS-N/NOAA HRPT minor frame format

HRPT minor frame format

| | Function | No. of Words | Word Position | Bit No. 1 2 3 4 5 6 7 8 9 10 | Plus word code & meaning |
|---|---|---|---|---|---|
| HEADER | Frame sync | 6 | 1 | 1 0 1 0 0 0 0 1 0 0 | First 60 bits from a 63-bit PN(1) generator started in the all 1's state. The generator polynominal is $X^6 + X^5 + X^2 + X + 1$ |
| | | | 2 | 0 1 0 1 1 0 1 1 1 1 | |
| | | | 3 | 1 1 0 1 0 1 1 1 0 0 | |
| | | | 4 | 0 1 1 0 0 1 1 1 0 1 | |
| | | | 5 | 1 0 0 0 0 0 1 1 1 1 | |
| | | | 6 | 0 0 1 0 0 1 0 1 0 1 | |
| | ID (AVHRR) | 2 | 7 | Bit 1; 0 = internal sync; 1 = AVHRR sync<br>Bits 2 & 3; 00 = not used; 01 = minor frame 1; 10 = minor frame 2, 11 = minor frame 3<br>Bits 4-7; spacecraft address; bit 4 = MSB, bit 7 = LSB<br>Bit 8; 0 = frame stable; 1 = frame resync occurred<br>Bits 9-10; spare; bit 9 = 0, bit 10 = 1 | |
| | | | 8 | Spare word; bit symbols undefined | |
| | Time code | 4 | 9 | Bits 1-9; binary day count; bit 1 = MSB; bit 9 = LSB<br>Bit 10; 0; spare | |
| | | | 10 | Bits 1-3; all 0's; spare 1, 0, 1<br>Bits 4-10; part of binary msec of day count; bit 4 = MSB of msec count | |
| | | | 11 | Bit 1-10; part of binary msec of day count; | |
| | | | 12 | Bit 1-10; remainder of binary msec of day count; bit 10 = LSB of msec count | |
| | Telemetry (AVHRR) | 10 | 13 | Ramp calibration AVHRR channel 1 | |
| | | | 14 | Ramp calibration AVHRR channel 2 | |
| | | | 15 | Ramp calibration AVHRR channel 3 | |
| | | | 16 | Ramp calibration AVHRR channel 4 | |

(1) PN = pseudo noise

continued

| | Function | No. of Words | Word Position | Bit No. 1 2 3 4 5 6 7 8 9 10 Plus Word Code & Meaning |
|---|---|---|---|---|
| HEADER | Telemetry (cont.) (AVHRR) | 10 | 17<br>18<br>19<br>20<br>21<br>22 | Ramp calibration AVHRR ch 5<br>AVHRR internal target[(2)] temperature data } Each of these words is a 5-ch subcom, 4 words of IR data plus a subcom referance value<br>AVHRR patch temperature<br>0 0 0 0 0 0 0 0 0 1 spare |
| | (AVHRR) Internal target data | 30 | 23 → 52 | 10 words of internal target data from each AVHRR ch 3, 4, and 5. These data are time multiplexed as ch 3 (word 1), ch 4 (word 1), ch 5 (word 1), ch 3 (word 2), ch 4 (word 2), ch 5 (word 2), etc. |
| | Space data (AVHRR) | 50 | 53 → 102 | 10 words of space-scan data from each AVHRR channel 1, 2, 3, 4, and 5. These data are time multiplexed as ch 1 (word 1), ch 2 (word 1), ch 3 (word 1), ch 4 (word 1), ch 5 (word 1), ch 1 (word 2), ch 2 (word 2), ch 3 (word 2), ch 4 (word 2), ch 5 (word 2), etc. |
| | Sync Δ (AVHRR) | 1 | 103 | Bit 1; 0 = AVHRR sync early; 1 = AVHRR sync late<br>Bits 2-10; 9-bit binary count of 0.9984-MHz periods; bit 2 = MSB, bit 10 = LSB |

(2) As measured by a platinum resistance thermometer embedded in the housing.

continued

| Function | No. of Words | Word Position | Bit No. 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Plus Word Code & Meaning |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Tip data | 520 | 104 → 623 | The 520 words contain five frames of TIP data (104 TIP data words/frame)<br>Bits 1-8: exact format as generated by TIP<br>Bit 9: even parity check over bits 1-8<br>Bit 10: - bit 1 | | | | | | | | | | |
| Spare words | 127 | 624 | 1 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | Derived by inverting the output of a 1023-bit PN sequence provided by a feedback shift register generating the polynominal: $X^{10} + X^5 + X^2 + X + 1$ The generator is started in the 1's state at the beginning of word 7 of each minor frame. |
| | | 625 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | |
| | | 626 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | |
| | | 627 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | |
| | | 628 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | 0 | |
| | | ↓ | | | | | | ↓ | | | | | |
| | | 748 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | |
| | | 749 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 0 | |
| | | 750 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |

continued

| Function | No. of Words | Word Position | Bit No. 1 2 3 4 5 6 7 8 9 10 | Plus Word Code & Meaning |
|---|---|---|---|---|
| Earth data (AVHRR) | 10,240 | 751 | Ch 1 - Sample 1 | Each minor frame contains the data obtained during one earth scan of the AVHRR sensor. The data from the five sensor channels of the AVHRR are time multiplexed as indicated |
| | | 752 | Ch 2 - Sample 1 | |
| | | 753 | Ch 3 - Sample 1 | |
| | | 754 | Ch 4 - Sample 1 | |
| | | 755 | Ch 5 - Sample 1 | |
| | | 756 | Ch 1 - Sample 2 | |
| | | ↓ | ↓ | |
| | | 10,985 | Ch 5 - Sample 2047 | |
| | | 10,986 | Ch 1 - Sample 2048 | |
| | | 10,987 | Ch 2 - Sample 2048 | |
| | | 10,988 | Ch 3 - Sample 2048 | |
| | | 10,989 | Ch 4 - Sample 2048 | |
| | | 10,990 | Ch 5 - Sample 2048 | |
| Auxiliary sync | 100 | 10,991 | 1 1 1 1 1 0 0 0 1 0 | Derived from the noninverted output of a 1023-bit PN sequence provided by a feedback shift register generating the polynominal: $X^{10} + X^5 + X^2 + X + 1$ The generator is started in the all 1's state at the beginning of word 10,991 |
| | | 10,992 | 1 1 1 1 1 1 0 0 1 1 | |
| | | 10,993 | 0 1 1 0 1 1 0 1 0 1 | |
| | | 10,994 | 1 0 1 0 1 1 1 1 0 1 | |
| | | ↓ | ↓ | |
| | | 11,089 | 0 1 1 1 1 1 0 0 0 0 | |
| | | 11,090 | 1 1 1 1 0 0 1 1 0 0 | |

| | |
|---|---|
| Type of transmitted signal | VHF, phase modulated, split phase 8320 bits per second |
| System output | |
| Frequency | 136.77 or 137.77 MHz |
| EIRP | +19.0 dBm worst case; +24 dBm nominal |
| Antenna | |
| Gain at 63° from nadir | -7.5 dBi, minimum[1] |
| Gain over 90% of sphere | - 18 dBi, minimum[1] |
| Polarization | Linear |
| Circuit Losses | 3.7 dB |
| Transmitter | |
| Power | 1.0 watt minimum |
| Modulation index | ±67.5 with a 7.5° tolerance |
| Premodulation filter, type | 7-pole linear phase filter |
| 3-dB bandwidth | 16 kHz minimum, 22 kHz maximum |
| Frequency stability | $+2 \times 10^{-5}$ |

[1]Observed by an optimum polarization diversity receiver.

Each TIP minor frame contains information identifying the major and minor frame count. The major frame counter is located in bits 4, 5, and 6 of TIP word 3 and cycles from 0 to 7. The minor frame counter is composed of 9 bits. MSB is bit 8 of word 4, and the LSB is bit 8 of word 5. The minor frame count will cycle between 0 and 319 for each major frame count.

A 40-bit time code is inserted into the TIP data stream once every 32 seconds.

These bits will be located in words 8 thru 12 of each minor frame 0. The format of this time code is as follows:

| | | |
|---|---|---|
| 9 bits day count | 0 1 0 1<br>4 spare bits | 27-bit milliseconds of day count |

| | |
|---|---|
| Major Frame | |
| Rate | 1 frame every 32 seconds |
| Number of minor frames | 320 per major frame |
| Minor frame | |
| Rate | 10 frames per second |
| Number of words | 104 |
| Format | See figure 6 |
| Word | |
| Rate | 1040 words per second |
| Number of bits | 8 |
| Order | Bit 1 = MSB<br>Bit 8 = LSB<br>Bit 1 transferred first |
| Bit | |
| Rate | 8320 bits per second |
| Format | Split phase |
| Data 1 definition |  |
| Data 0 definition | |

# Appendix 2

This appendix contains most of the Hydrological conventional data received from the Institute of Hydrology and Yorkshire Water Authority. The data not included in this appendix are the map depicting the basins perimeter, and the average precipitation over the basin as it was also provided on a map.

