Advances in Rainfall-runoff Modelling and Numerical Weather Prediction for Real-time Flood Forecasting

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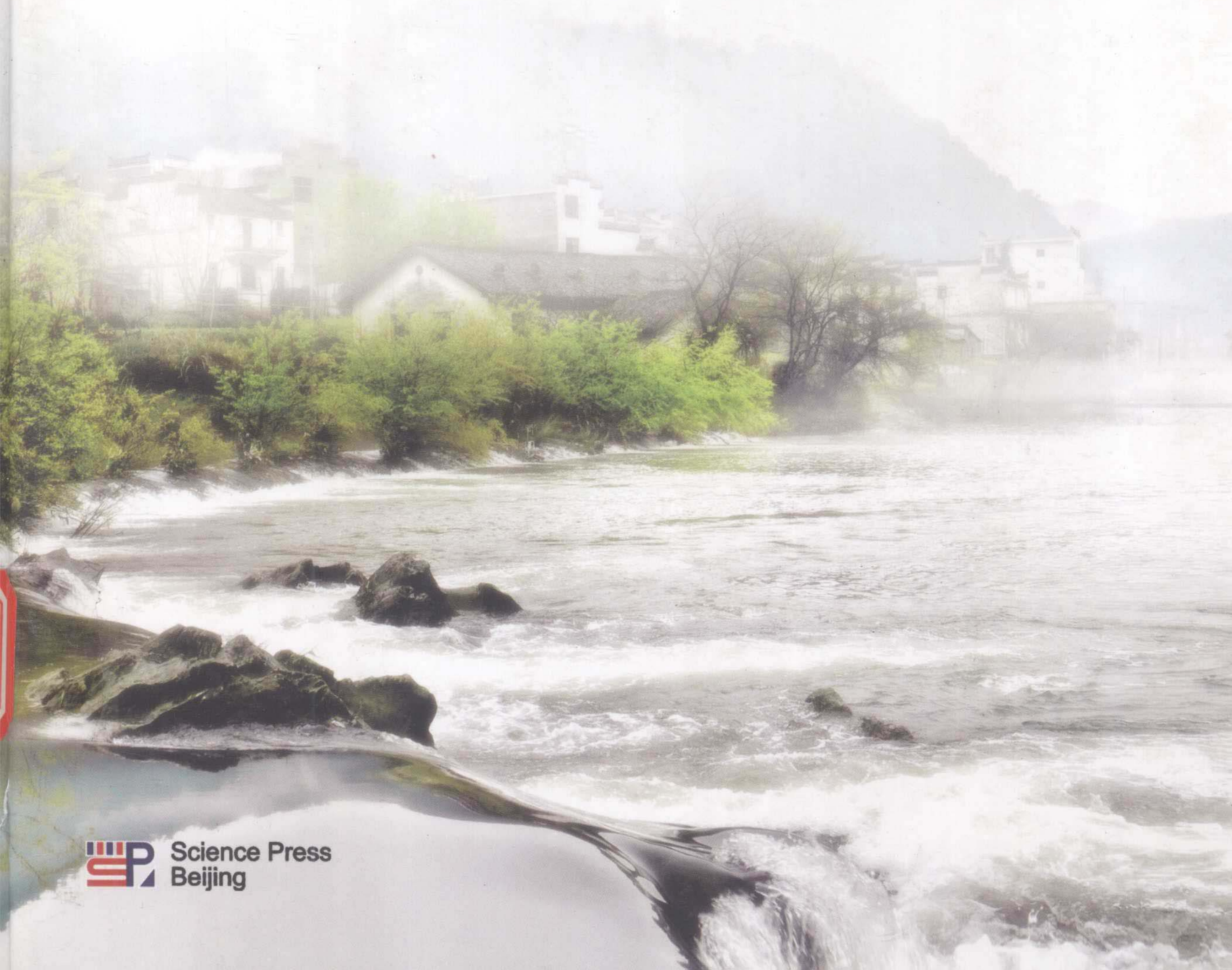

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Responsible Editors: Li Min Lv Cai Xia

Brief Introduction

This book introduces advanced technologies and methodologies in rainfall-runoff modelling and numerical weather prediction for the purpose of real-time flood forecasting. The Weather Research & Forecasting (WRF) model is integrated with the Probability Distribution Model (PDM) to make real-time flow forecasts in a UK catchment with a small concentration area. PART I (Chapter 1 and 2) gives a brief introduction of the book and introduces the study site and the data sources used in the studies. PART II (Chapter 3 and 4) explores two data mining issues regarding rainfall-runoff modelling in order to enable a better calibrated model for real-time flood forecasting. PART III (Chapter 5 ~ 8) introduces concepts and the development of numerical weather prediction, then sensitivity studies and variational data assimilation are carried out to improve the performance of the WRF model in high-resolution rainfall prediction. Finally, in PART IV (Chapter 9 and 10) the rainfall-runoff model PDM and the WRF model are integrated to make real-time flood forecasting in the study catchment. Issues for constructing a reliable forecasting system are concerned, conclusions and recommendations of this book are finally made.