# AIRE AT KILDWICK BRIDGE

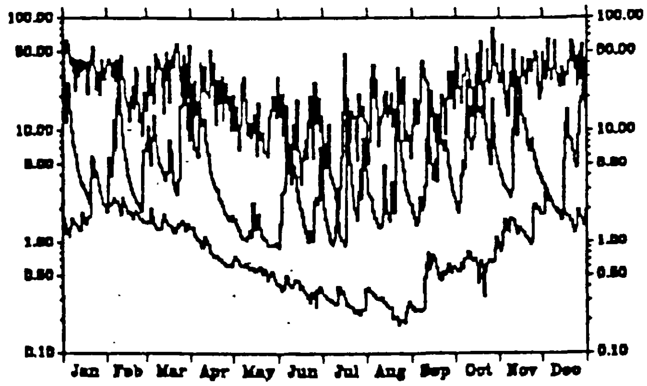
Station Number
027035

Gauged Flows
1968-1987

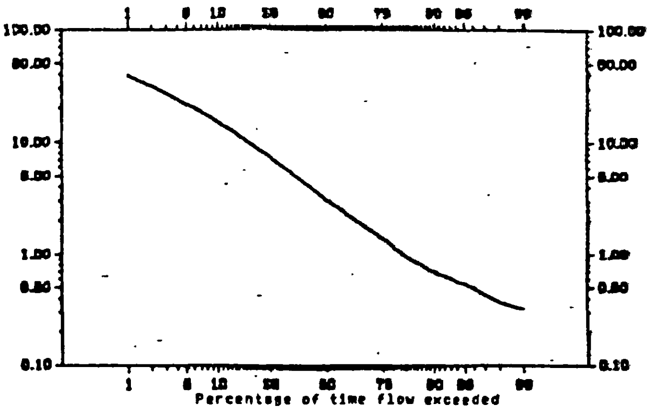
Measuring Authority: Yorkshire Water

Grid Reference: 44 (SE) 013 457

Daily Flow Hydrograph ($m^3s^{-1}$)
Max. and min. daily mean flows from 1968 to 1987 with an example yearly hydrograph (1987)




Flow Duration Curve ($m^3s^{-1}$)




## Flow Statistics

Units: $m^3s^{-1}$ unless otherwise stated

| | | |
|---|---|---|
| Mean flow | 6.13 | |
| Mean flow ($ls^{-1}/km^2$) | 21.73 | |
| Mean flow ($10^6m^3/yr$) | 193.6 | |
| Peak flow & date | 98.1 | 5 Dec 1972 |
| Highest daily mean & date | 79.9 | 27 Oct 1980 |
| Lowest daily mean & date | 0.180 | 23 Aug 1976 |
| 10 day minimum & end date | 0.201 | 28 Aug 1976 |
| 60 day minimum & end date | 0.388 | 10 Sep 1976 |
| 10 percentile | 15.6 | |
| 50 percentile | 3.1 | |
| 95 percentile | 0.5 | |
| Mean annual flood | 64.3 | |
| Bankfull flow | 77.00 | |

## Catchment Characteristics

| | |
|---|---|
| Catchment area ($km^2$) | 282.3 |
| Level stn. (mOD) | 87.30 |
| Max alt. (mOD) | 594 |
| IH Baseflow index | 0.37 |
| FSR slope (m/km) | 4.47 |
| 1941-70 rainfall (mm) | 1134 |
| FSR stream freq. (junctions/$km^2$) | 1.80 |
| FSR percentage urban | 0 |

## Factors Affecting Flow Regime

- Reservoir(s) in catchment.

## Rainfall and Runoff

| | Rainfall (mm) (1968-1987) | | | | | Runoff (mm) (1968-1987) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Max/Yr | | Min/Yr | | Mean | Max/Yr | | Min/Yr | |
| Jan | 120 | 222 | 1984 | 45 | 1987 | 102 | 176 | 1984 | 42 | 1973 |
| Feb | 71 | 139 | 1977 | 13 | 1986 | 67 | 117 | 1984 | 30 | 1986 |
| Mar | 104 | 233 | 1981 | 44 | 1975 | 72 | 214 | 1981 | 23 | 1985 |
| Apr | 70 | 135 | 1970 | 3 | 1980 | 47 | 105 | 1986 | 8 | 1974 |
| May | 75 | 142 | 1972 | 10 | 1970 | 29 | 78 | 1983 | .6 | 1974 |
| Jun | 78 | 155 | 1980 | 23 | 1976 | 22 | 59 | 1982 | 6 | 1970 |
| Jul | 74 | 151 | 1973 | 17 | 1982 | 16 | 56 | 1973 | 3 | 1984 |
| Aug | 93 | 171 | 1985 | 17 | 1976 | 29 | 108 | 1985 | 3 | 1976 |
| Sep | 111 | 250 | 1968 | 22 | 1986 | 35 | 95 | 1974 | 11 | 1971 |
| Oct | 114 | 213 | 1980 | 37 | 1969 | 68 | 167 | 1981 | 7 | 1972 |
| Nov | 130 | 187 | 1970 | 55 | 1983 | 96 | 152 | 1984 | 33 | 1975 |
| Dec | 124 | 238 | 1979 | 42 | 1971 | 103 | 198 | 1979 | 30 | 1971 |
| Annual | 1164 | 1347 | 1979 | 919 | 1971 | 685 | 900 | 1981 | 408 | 1971 |

## Station and Catchment Description

Velocity-area station rated by current meter cableway 150m downstream. Low flow control is the sills of the bridge. Mashland storage and headwater reservoirs influence the flow pattern.

Geology is mainly Carboniferous Limestone with some Millstone Grit series. Rural catchment draining part of the eastern Pennines.

## Summary of Archived Data

### Gauged Flows and Rainfall

Key:

| | All rainfall | Some or no rainfall |
|---|---|---|
| All daily, all peaks | A | a |
| All daily, some peaks | B | b |
| All daily, no peaks | C | c |
| Some daily, all peaks | D | d |
| Some daily, some peaks | E | e |
| Some daily, no peaks | F | f |
| No gauged flow data | * | - |

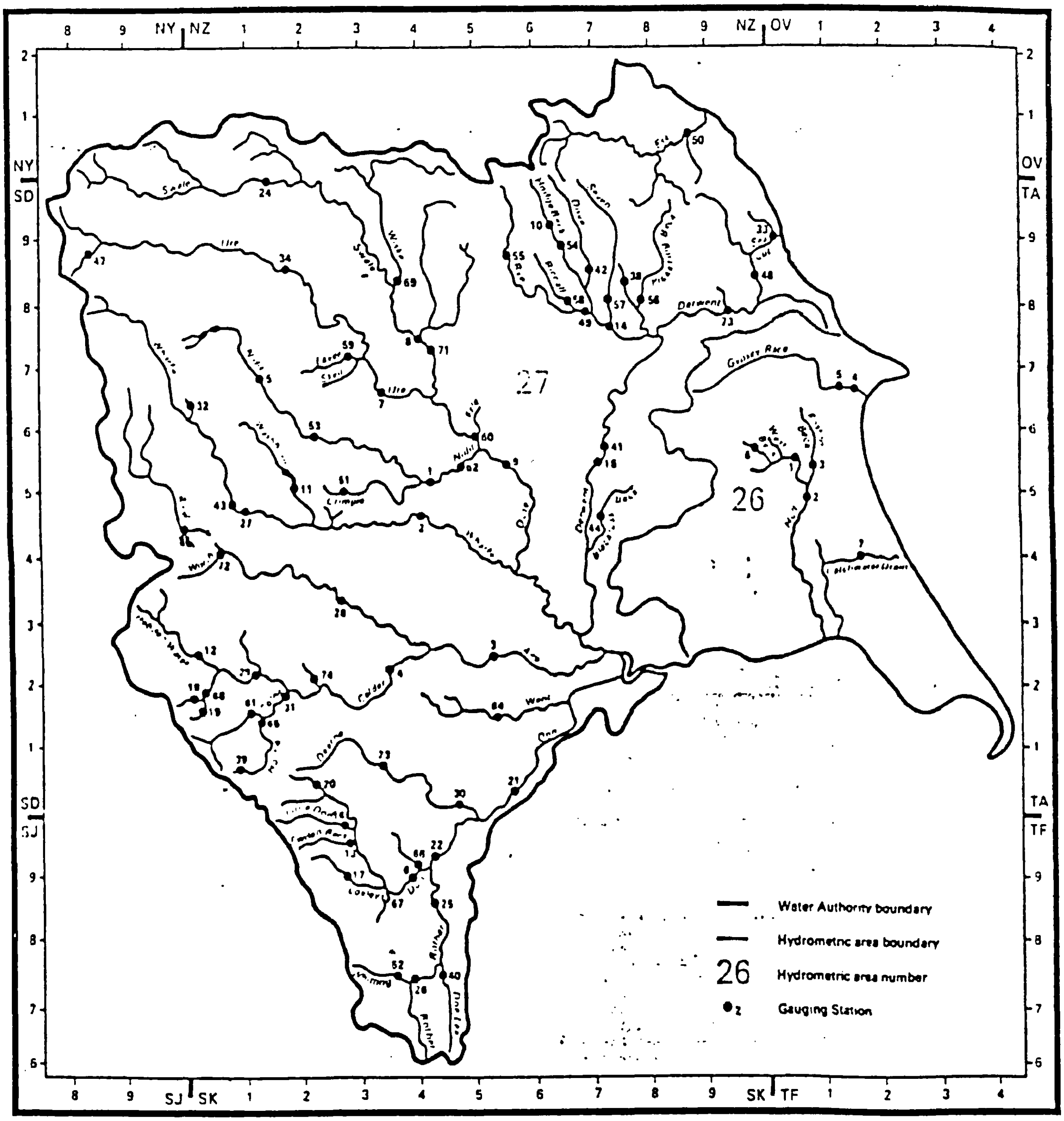
| | 01234 56789 |
|---|---|
| 1960s | ----- ---EA |
| 1970s | AAAAB AEAAA |
| 1980s | EAAAA AAA |

### Naturalised Flows

Key:

| | |
|---|---|
| All daily, all monthly | A |
| All daily, some monthly | B |
| All daily, no monthly | C |
| Some daily, all monthly | D |
| Some daily, some monthly | E |
| Some daily, no monthly | F |
| No naturalised flow data | - |

No naturalised flow data available.



27
26
Water Authority boundary
Hydrometric area boundary
26 Hydrometric area number
Gauging Station

YORKSHIRE WATER AUTHORITY

# Accumulated snow measurements

MONTH: JAN YEAR: 86

STATION: SKIPTON BATHS STATION NO. .................... WEIGHT OF SAMPLER (gms) ....................

| 1 DATE | 2 TIME | 3 SAMPLE NO. | 4 SNOW DEPTH (cm) | 5 WEIGHT OF SAMPLER + SNOW (gms) | 6 WEIGHT OF SNOW (gms) | 7 WATER EQUIVALENT (mm) | 8 DENSITY | 9 REMARKS |
|---|---|---|---|---|---|---|---|---|
| 4/1/86 | 9 am. | 1 | ½ | | | | | Snow THAW. |
| | | 2 | 1 | | | | | |
| | | 3 | ½ | | | | | |
| 5/1/86 | 9 am. | 1 | | | | | | Snow commencing to fall. |
| | | 2 | | | | | | |
| | | 3 | | | | | | |
| 6/1/86 | 9 AM | 1 | 2 | | | | | |
| | | 2 | 1½ | | | | | |
| | | 3 | 2 | | | | | Snow |
| 7/1/86 | 9 AM | 1 | 2½ | | | | | |
| | | 2 | 2 | | | | | |
| | | 3 | 2½ | | | | | Snow |
| 8/1/86 | 9 AM | 1 | 3 | | | | | |
| | | 2 | 2½ | | | | | |
| | | 3 | 3 | | | | | Snow |
| [illegible] | 9 am | 1 | 2 | | | | | Snow still on ground |
| | | 2 | 2 | | | | | |
| | | 3 | 2½ | | | | | |
| 11/1/86 | 9 am | 1 | 1 | | | | | — |
| | | 2 | 1 | | | | | |
| | | 3 | 1 | | | | | |
| 14/1/86 | 9 am | 1 | ½ | | | | | Snow still on ground however not in any quantity. |
| | | 2 | ½ | | | | | |
| | | 3 | ½ | | | | | |
| 16/1/86 | 9 AM | 1 | ½ | | | | | |
| | | 2 | ½ | | | | | |
| | | 3 | 9 | | | | | |

FOR OFFICE USE

# Accumulated snow measurements

MONTH: JAN   YEAR: 86

STATION: [illegible] ......   STATION NO: 4017   WEIGHT OF SAMPLER (gms): 3000

| 1 DATE | 2 TIME | 3 SAMPLE NO. | 4 SNOW DEPTH (cm) | 5 WEIGHT OF SAMPLER + SNOW (gms) | 6 WEIGHT OF SNOW (gms) | 7 WATER EQUIVALENT (mm) | 8 DENSITY | 9 REMARKS |
|---|---|---|---|---|---|---|---|---|
| 2[illegible] | 9.15 | 1 | 1 | | | | | Light snowfall overnight all snow gone by 2pm |
| | | 2 | 1 | | | | | |
| | | 3 | 1 | | | | | |
| 2[illegible] | 9.20 | 1 | 9 | 3360 | 360 | 13.6 | 0.14 | Snow showers from 10am previous day until 9pm strong winds, some drifting |
| | | 2 | 9 | | | | | |
| | | 3 | 10 | | | | | |
| 2[illegible] | 9.15 | 1 | 8 | 3410 | 410 | 15.5 | 0.19 | Sunshine all day, melting in areas |
| | | 2 | 8 | | | | | |
| | | 3 | 8 | | | | | |
| 2[illegible] | 9.20 | 1 | 7 | 3340 | 340 | 14.8 | 0.21 | Sunshine all day melting in areas |
| | | 2 | 7 | | | | | |
| | | 3 | 6 | | | | | |
| 2[illegible] | 9.20 | 1 | 7 | 3400 | 400 | 15.2 | 0.23 | rain overnight, snow showers throughout day |
| | | 2 | 6 | | | | | |
| | | 3 | 6 | | | | | |
| 2[illegible] | 9.10 | 1 | 8 | 3480 | 480 | 18.2 | 0.21 | Snow overnight and snow showers throughout day |
| | | 2 | 8 | | | | | |
| | | 3 | 9 | | | | | |
| 2[illegible] | 9.30 | 1 | 15 | 3770 | 770 | 29.2 | 0.17 | Snow overnight. Snow showers throughout day |
| | | 2 | 17 | | | | | |
| | | 3 | 17 | | | | | |
| 3[illegible] | 9.25 | 1 | 24 | 3420 | 420 | 47.7 | 0.20 | Snow wet & temps above freezing but drifting overnight, deep in places. |
| | | 2 | 23 | 3460 | 460 | 52.3 | 0.23 | |
| | | 3 | 24 | 3520 | 520 | 59.1 | 0.25 | |
| [illegible] | 9.20 | 1 | 19 | 4020 | 1020 | 38.6 | 0.19 | Snow wet, rain overnight & during day, temps above freezing Strong winds |
| | | 2 | 20 | | | | | |
| | | 3 | 19 | | | | | |

FOR OFFICE USE

# Accumulated snow measurements

... Febuary. YEAR 1986

STATION Milham Tarn   STATION NO. 4017   WEIGHT OF SAMPLER (gms) 3000

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| DATE | TIME | SAMPLE NO. | SNOW DEPTH (cm) | WEIGHT OF SAMPLER + SNOW (gms) | WEIGHT OF SNOW (gms) | WATER EQUIVALENT (mm) | DENSITY | REMARKS |
| 1st | 10.30 | 1 | 17.5 | | | | | Blown snow but compact underneath |
| | | 2 | 17.5 | 3640 | 640 | 24.2 | 0.14 | |
| | | 3 | 18 | | | | | |
| 2nd | 1100am | 1 | 19 | | | | | Blown snow but compact underneath |
| | | 2 | 18 | 3660 | 660 | 25.0 | 0.13 | |
| | | 3 | 19 | | | | | |
| 3rd | 10.00am | 1 | 18 | | | | | very compact snow underneath slight fresh loose snow on top |
| | | 2 | 18 | 4200 | 1200 | 45.4 | 0.25 | |
| | | 3 | 19 | | | | | |
| 4th | 9.30am | 1 | 14 | | | | | hard crust on surface of snow loose snow blowing forming deep drifts, but no fresh snow |
| | | 2 | 15 | 3960 | 960 | 36.4 | 0.24 | |
| | | 3 | 15 | | | | | |
| 5th | 9.50 | 1 | 15 | | | | | hard crust on surface of snow, light snowfall in morning & afternoon |
| | | 2 | 17 | 3980 | 980 | 37.1 | 0.22 | |
| | | 3 | 18 | | | | | |
| 6th | 9.25 | 1 | 21 | 3420 | 420 | 47.7 | 0.23 | snow overnight, deep drifting in places, strong winds all day. |
| | | 2 | 19 | 3460 | 460 | 52.3 | 0.27 | |
| | | 3 | 22 | 3480 | 480 | 54.5 | 0.25 | |
| 7th | 9.25 | 1 | 17 | | | | | hard crust on surface of snow blowing snow all day |
| | | 2 | 16 | 4200 | 1200 | 45.4 | 0.27 | |
| | | 3 | 18 | | | | | |
| 8th | 9.30 | 1 | 16 | | | | | hard crust on surface of snow slight snowfall during day drifted on top |
| | | 2 | 16 | 4150 | 1150 | 43.5 | 0.27 | |
| | | 3 | 17 | | | | | |
| 9th | 9.35 | 1 | 17 | | | | | fresh snow on top but hard & compact beneath, light blowing snow |
| | | 2 | 17.5 | 4350 | 1350 | 51.1 | 0.30 | |
| | | 3 | 16.5 | | | | | |