This book can be used as a reference for researchers and students majored in hydrological engineering, environmental engineering and geosciences.

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Preface

This book focuses on integrating rainfall-runoff modelling with a mesoscale numerical weather prediction (NWP) model to make real-time flood forecasting at the catchment scale. Studies carried out are based on catchments in Southwest England with a main focus on the Brue catchment of an area of 135 km^2 and covered by a dense network of 49 rain gauges and a C-band weather radar. Studies in this book are composed of three main parts:

Firstly, two data mining issues are investigated to enable a better calibrated rainfall-runoff model for flood forecasting. The Probability Distributed Model (PDM), which is widely used in the UK, is chosen. One of the issues is the selection of appropriate data for model calibration regarding the data length and duration. It is found that the information quality of the calibration data is more important than the data length in determining the model performance after calibration. An novel index named the Information Cost Function (ICF) is developed on discrete wavelet decomposition, which is found to be efficient in identifying the most appropriate calibration data scenario. The other issue is the impact of the temporal resolution of the model input data in real-time forecasting. Through case studies and spectral analyses, the optimal choice of the data time interval is found to have a positive relation with the forecast lead time, i. e., the longer is the lead time, the larger should the time interval be. This positive relation is also found to be more obvious in catchments with longer concentration times. A hypothetical curve is finally concluded to describe the general impact of data time interval in real-time flood forecasting.

The development of the NWP model together with the weather radar allows rainfall forecasts to be made in high resolutions of time and space. In the second part of the book, experiments for improving numerical rainfall prediction are carried out based on the newest generation mesoscale NWP model, the Weather Research & Forecasting (WRF) model. The sensitivity of the WRF performance in rainfall simulation is firstly investigated for different domain configurations and various storm types regarding the evenness of rainfall distribution in time and space. Meanwhile a two-dimensional verification scheme is developed to quantitatively evaluate the WRF performance in temporal and spatial dimensions. Following that the WRF model is run in the cycling mode in tandem with the three-dimensional variational assimilation technique for continuous assimilating radar reflectivity and traditional surface/upper-air observations. The WRF model has shown its best performance in regenerating and forecasting rainfall for the storm events with two dimensional evenness of rainfall distribution; while for highly convective storms with rainfall concentrated in a small area and a short time period, the results are not ideal and further work needs to be done in the future.

Finally, the rainfall-runoff model PDM and the mesoscale NWP model WRF are integrated together with a real-time updating scheme, the Auto-Regressive and Moving Average (ARMA) model, to constitute a real-time flood forecasting system. The system is tested to be reliable in small catchments such as Brue and the use of the NWP rainfall products has shown great advantages in long lead-time forecasting when the lead time is beyond the catchment concentration time.

The following organisations are thanked for their models or datasets used in the studies of this book: British Atmospheric Data Centre (BADC), European Centre for Medium-Range Weather Forecasts (ECMWF), National Oceanic & Atmospheric Administration (NOAA), National Centers for Environmental Prediction (NCEP), National Center for Atmospheric Research (NCAR) and NERC Hydrological Radar EXperiment (HYREX). Special thanks go to Prof. Dawei Han in University of Bristol and Dr. Michaela Bray in Cardiff University, for their invaluable help and tremendous support in the book. The main results of the studies are based on the PhD work of the author, which was completed in the University of Bristol, UK.

This book was supported by the International Science and Technology Cooperation Program of China (Grant No. 2013DFG70990), the National Natural Science Foundation of China (Grant No. 51209225), and the Talent Cultivation Project of State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research (Grant No. 2014RC06).