FOR OFFICE USE

YORKSHIRE WATER AUTHORITY

# Accumulated snow measurements

MONTH JAN YEAR 86

STATION Malham Tarn [illegible] STATION NO. 4017 WEIGHT OF SAMPLER (gms) 3000

| 1 DATE | 2 TIME | 3 SAMPLE NO. | 4 SNOW DEPTH (cm) | 5 WEIGHT OF SAMPLER + SNOW (gms) | 6 WEIGHT OF SNOW (gms) | 7 WATER EQUIVALENT (mm) | 8 DENSITY | 9 REMARKS |
|---|---|---|---|---|---|---|---|---|
| 2[illegible] | 9.15 | 1 | 1 | | | | | Light snowfall overnight all snow gone by 2pm |
| | | 2 | 1 | | | | | |
| | | 3 | 1 | | | | | |
| 2[illegible] | 9.20 | 1 | 9 | 3360 | 360 | 13.6 | 0.14 | Snow showers from 10am previous day until 9pm strong winds, some drifting |
| | | 2 | 9 | | | | | |
| | | 3 | 10 | | | | | |
| 2[illegible] | 9.15 | 1 | 8 | 3410 | 410 | 15.5 | 0.19 | sunshine all day, melting in areas |
| | | 2 | 8 | | | | | |
| | | 3 | 8 | | | | | |
| 2[illegible] | 9.20 | 1 | 7 | 3390 | 390 | 14.8 | 0.21 | sunshine all day melting in areas |
| | | 2 | 7 | | | | | |
| | | 3 | 6 | | | | | |
| 2[illegible] | 9.20 | 1 | 7 | 3400 | 400 | 15.2 | 0.23 | rain overnight, snow showers throughout day |
| | | 2 | 6 | | | | | |
| | | 3 | 6 | | | | | |
| 2[illegible] | 9.10 | 1 | 8 | 3480 | 480 | 18.2 | 0.21 | Snow overnight and snow showers throughout day |
| | | 2 | 8 | | | | | |
| | | 3 | 9 | | | | | |
| 2[illegible] | 9.30 | 1 | 15 | 3770 | 770 | 29.2 | 0.17 | Snow overnight. Snow showers throughout day |
| | | 2 | 17 | | | | | |
| | | 3 | 17 | | | | | |
| 3[illegible] | 9.25 | 1 | 24 | 3420 | 420 | 47.7 | 0.20 | Snow wet & temps above freezing but drifting overnight, deep in places. |
| | | 2 | 23 | 3460 | 460 | 52.3 | 0.23 | |
| | | 3 | 24 | 3520 | 520 | 59.1 | 0.25 | |
| [illegible] | 9.20 | 1 | 19 | 4020 | 1020 | 38.6 | 0.19 | Snow wet, rain overnight & during day, temps above freezing Strong winds |
| | | 2 | 20 | | | | | |
| | | 3 | 19 | | | | | |

FOR OFFICE USE

JANUARY 1986 CLIMATE STATION : MALHAM TARN

| DAY | -- TEMPERATURES (C) -- WET | DRY | MAX | MIN | SUN HRS | WIND RUN | RAIN MM | P.E. MM | A.E. MM | SMD MM | ERF MM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.5 | 1.5 | 1.7 | -0.8 | 0.0 | 498.3 | 1.1 | 0.0 | 0.0 | 0.0 | 1.1 |
| 2 | 0.1 | 0.3 | 1.6 | -1.2 | 0.0 | 428.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 3 | -1.9 | -1.8 | 0.4 | -3.8 | 6.4 | 100.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4 | -5.5 | -5.4 | 0.5 | -7.3 | 0.0 | 180.9 | 0.3 | 0.0 | 0.0 | 0.0 | 0.3 |
| 5 | -2.3 | -2.2 | 0.2 | -6.0 | 0.0 | 181.5 | 1.7 | 0.0 | 0.0 | 0.0 | 1.7 |
| 6 | -3.1 | -3.0 | -0.5 | -3.5 | 4.7 | 330.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 7 | -3.8 | -3.8 | -0.5 | -8.4 | 0.0 | 963.2 | 0.9 | 0.0 | 0.0 | 0.0 | 0.9 |
| 8 | -1.5 | -1.5 | -0.8 | -6.5 | 0.0 | 440.4 | 0.7 | 0.0 | 0.0 | 0.0 | 0.7 |
| 9 | -0.9 | -0.8 | 5.5 | -2.0 | 0.0 | 329.1 | 15.2 | 0.0 | 0.0 | 0.0 | 15.2 |
| 10 | 5.1 | 5.1 | 5.5 | -1.5 | 1.2 | 816.4 | 8.5 | 0.0 | 0.0 | 0.0 | 8.5 |
| 11 | 1.5 | 1.9 | 5.1 | -0.2 | 0.8 | 960.0 | 4.1 | 0.0 | 0.0 | 0.0 | 4.1 |
| 12 | 1.9 | 2.3 | 6.5 | -1.0 | 0.0 | 1000.7 | 39.7 | 0.0 | 0.0 | 0.0 | 39.7 |
| 13 | 5.6 | 5.8 | 7.8 | -0.2 | 0.0 | 1040.5 | 17.8 | 0.0 | 0.0 | 0.0 | 17.8 |
| 14 | 1.0 | 2.1 | 5.8 | -3.0 | 0.2 | 847.0 | 8.9 | 0.0 | 0.0 | 0.0 | 8.9 |
| 15 | 1.7 | 2.5 | 4.5 | 1.1 | 3.4 | 198.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 16 | -2.5 | -2.0 | 2.5 | -3.1 | 2.7 | 113.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 17 | -2.3 | -2.3 | 7.5 | -3.7 | 0.0 | 438.8 | 19.1 | 0.0 | 0.0 | 0.0 | 19.1 |
| 18 | 5.4 | 5.6 | 7.3 | -2.5 | 0.0 | 727.0 | 24.0 | 0.0 | 0.0 | 0.0 | 24.0 |
| 19 | 6.0 | 6.4 | 6.8 | 4.0 | 0.0 | 803.4 | 10.2 | 0.0 | 0.0 | 0.0 | 10.2 |
| 20 | 2.8 | 3.2 | 6.4 | 0.0 | 0.0 | 708.9 | 42.0 | 0.0 | 0.0 | 0.0 | 42.0 |
| 21 | 2.6 | 3.0 | 3.5 | 2.0 | 0.0 | 607.8 | 5.7 | 0.0 | 0.0 | 0.0 | 5.7 |
| 22 | 1.6 | 1.7 | 5.2 | 0.0 | 0.0 | 877.8 | 18.1 | 0.0 | 0.0 | 0.0 | 18.1 |
| 23 | 0.1 | 0.7 | 1.7 | -0.7 | 0.6 | 696.9 | 5.5 | 0.0 | 0.0 | 0.0 | 5.5 |
| 24 | -1.8 | -1.5 | 0.7 | -3.2 | 6.8 | 332.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 25 | -1.7 | -1.6 | 1.3 | -5.6 | 6.9 | 71.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 26 | -3.9 | -3.8 | 2.8 | -6.7 | 6.7 | 137.7 | 2.7 | 0.0 | 0.0 | 0.0 | 2.6 |
| 27 | 0.7 | 0.7 | 0.9 | -6.8 | 0.6 | 316.5 | 2.9 | 0.0 | 0.0 | 0.0 | 2.9 |
| 28 | -1.3 | -1.2 | 0.7 | -4.0 | 0.0 | 211.7 | 2.5 | 0.0 | 0.0 | 0.0 | 2.5 |
| 29 | -1.0 | -1.0 | 1.0 | -2.2 | 0.1 | 579.4 | 5.4 | 0.0 | 0.0 | 0.0 | 5.4 |
| 30 | 0.6 | 0.6 | 0.7 | -1.5 | 0.0 | 795.6 | 0.7 | 0.0 | 0.0 | 0.0 | 0.7 |
| 31 | 0.3 | 0.4 | 0.6 | -3.8 | 0.0 | 815.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| TOTALS | | | | | | | 237.7 | 0.2 | 0.2 | | 237.6 |

WIND RUN IN KM/D MEASURED AT 2.0 M LAT. 54.06 N ALT. 385.0 M ALBEDO 0.25

P.E. APPORTIONED ON A DAILY BASIS FROM MONTHLY TOTALS USING SUNSHINE HOURS

1986 027035 Aire at Kildwick Bridge 1986

| Day | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 17.250 | 9.300 | 1.595 | 10.330 | 3.321 | 2.456 | 0.370 | 1.255 | 2.064 | 0.574 | 26.570 | 6.316 |
| 2 | 13.160 | 10.030 | 1.540 | 7.650 | 2.912 | 2.265 | 0.370 | 1.271 | 3.057 | 0.554 | 11.310 | 5.374 |
| 3 | 7.951 | 8.261 | 1.461 | 5.930 | 7.614 | 2.092 | 0.742 | 1.013 | 10.370 | 0.540 | 8.907 | 17.730 |
| 4 | 6.192 | 6.793 | 21.190 | 4.357 | 5.452 | 1.864 | 0.959 | 0.933 | 3.933 | 0.541 | 6.689 | 26.900 |
| 5 | 5.431 | 5.732 | 25.730 | 4.375 | 5.113 | 1.723 | 1.051 | 0.946 | 2.681 | 0.640 | 7.593 | 19.170 |
| 6 | 4.560 | 4.922 | 9.475 | 4.039 | 5.217 | 1.622 | 0.910 | 2.197 | 2.145 | 0.572 | 6.221 | 11.970 |
| 7 | 4.007 | 4.325 | 6.391 | 5.112 | 25.750 | 1.511 | 0.929 | 4.080 | 1.743 | 0.759 | 5.539 | 10.310 |
| 8 | 3.760 | 4.059 | 5.031 | 6.361 | 13.230 | 1.436 | 0.751 | 1.937 | 1.503 | 0.814 | 6.015 | 24.050 |
| 9 | 7.177 | 3.701 | 5.821 | 4.763 | 9.046 | 1.659 | 0.691 | 1.332 | 1.305 | 0.712 | 9.511 | 18.810 |
| 10 | 41.960 | 3.328 | 5.433 | 3.632 | 7.973 | 7.623 | 0.699 | 1.355 | 1.201 | 0.812 | 14.740 | 11.230 |
| 11 | 18.670 | 3.036 | 4.453 | 3.033 | 9.200 | 7.114 | 0.678 | 0.951 | 1.094 | 0.720 | 12.750 | 25.180 |
| 12 | 13.630 | 2.311 | 3.770 | 2.337 | 9.155 | 3.378 | 0.696 | 0.962 | 1.026 | 0.682 | 9.046 | 15.320 |
| 13 | 23.420 | 2.653 | 3.200 | 3.137 | 5.759 | 2.779 | 0.635 | 1.012 | 0.938 | 0.659 | 8.193 | 19.670 |
| 14 | 19.250 | 2.581 | 2.775 | 7.656 | 5.316 | 2.341 | 0.656 | 0.762 | 0.942 | 0.696 | 10.810 | 11.620 |
| 15 | 12.760 | 2.429 | 2.790 | 51.850 | 5.779 | 1.937 | 0.635 | 0.927 | 0.883 | 0.724 | 9.457 | 10.770 |
| 16 | 8.524 | 2.320 | 3.207 | 25.690 | 6.262 | 1.765 | 0.674 | 0.902 | 0.855 | 0.690 | 7.813 | 25.240 |
| 17 | 7.475 | 2.208 | 3.057 | 39.830 | 5.870 | 1.611 | 0.617 | 0.864 | 0.779 | 0.664 | 8.436 | 32.770 |
| 18 | 21.440 | 2.080 | 2.471 | 17.430 | 5.536 | 1.509 | 0.728 | 0.805 | 0.725 | 0.720 | 26.810 | 30.340 |
| 19 | 40.680 | 2.015 | 3.374 | 11.350 | 4.041 | 1.401 | 0.655 | 0.638 | 0.681 | 2.496 | 28.680 | 27.040 |
| 20 | 35.250 | 1.973 | 3.188 | 27.470 | 8.335 | 1.313 | 0.539 | 0.728 | 0.680 | 5.835 | 15.830 | 13.670 |
| 21 | 44.800 | 1.929 | 2.805 | 17.410 | 9.669 | 1.236 | 0.691 | 0.680 | 0.664 | 20.350 | 15.350 | 12.690 |
| 22 | 37.100 | 1.829 | 15.350 | 15.140 | 6.536 | 1.325 | 0.710 | 0.767 | 0.694 | 17.230 | 15.040 | 8.612 |
| 23 | 27.040 | 1.732 | 19.350 | 10.369 | 4.509 | 1.558 | 0.647 | 0.730 | 0.693 | 12.890 | 21.750 | 7.008 |
| 24 | 15.070 | 1.636 | 13.050 | 12.430 | 3.736 | 2.011 | 0.654 | 0.663 | 0.663 | 9.490 | 21.770 | 7.802 |
| 25 | 9.430 | 1.583 | 15.790 | 10.210 | 8.227 | 1.336 | 0.693 | 9.741 | 0.643 | 26.130 | 33.070 | 17.060 |
| 26 | 7.692 | 1.555 | 12.710 | 7.739 | 5.226 | 1.162 | 0.613 | 29.440 | 0.633 | 10.530 | 28.550 | 9.639 |
| 27 | 7.355 | 1.506 | 16.830 | 6.046 | 3.349 | 1.092 | 0.575 | 8.237 | 0.604 | 16.970 | 15.730 | 10.930 |
| 28 | 6.613 | 1.519 | 10.120 | 5.376 | 3.294 | 1.023 | 0.666 | 4.860 | 0.595 | 22.310 | 10.340 | 11.260 |
| 29 | 8.605 | | 13.000 | 4.760 | 2.765 | 0.930 | 0.953 | 3.478 | 0.607 | 13.510 | 7.903 | 15.430 |
| 30 | 18.330 | | 10.360 | 4.036 | 2.511 | 0.701 | 1.333 | 2.554 | 0.604 | 15.780 | 6.443 | 43.010 |
| 31 | 13.210 | | 12.940 | | 2.561 | | 1.834 | 2.028 | | 15.320 | | 27.620 |
| Missing days | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Mean | 16.380 | 3.529 | 8.339 | 11.400 | 6.430 | 2.066 | 0.780 | 2.336 | 1.517 | 6.488 | 13.880 | 18.020 |
| Min | 3.760 | 1.506 | 1.461 | 2.339 | 2.511 | 0.901 | 0.575 | 0.663 | 0.595 | 0.540 | 5.589 | 5.374 |
| Max | 44.800 | 10.080 | 25.730 | 51.850 | 25.750 | 7.623 | 1.834 | 29.440 | 10.370 | 26.130 | 33.070 | 43.010 |
| Monthly totals (million cubic metres) | 43.880 | 8.537 | 22.110 | 29.550 | 17.360 | 5.355 | 2.092 | 7.595 | 3.932 | 17.380 | 35.930 | 43.240 |

1986 Summary

Max 51.850 on 15 Apr    Min 0.540 on 3 Oct    Mean 7.6??

Runoff 355 mm    Total 242.?? million cubic metres

Station and Catchment Description

027035 Catchment area : 282.3 sq km    Grid reference : 4013 4457

Velocity-area station rated by current meter cableway 150m downstream. Low flow control is the sills of the bridge. Highland