刘佳 Jia Liu

5 May 2014 in Beijing

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PART Ⅱ Data mining issues for rainfall-runoff modelling

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PART Ⅰ Introduction and the study site

Chapter 1 Introduction

This chapter introduces the background and motivation of this book. Aims and objectives are proposed based on the uncertainty issues in real-time flood forecasting regarding to rainfall-runoff modelling and numerical weather prediction. The structure and layout of the book are then presented with brief introductions of the contents of each chapter.

Chapter 2 Study site and data sources

This chapter provides detailed description of the study site, the Brue catchment, located in Southwest England. Information about the HYREX experiment which provides most of the hydrological data and weather radar measurements used in this study is given. The initial input to the numerical weather model is also introduced and the utilisation of the all kinds of data sources is further explained.

Chapter 1 Introduction

1.1 Background and motivation

Floods are a regular feature of the British climate which can lead to severe damages and financial, environmental and human losses. Recent catastrophic events of this nature have included the 1998 Easter floods (Bye and Horner, 1998), the Autumn 2000 floods (Environment Agency, 2001), the 2004 Boscastle flood (Golding et al., 2005) and the Summer 2007 floods (Pitt, 2008). Earlier events that are still of significance are the 1953 East Coast floods caused by a storm surge, in which 200 people died; the 1952 Lynmouth flood, a summer thunderstorm event, in which 34 people died; and another summer thunderstorm event, the 1975 Hampstead storm, which interrupted rail and underground services in parts of London for several days (Golding, 2009). Due to the global climate warming and landuse changes, it appears that the envelope of extreme floods is still being pushed (Reynard et al., 2004). Therefore, there is an urgent need for more effective and reliable flood forecasting systems.

Ideally, a flood forecasting system should be able to provide not only accurate forecasts but also long enough lead times for appropriate actions to be taken. The core state-of-the-art of a tradition flood forecasting system is a rainfall-runoff model that utilises information of the current state of catchment together with forecasts of the model forcing (i.e., rainfall, etc.) to provide forecasts of water levels or discharges in the river system. Besides, the forecasting system also involves a real-time updating scheme and an external model to provide the forecasted rainfall. The updating scheme is used to assimilate real-time observations into the rainfall-runoff model for the improvement of the model outputs. For the forecasted rainfall, nowcasting methods are normally used to derive short lead-time forecasts based on extrapolation of the radar data (Ebert et al., 2004; Mecklenburg et al., 2002). Nowadays, the advancement in numerical weather prediction (NWP) has made it possible to increase the forecast lead time from a few hours to a few days (He et al., 2009). The mesoscale NWP model, which is used to downscale the low spatial resolution global NWP products to the catchment scale, has gained wide popularity in real-time flood forecasting. Its performance in accurately capturing some features of rainfall have been validated through increasingly more studies (e.g., Colle and Mass, 2000; Done et al., 2004; Davis et al., 2006; Etherton and Santos, 2008; Chang et al., 2009; Chen et al., 2010, etc.)

However, in the development of the flood forecasting system, many sources of uncertainty are included (Werner et al., 2009), i. e., the length and quality of historical data at the site, the structure of the rainfall-runoff model and the success with which the model is calibrated. When running operationally, these uncertainties also include the quality of the real-time observations used to update rainfall-runoff model, the function of the updating scheme, and not the least the uncertainties in the forecasted rainfall. Using the NWP rainfall products as the system inputs, the uncertainties include the domain configurations of the mesoscale NWP model, the use of appropriate parameterisations and the procedure of data assimilation, etc. The motivation of this study is to reduce the uncertainties during the construction of a reliable flood forecasting system, especially in the aspects of efficient utilisation of the hydrological observations, appropriate calibration of the rainfall-runoff model, and improving the NWP rainfall products through domain configuration and assimilation of the real-time meteorological and radar observations.

1.2 Scope and aim of the book

This book focuses on integrating aconceptual rainfall-runoff model with a mesoscale NWP model together with an updating scheme for real-time flood forecasting. The uncertainties addressed in this study are attributed to two parts, one is related to the rainfall-runoff model, and the other is in the rainfall products of the mesoscale NWP model. Aiming at reducing these uncertainties and improving the reliability of the flood forecasting system, the following issues are mainly addressed in this book:

1) Develop a numerical index for appropriate selection of the calibration data for the rainfall-runoff model regarding the data length and duration;

2) Investigate the impact of data time interval on the forecast accuracy when using the rainfall-runoff model and an updating scheme for real-time forecasting;

3) Provide guidance on the domain configuration of a newest-generation mesoscale NWP model and test the model's performance on simulating severe storms of different types;

4) Improve the NWP rainfall forecasts for different types of storm events by assimilating meteorological observations and the weather radar reflectivity;

5) Integrate the NWP rainfall products with the rainfall-runoff model, together with a real-time updating scheme, to make reliable real-time flood forecasting.