027035 Aire at Kildwick Bridge

| Date | | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1968 | Rainfall | 103 | 42 | 144 | 74 | 128 | 117 | 95 | 55 | 250 | 151 | 84 | 56 | 1304 |
| | Runoff | – | – | – | – | – | – | – | – | – | – | – | 45 | – |
| 1969 | Rainfall | 89 | 63 | 106 | 99 | 104 | 87 | 49 | 68 | 77 | 137 | 181 | 86 | 1046 |
| | Runoff | 65 | 42 | 54 | 56 | 45 | 33 | 3 | 9 | 13 | 13 | 112 | 74 | 575 |
| 1970 | Rainfall | 109 | 109 | 73 | 135 | 10 | 66 | 102 | 63 | 100 | 142 | 187 | 54 | 1150 |
| | Runoff | 82 | 91 | 30 | 88 | 14 | 6 | 18 | 9 | 23 | 56 | 143 | 56 | 606 |
| 1971 | Rainfall | 71 | 84 | 74 | 49 | 77 | 80 | 66 | 149 | 27 | 115 | 95 | 42 | 919 |
| | Runoff | 44 | 67 | 45 | 17 | 17 | 13 | 8 | 53 | 11 | 56 | 69 | 30 | 402 |
| 1972 | Rainfall | 113 | 85 | 94 | 94 | 142 | 97 | 81 | 48 | 37 | 41 | 182 | 135 | 1149 |
| | Runoff | 81 | 71 | 44 | 77 | 53 | 56 | 25 | 18 | 11 | 7 | 84 | 137 | 664 |
| 1973 | Rainfall | 67 | 88 | 45 | 90 | 81 | 46 | 151 | 103 | 93 | 75 | 80 | 107 | 1033 |
| | Runoff | 42 | 65 | 47 | 41 | 23 | 5 | 56 | 33 | 32 | 51 | 54 | 78 | 530 |
| 1974 | Rainfall | 169 | 110 | 73 | 8 | 44 | 83 | 143 | 78 | 185 | 81 | 154 | 157 | 1285 |
| | Runoff | 132 | 92 | 54 | 8 | 6 | 11 | 25 | 24 | 75 | 50 | 115 | 135 | 743 |
| 1975 | Rainfall | 159 | 35 | 44 | 81 | 33 | 23 | 133 | 100 | 140 | 68 | 76 | 80 | 972 |
| | Runoff | 126 | 41 | 25 | 25 | 22 | 6 | 13 | 16 | 39 | 58 | 33 | 55 | 464 |
| 1976 | Rainfall | 143 | 56 | 77 | 33 | 129 | 23 | 50 | 17 | 153 | 189 | 89 | 79 | 1043 |
| | Runoff | 121 | 42 | 37 | 25 | 32 | – | 5 | 3 | 13 | 116 | 55 | 73 | – |
| 1977 | Rainfall | 90 | 139 | 82 | 102 | 52 | 100 | 49 | 77 | 89 | 111 | 183 | 121 | 1195 |
| | Runoff | 76 | 108 | 52 | 56 | 38 | 15 | 9 | 7 | 13 | 50 | 136 | 87 | 647 |
| 1978 | Rainfall | 160 | 82 | 135 | 34 | 34 | 65 | 59 | 111 | 158 | 41 | 127 | 194 | 1200 |
| | Runoff | 124 | 73 | 94 | 23 | 11 | 6 | 5 | 26 | 61 | 25 | 87 | 128 | 663 |
| 1979 | Rainfall | 93 | 49 | 165 | 97 | 131 | 50 | 47 | 151 | 86 | 73 | 167 | 238 | 1347 |
| | Runoff | 71 | 61 | 153 | 63 | 57 | 31 | 7 | 59 | 32 | 25 | 130 | 198 | 892 |
| 1980 | Rainfall | 119 | 105 | 110 | 3 | 27 | 155 | 71 | 133 | 103 | 213 | 152 | 128 | 1319 |
| | Runoff | – | 114 | 82 | 17 | 7 | 24 | 20 | 67 | 55 | 164 | 142 | 112 | – |
| 1981 | Rainfall | 107 | 88 | 233 | 64 | 72 | 67 | 49 | 57 | 167 | 187 | 133 | 68 | 1292 |
| | Runoff | 118 | 69 | 214 | 39 | 23 | 30 | 11 | 11 | 47 | 167 | 113 | 60 | 902 |
| 1982 | Rainfall | 98 | 48 | 139 | 24 | 56 | 143 | 17 | 151 | 74 | 79 | 143 | 163 | 1175 |
| | Runoff | 122 | 41 | 119 | 13 | 11 | 59 | 13 | 40 | 37 | 49 | 138 | 150 | 781 |
| 1983 | Rainfall | 194 | 44 | 111 | 107 | 123 | 55 | 22 | 53 | 100 | 163 | 55 | 205 | 1234 |
| | Runoff | 163 | 63 | 84 | 67 | 78 | 33 | 6 | 5 | 20 | 96 | 34 | 168 | 815 |
| 1984 | Rainfall | 222 | 82 | 67 | 16 | 32 | 75 | 21 | 71 | 152 | 157 | 178 | 78 | 1152 |
| | Runoff | 175 | 117 | 40 | 14 | 7 | 19 | 3 | 5 | 40 | 35 | 152 | 40 | 739 |
| 1985 | Rainfall | 77 | 14 | 62 | 92 | 75 | 64 | 113 | 171 | 27 | 69 | 41 | 169 | 1020 |
| | Runoff | 63 | 33 | 23 | 45 | 23 | 11 | 32 | 104 | 22 | 53 | 32 | 142 | 711 |
| 1986 | Rainfall | 161 | 13 | 113 | 139 | 112 | 47 | 42 | 113 | 22 | 159 | 141 | 217 | 1277 |
| | Runoff | 155 | 30 | 79 | 105 | 61 | 12 | 7 | 27 | 14 | 62 | 127 | 171 | 157 |
| 1987 | Rainfall | 45 | 80 | 126 | 57 | 43 | 115 | 133 | 90 | 102 | 133 | 88 | 98 | 1085 |
| | Runoff | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | | | | | | | | | | | | | | |
| Mean | (mm) | 120 | 71 | 104 | [illegible] | 75 | 78 | 74 | 93 | 111 | 114 | 130 | 124 | 1163 |
| Min | (mm) | 45 | 13 | 44 | 3 | 10 | 23 | 17 | 17 | 22 | 37 | 55 | 42 | 919 |
| | Year | [illegible] | 1986 | 1975 | 1980 | 1970 | 1976 | 1982 | 1976 | 1986 | 1969 | 1983 | 1971 | 1971 |
| Max | (mm) | 222 | 139 | 233 | 135 | 142 | 155 | 151 | 171 | 250 | 213 | 187 | 238 | 1347 |
| | Year | 1984 | 1977 | 1981 | 1970 | 1972 | 1980 | 1973 | 1985 | 1968 | 1980 | 1970 | 1979 | 1979 |
| Runoff | | | | | | | | | | | | | | |
| Mean | (mm) | 102 | 67 | 72 | 47 | 29 | 23 | 16 | 30 | 35 | 68 | 96 | 103 | 686 |
| Min | (mm) | 42 | 30 | 23 | 8 | 6 | 6 | 3 | 3 | 11 | 7 | 33 | 30 | 409 |
| | Year | 1973 | 1986 | 1985 | 1974 | 1974 | 1975 | 1984 | 1976 | 1972 | 1972 | 1975 | 1971 | 1971 |
| Max | (mm) | 176 | 117 | 214 | 105 | 73 | 59 | 56 | 108 | 95 | 167 | 152 | 198 | 902 |
| | Year | 1984 | 1984 | 1981 | [illegible] | 1983 | 1982 | 1973 | 1985 | 1974 | 1981 | 1984 | 1979 | 1981 |
| % Runoff | | | | | | | | | | | | | | |
| Mean | (%) | 85 | 94 | 69 | 67 | 39 | 29 | 22 | 32 | 32 | 60 | 74 | 83 | 59 |
| Min | (%) | 62 | 67 | 37 | 31 | 14 | 9 | 8 | 7 | 8 | 17 | 43 | 66 | 45 |
| | Year | 1971 | 1969 | 1985 | [illegible] | 1974 | 1973 | 1978 | 1984 | 1976 | 1972 | 1975 | 1978 | 1971 |
| Max | (%) | >100 | >100 | >100 | >100 | >100 | 62 | 76 | 63 | 74 | 89 | 93 | >100 | 70 |
| | Year | [illegible] | 1985 | 1973 | [illegible] | 1970 | 1979 | 1982 | 1985 | 1985 | 1981 | 1980 | 1970 | 1981 |

The summary relates exclusively to the years shown.

Period requested : Full record

Rainfall data available : Jan 1968 - Dec 1987
Gauged flow data available : Dec 1968 - Dec 1987

Station and Catchment Description
==================================
027035   Catchment area : 282.3 sq km   Grid reference : 4013 4457

Velocity-area station rated by current meter cableway 150m downstream. Low flow control is the sills of the bridge. Washland storage and headwater reservoirs influence the flow pattern. Geology is mainly Carboniferous Limestone with some Millstone Grit series. Rural catchment draining part of the eastern Pennines.

# Appendix 3

This appendix contains examples of SQL queries and the returned answers of the ORACLE database to these queries. The lines preceded by SQL> are the commands issued by the user. The queries in this appendix consist mostly of the queries used in program ASSEMBLE.FOR. Some other queries are also available, these are the first two queries. A blank space indicates a null value.

**SQL> DESCRIBE RS_DBASE**

| Name | Null? | Type |
|---|---|---|
| DAY | | NUMBER(6) |
| XNGRN | | NUMBER(7) |
| YNGRN | | NUMBER(7) |
| ZONE | | NUMBER(1) |
| ELEV | | NUMBER(4) |
| PRECIPITATION | | NUMBER(5,2) |
| TEMPERATURE | | NUMBER(5,2) |
| EVAPORATION | | NUMBER(5,2) |
| TMIN | | NUMBER(5,2) |
| TMAX | | NUMBER(5,2) |
| CLASSES | | NUMBER(2) |
| SNOWCLASS | | NUMBER(2) |

**SQL> DESCRIBE CON_DBASE**

| Name | Null? | Type |
|---|---|---|
| DAY | | NUMBER(6) |
| ZONE | | NUMBER(1) |
| ELEV | | NUMBER(5) |
| GPREC | | NUMBER(4,1) |
| GTMAX | | NUMBER(3,1) |
| GTMIN | | NUMBER(3,1) |
| GTMEAN | | NUMBER(3,1) |
| GEVAP | | NUMBER(3,1) |
| ACTUAL_DISCHARGE | | NUMBER(7,3) |

**SQL> SELECT ZONE,COUNT(*),AVG(ELEV) FROM RS_DBASE WHERE DAY =860124 GROUP BY ZONE ORDER BY ZONE;**

| ZONE | COUNT(*) | AVG(ELEV) |
|---|---|---|
| 0 | 262 | 1169.08397 |
| 1 | 145 | 963.448276 |
| 2 | 96 | 1130.20833 |
| 3 | 37 | 1394.59459 |

**SQL> SELECT ACTUAL_DISCHARGE,DAY**
**2 FROM CON_DBASE WHERE DAY>= 860124 AND**
**3 DAY<=860129 ;**

| ACTUAL_DISCHARGE | DAY |
|---|---|
| 15.07 | 860124 |
| 9.43 | 860125 |
| 7.692 | 860126 |
| 7.335 | 860127 |
| 6.613 | 860128 |
| 8.603 | 860129 |

6 records selected.

**SQL> SELECT DAY,ZONE,AVG(TEMPERATURE)**
**2 FROM RS_DBASE**
**3 WHERE DAY BETWEEN 860124 AND 860129**
**4 GROUP BY DAY,ZONE;**

| DAY | ZONE | AVG(TEMPERATURE) |
|---|---|---|
| 860124 | 0 | 1.30916031 |
| 860124 | 1 | 2.04827586 |
| 860124 | 2 | 1.70833333 |
| 860124 | 3 | .378378378 |
| 860125 | 0 | 1.54961832 |
| 860125 | 1 | 2.53793103 |
| 860125 | 2 | 1.83333333 |
| 860125 | 3 | .135135135 |
| 860126 | 0 | 2.58396947 |
| 860126 | 1 | 2.57241379 |
| 860126 | 2 | 2.80208333 |

```
  860126        3        2.59459459
  860127        0
  860127        1
  860127        2
  860127        3
  860128        0
  860128        1
  860128        2
  860128        3
  860129        0
  860129        1
  860129        2
  860129        3

24 records selected.
```

**SQL> SELECT DAY,ZONE,GTMAX,GTMIN**
**2 FROM CON_DBASE;**

```
       DAY       ZONE      GTMAX      GTMIN
---------- ---------- ---------- ----------
    860124                    .7       -3.2
    860125                   1.3       -5.6
    860126                   2.8       -6.7
    860127                    .9       -6.8
    860128                    .7         -4
    860129                     1       -2.2

6 records selected.
```

**SQL> SELECT DAY,ZONE,AVG(PRECIPITATION)**
**2 FROM RS_DBASE**
**3 GROUP BY DAY,ZONE;**

```
       DAY       ZONE AVG(PRECIPITATION)
---------- ---------- ------------------
    860124          0                  0
    860124          1                  0
    860124          2                  0
    860124          3                  0
    860125          0                  0
    860125          1                  0
    860125          2                  0
    860125          3                  0
    860126          0                  0
    860126          1                  0
```

| | | |
|---|---|---|
| 860126 | 2 | 0 |
| 860126 | 3 | 0 |
| 860127 | 0 | 0 |
| 860127 | 1 | 0 |
| 860127 | 2 | 0 |
| 860127 | 3 | 0 |
| 860128 | 0 | 1.9351145 |
| 860128 | 1 | 1.39310345 |
| 860128 | 2 | 1.20833333 |
| 860128 | 3 | 1.2972973 |
| 860129 | 0 | 4.99236641 |
| 860129 | 1 | 4.97931034 |
| 860129 | 2 | 5 |
| 860129 | 3 | 4.35135135 |

24 records selected.

**SQL> SELECT DAY,ZONE,COUNT(SNOWCLASS) FROM**
**2 RS_DBASE WHERE SNOWCLASS>0 GROUP BY**
**3 DAY,ZONE;**

| DAY | ZONE | COUNT(SNOWCLASS) |
|---|---|---|
| 860124 | 0 | 83 |
| 860124 | 1 | 1 |
| 860124 | 2 | 23 |
| 860124 | 3 | 27 |
| 860125 | 0 | 113 |
| 860125 | 1 | 6 |
| 860125 | 2 | 31 |
| 860125 | 3 | 37 |
| 860126 | 0 | 12 |
| 860126 | 1 | 12 |
| 860126 | 2 | 9 |

11 records selected.

# Appendix 4

This appendix contains the complete listing of the the different runs done using the hydrological model SRM. The first run denoted RUN @1 presents the output obtained from running SRM using remote sensing derived hydrological data supplemented by conventional means of collecting these data. This run was done without offsetting the starting date of the simulation to the beginning of the simulation month. RUN @2 is the second run of SRM, the data used for this run is the same as that of the RUN @1 but with the data offset to the beginning of the month.

The last run presented in this appendix is the output of the simulation for data collected mainly by conventional means and supplemented by remote sensing.

The output of the different simulations start with presenting the different basin and operational data as chosen by the user. The results of the simulation are presented later.

# RUN @ 1

1RUN # 1 BASIN=AIRE RIVER YEAR= 1986

MODE (0=SIMULATED,1==FORCAST)= 0

PROGRAM OPTIONS (0=OFF,1=ON)

PLOT OPTION= 0 PRINT OPTION= 0
UNITS(0=METRIC,1=ENGLISH)= 0

ACTUAL DATA FLAG= 1 ZONE INPUT
DATA(TEMP.,PRECIP.,RUNOFF COEF.,TCRIT)= 0 1 0 0

LAPSE RATE DATA FLAG= 0 DEGREE-DAY
METHOD(0=MEAN,1=EFFECTIVE MINIMUM)= 1

TEMPERATURE PROCESSING FLAG= 1 RUNOFF BY ZONE OUTPUT
OPTION= 1

FLAG TO EXTRAPOLATE TEMPERATURES(0=EXTRAPOLATE USING
GIVEN LAPSE RATES, 1=AUTOMATICALLY EXTRAPOLATE)= 1

FLAG TO COMPUTE DEGREE-DAYS= 1

FLAG TO INDICATE INPUT TEMPS ARE MAX-MIN= 0

START MONTH= 1 END MONTH= 1

NUMBER OF SNOWMELT DAYS= 7 NUMBER OF ELEVATION
ZONES= 3

RECESSION COEFFIECIENT FACTORS:

X FACTOR= 0.884000 Y FACTOR=-0.067700 EFFECTIVE DATE=
1/ 1

INITIAL RUNOFF VALUE= 15.070 LAG= 14 HOURS

AREA IN EACH ELEVATION ZONE

| ZONE | AREA (SQ. METERS ) |
|---|---|
| 1 | 0.1450E+09 |
| 2 | 0.9600E+08 |
| 3 | 0.3700E+08 |

HYPSOMETRIC MEAN ELEVATION IN EACH ZONE (METERS )

| | |
|---|---|
| 1 | 0.3400E+03 |
| 2 | 0.3800E+03 |
| 3 | 0.4760E+03 |

BASE STATION ELEVATION (METERS )

0.3000E+03

NO TEMPERATURE LAPSE RATE DATA INPUT

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE A

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.001 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE B

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY
COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)
RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE C

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY COMPUTED AND ACTUAL SNOWMELT RUNOFF DATA

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

| DAY | JAN | |
|---|---|---|
| | COMPUTED | ACTUAL |
| 1 | 14.154 | 0.000 |
| 2 | 10.457 | 0.000 |
| 3 | 7.886 | 0.000 |
| 4 | 6.062 | 0.000 |
| 5 | 4.743 | 0.000 |
| 6 | 3.773 | 0.000 |
| 7 | 3.049 | 0.000 |
| 8 | 2.499 | 0.000 |
| 9 | 2.077 | 0.000 |
| 10 | 1.747 | 0.000 |
| 11 | 1.487 | 0.000 |
| 12 | 1.280 | 0.000 |
| 13 | 1.113 | 0.000 |
| 14 | 0.976 | 0.000 |
| 15 | 0.865 | 0.000 |
| 16 | 0.772 | 0.000 |
| 17 | 0.694 | 0.000 |
| 18 | 0.629 | 0.000 |
| 19 | 0.574 | 0.000 |
| 20 | 0.527 | 0.000 |
| 21 | 0.486 | 0.000 |
| 22 | 0.451 | 0.000 |
| 23 | 0.421 | 0.000 |

| | | |
|---|---|---|
| 24 | 0.395 | 0.000 |
| 25 | 0.372 | 15.070 |
| 26 | 0.351 | 9.430 |
| 27 | 0.334 | 7.692 |
| 28 | 0.318 | 7.335 |
| 29 | 0.304 | 6.613 |
| 30 | 0.291 | 8.603 |
| 31 | 0.280 | 0.000 |

TOTAL ACTUAL STREAMFLOW= 54.7430
MEAN ACTUAL STREAMFLOW= 7.8204

TOTAL COMPUTED VOLUME= 69.3662
MEAN COMPUTED VOLUME= 9.9095

GOODNESS OF FIT MEASURE= 0.3768

PERCENT SEASONAL DIFFERENCE= -26.7124

END OF DATA

# RUN @ 2

1RUN # 2 BASIN=AIRE RIVER YEAR= 1986

MODE (0=SIMULATED,1==FORCAST)= 0

PROGRAM OPTIONS (0=OFF,1=ON)

PLOT OPTION= 0 PRINT OPTION= 0
UNITS(0=METRIC,1=ENGLISH)= 0

ACTUAL DATA FLAG= 1 ZONE INPUT
DATA(TEMP.,PRECIP.,RUNOFF COEF.,TCRIT)= 0 1 0 0

LAPSE RATE DATA FLAG= 0 DEGREE-DAY
METHOD(0=MEAN,1=EFFECTIVE MINIMUM)= 1

TEMPERATURE PROCESSING FLAG= 1 RUNOFF BY ZONE OUTPUT
OPTION= 1

FLAG TO EXTRAPOLATE TEMPERATURES(0=EXTRAPOLATE USING
GIVEN LAPSE RATES, 1=AUTOMATICALLY EXTRAPOLATE)= 1

FLAG TO COMPUTE DEGREE-DAYS= 1

FLAG TO INDICATE INPUT TEMPS ARE MAX-MIN= 0

START MONTH= 1 END MONTH= 1

NUMBER OF SNOWMELT DAYS= 7 NUMBER OF ELEVATION
ZONES= 3

RECESSION COEFFIECIENT FACTORS:

X FACTOR= 0.884000 Y FACTOR=-0.067700 EFFECTIVE DATE=
1/ 1

INITIAL RUNOFF VALUE= 15.070 LAG= 14 HOURS

AREA IN EACH ELEVATION ZONE

| ZONE | AREA (SQ. METERS ) |
|---|---|
| 1 | 0.1450E+09 |
| 2 | 0.9600E+08 |
| 3 | 0.3700E+08 |

HYPSOMETRIC MEAN ELEVATION IN EACH ZONE (METERS )

| | |
|---|---|
| 1 | 0.3400E+03 |
| 2 | 0.3800E+03 |
| 3 | 0.4760E+03 |

BASE STATION ELEVATION (METERS )

0.3000E+03

NO TEMPERATURE LAPSE RATE DATA INPUT

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE A

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.003 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE B

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |
| 19 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE C

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY COMPUTED AND ACTUAL SNOWMELT RUNOFF DATA

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

| DAY | JAN | |
|---|---|---|
| | COMPUTED | ACTUAL |
| 1 | 14.154 | 15.070 |
| 2 | 10.457 | 9.430 |
| 3 | 7.889 | 7.692 |
| 4 | 6.073 | 7.335 |
| 5 | 4.751 | 6.613 |
| 6 | 3.779 | 8.603 |
| 7 | 3.053 | 0.000 |
| 8 | 2.503 | 0.000 |
| 9 | 2.079 | 0.000 |
| 10 | 1.749 | 0.000 |
| 11 | 1.489 | 0.000 |
| 12 | 1.281 | 0.000 |
| 13 | 1.114 | 0.000 |
| 14 | 0.977 | 0.000 |
| 15 | 0.865 | 0.000 |
| 16 | 0.772 | 0.000 |
| 17 | 0.695 | 0.000 |
| 18 | 0.630 | 0.000 |
| 19 | 0.574 | 0.000 |
| 20 | 0.527 | 0.000 |
| 21 | 0.487 | 0.000 |
| 22 | 0.452 | 0.000 |
| 23 | 0.421 | 0.000 |
| 24 | 0.395 | 0.000 |
| 25 | 0.372 | 0.000 |
| 26 | 0.351 | 0.000 |

| | | |
|---|---|---|
| 27 | 0.333 | 0.000 |
| 28 | 0.318 | 0.000 |
| 29 | 0.303 | 0.000 |
| 30 | 0.291 | 0.000 |
| 31 | 0.279 | 0.000 |

TOTAL ACTUAL STREAMFLOW= 54.7430
MEAN ACTUAL STREAMFLOW= 7.8204

TOTAL COMPUTED VOLUME= 69.4141
MEAN COMPUTED VOLUME= 9.9163

GOODNESS OF FIT MEASURE= 0.9599

PERCENT SEASONAL DIFFERENCE= -26.8000

END OF DATA

## RUN @ 3

1RUN # 2 BASIN=AIRE RIVER YEAR= 1986

MODE (0=SIMULATED,1==FORCAST)= 0

PROGRAM OPTIONS (0=OFF,1=ON)

PLOT OPTION= 0 PRINT OPTION= 0
UNITS(0=METRIC,1=ENGLISH)= 0

ACTUAL DATA FLAG= 1 ZONE INPUT
DATA(TEMP.,PRECIP.,RUNOFF COEF.,TCRIT)= 0 1 0 0

LAPSE RATE DATA FLAG= 0 DEGREE-DAY
METHOD(0=MEAN,1=EFFECTIVE MINIMUM)= 1

TEMPERATURE PROCESSING FLAG= 1 RUNOFF BY ZONE OUTPUT
OPTION= 1

FLAG TO EXTRAPOLATE TEMPERATURES(0=EXTRAPOLATE USING
GIVEN LAPSE RATES, 1=AUTOMATICALLY EXTRAPOLATE)= 1

FLAG TO COMPUTE DEGREE-DAYS= 1

FLAG TO INDICATE INPUT TEMPS ARE MAX-MIN= 0

START MONTH= 1 END MONTH= 1

NUMBER OF SNOWMELT DAYS= 7 NUMBER OF ELEVATION
ZONES= 3

RECESSION COEFFIECIENT FACTORS:

X FACTOR= 0.884000 Y FACTOR=-0.067700 EFFECTIVE DATE=
1/ 1

INITIAL RUNOFF VALUE= 15.070 LAG= 14 HOURS

AREA IN EACH ELEVATION ZONE

| ZONE | AREA (SQ. METERS ) |
|---|---|
| 1 | 0.1450E+09 |
| 2 | 0.9600E+08 |
| 3 | 0.3700E+08 |

HYPSOMETRIC MEAN ELEVATION IN EACH ZONE (METERS )

| | |
|---|---|
| 1 | 0.3400E+03 |
| 2 | 0.3800E+03 |
| 3 | 0.4760E+03 |

BASE STATION ELEVATION (METERS )

0.3000E+03

NO TEMPERATURE LAPSE RATE DATA INPUT

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE A

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE B

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 19 | 0.000 | 0.000 |
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY SNOW DEPTH BY ZONE IN CM.M**2(DPTH), DAILY COMPUTED PRECIP CONTRIBUTING TO RUNOFF(CPRE)

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

DATA FOR ZONE C

| DAY | JAN | |
|---|---|---|
| | DPTH | CPRE |
| 1 | 0.000 | 0.000 |
| 2 | 0.000 | 0.000 |
| 3 | 0.000 | 0.000 |
| 4 | 0.000 | 0.000 |
| 5 | 0.000 | 0.000 |
| 6 | 0.000 | 0.000 |
| 7 | 0.000 | 0.000 |
| 8 | 0.000 | 0.000 |
| 9 | 0.000 | 0.000 |
| 10 | 0.000 | 0.000 |
| 11 | 0.000 | 0.000 |
| 12 | 0.000 | 0.000 |
| 13 | 0.000 | 0.000 |
| 14 | 0.000 | 0.000 |
| 15 | 0.000 | 0.000 |
| 16 | 0.000 | 0.000 |
| 17 | 0.000 | 0.000 |
| 18 | 0.000 | 0.000 |
| 19 | 0.000 | 0.000 |

| | | |
|---|---|---|
| 20 | 0.000 | 0.000 |
| 21 | 0.000 | 0.000 |
| 22 | 0.000 | 0.000 |
| 23 | 0.000 | 0.000 |
| 24 | 0.000 | 0.000 |
| 25 | 0.000 | 0.000 |
| 26 | 0.000 | 0.000 |
| 27 | 0.000 | 0.000 |
| 28 | 0.000 | 0.000 |
| 29 | 0.000 | 0.000 |
| 30 | 0.000 | 0.000 |
| 31 | 0.000 | 0.000 |

C

DAILY COMPUTED AND ACTUAL SNOWMELT RUNOFF DATA

RANGO-MARTINEC MODEL FOR AIRE RIVER YEAR= 1986

| DAY | JAN | |
|---|---|---|
| | COMPUTED | ACTUAL |
| 1 | 14.154 | 15.070 |
| 2 | 10.457 | 9.430 |
| 3 | 7.886 | 7.692 |
| 4 | 6.062 | 7.335 |
| 5 | 4.743 | 6.613 |
| 6 | 3.773 | 8.603 |
| 7 | 3.049 | 0.000 |
| 8 | 2.499 | 0.000 |
| 9 | 2.077 | 0.000 |
| 10 | 1.747 | 0.000 |
| 11 | 1.487 | 0.000 |
| 12 | 1.280 | 0.000 |
| 13 | 1.113 | 0.000 |
| 14 | 0.976 | 0.000 |
| 15 | 0.865 | 0.000 |
| 16 | 0.772 | 0.000 |
| 17 | 0.694 | 0.000 |
| 18 | 0.629 | 0.000 |
| 19 | 0.574 | 0.000 |
| 20 | 0.527 | 0.000 |
| 21 | 0.486 | 0.000 |
| 22 | 0.451 | 0.000 |

| | | |
|---|---|---|
| 23 | 0.421 | 0.000 |
| 24 | 0.395 | 0.000 |
| 25 | 0.372 | 0.000 |
| 26 | 0.351 | 0.000 |
| 27 | 0.333 | 0.000 |
| 28 | 0.317 | 0.000 |
| 29 | 0.303 | 0.000 |
| 30 | 0.291 | 0.000 |
| 31 | 0.279 | 0.000 |

TOTAL ACTUAL STREAMFLOW= 54.7430
MEAN ACTUAL STREAMFLOW= 7.8204

TOTAL COMPUTED VOLUME= 69.3641
MEAN COMPUTED VOLUME= 9.9092

GOODNESS OF FIT MEASURE= 0.9599

PERCENT SEASONAL DIFFERENCE= -26.7086

END OF DATA

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