1.3 Layout and structure

Studies in this book are mainly conducted upon the Brue catchment, Somerset, based on the HYREX (HYdrological Radar EXperiment) dataset. Chapter 2 gives a detailed description of the catchment, the HYREX data from the rain gauge network and the weather radar, and also the input data used to drive the mesoscale NWP model.

The contents of the book can be divided into three main parts, as illustrated by Figure 1-1. Studies are focused on a lumped rainfall-runoff model, the PDM (Probability Distributed Model) and the newest generation of the mesoscale NWP model, the WRF (Weather Research and Forecasting) model. The first two parts of studies are carried out respectively to deal with the uncertainty issues related to these two models. In the third part, the two models are integrated together with a real-time updating scheme, which is chosen as the widely applied ARMA (AutoRegressive-Moving Average) model, for real-time flood forecasting.

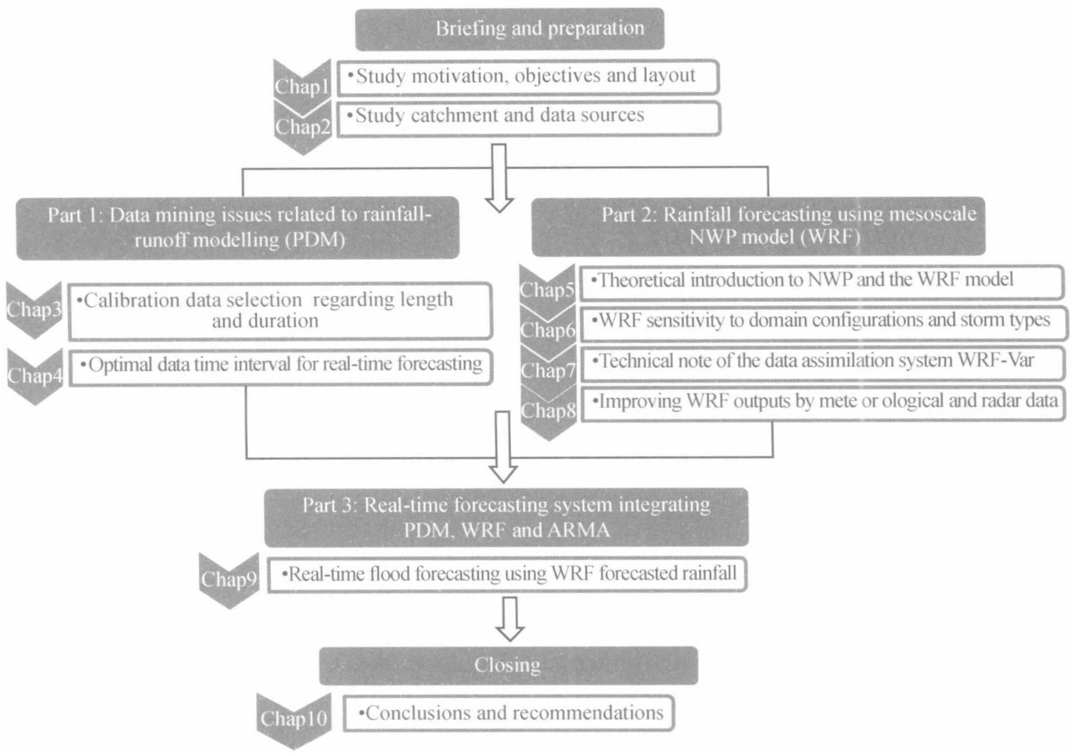

Figure 1-1 Layout and structure of the book

The first part study includes Chapter 3 and Chapter 4 in the book, regarding two data mining issues related to the rainfall-runoff model. It is known that the rainfall-runoff model is widely used in solving practical water problems, especially real-time flood forecasting. However, the confidence of the model depends on how successful the model parameters are calibrated. In Chapter 3, several spectral analysis methods are investigated to find a quantitative but efficient way for the selection of calibration data with appropriate lengths and durations. An index named Information Cost Function (ICF) is constructed based on the discrete wavelet decomposition and finally found to be effective in picking up the best data scenario for the calibration of the rainfall-runoff model. Besides the data length and duration, the temporal resolution of data used for model construction is also of great importance. Chapter 4 investigates the spectral characteristics and differences of hydrological data with various sampling intervals and tries to illustrate the impact of the data time interval on the forecasting accuracy through case studies. The case studies are carried out with four UK catchments including the Brue with different sizes of drainage areas. It is found that the optimal choice for the data time interval in real-time forecasting has a positive relation with the forecast lead time, and is highly affected by the catchment concentration time. A generalised pattern for the selection of the optimal time interval is finally proposed based on the results of the case studies. In Chapter 4, the real-time flood forecasting system is initially set up by using the PDM model and ARMA updating scheme, however, the perfect knowledge of future rainfall is assumed in Chapter 4 before it is provided later by the WRF model.

Chapters 5, 6, 7 and 8 constitute the second part of the book, which aims at providing more accurate rainfall forecasts from the NWP model for flood forecasting. Chapter 5 tells about the basic principles of numerical weather modelling, followed by a brief introduction of the WRF model. Among the various uncertainties in NWP modelling, the sensitivity of the WRF performance to different domain settings and various storm types is studied in Chapter 6. A two-dimensional verification scheme is proposed and proved to be successful in evaluating the grid-based WRF rainfall outputs according to the point-based observations from the rain gauge network. Then by fixing WRF on appropriate domain settings concluded from Chapter 6, data assimilation is carried out to further improve the accuracy of the WRF forecasted rainfall. Chapter 7 introduces the three-dimensional variational data assimilation system (WRF-3DVar) especially designed for WRF and detailed technical instructions are given on how to use each component of the system in operation. Following that in Chapter 8, WRF is run for different types of storm events together with WRF-3DVar to assimilate meteorological observations and radar reflectivity. Obvious improvements are seen in the rainfall forecasts after the data assimilation by WRF-3DVar. The improvements are further compared on different types of storms and on assimilating different kinds of observations.

In the third part, Chapter 9, the improved WRF rainfall forecasts by WRF-3DVar from Chapter 8 are put into the real-time forecasting system initially set up in Chapter 4 for flood forecasting. By now, the construction of an integral forecasting system is fulfilled, which consists of the NWP products, i. e., the rainfall forecasts from WRF, the rainfall-runoff model PDM and the updating scheme realised by the ARMA model. Uncertainty issues regarding the construction of the forecasting system are further studied in Chapter 9, including the reconsideration of the calibration data length of the PDM model, the calibration artifice of the ARMA parameters and the generation of synthetic potential evaporation data as another input of the forecasting system. Finally, the performance of the forecasting system is tested through different types of storm events and the use of the WRF forecasted rainfall is evaluated by a comparison with using perfect rainfall, naive rainfall and zero rainfall after the forecast origin. In the end, the last chapter, Chapter 10, summarises the findings made in this book and proposes ways in which this work can be advanced in the future.

Chapter 2 Study site and data sources

2.1 The Brue catchment

The Brue catchment is chosen as the study site for the main investigations carried out in this book. The catchment is located in Somerset, South West of England, as shown in Figure 2-1.

Figure 2-1 Location of the Brue catchment

It has a drainage area of 135 km^2 and an elevation range between 35 m to 190 m above the sea level. The whole catchment is dominated by pasture land on clay soils with some patches of woodland in the higher relief eastern half of the catchment. Figure 2-2 shows a three-dimensional view of the catchment relief in the National Grid Reference (NGR) coordinate. Average annual rainfall for the period 1961 to 1990 is 867 mm. River flow has a mean of 1.88 m^3/s and reached an instantaneous recorded maximum since 1965 of 96 m^3/s. The catchment has experienced exceptional storms and flooding as reported by Clark (1996), notably affecting the town of Bruton. Until the Martinstown (Dorset) storm of 1955, Bruton held the national record for the highest one-day rainfall at 243 mm on 28 July 1917; flooding was even greater in 1768 (Clark, 1999). A flood-detention reservoir now affords protection to Bruton, providing storage when inflows exceed about 8 m^3/s. More detailed geographic descriptions of the catchment are presented in Chapter 4 (Section 4.4.1) by descriptors in the Flood Estimation Handbook (Bayliss, 1999).

The choice of the study area was based on its representative of the UK catchments and the availability of dense rain gauge and radar data. Its size and relief together with previous history of notable storms and floods are representative of many catchments in the UK requiring flood warning using rainfall-runoff modelling methods. Furthermore, with six years of continuous data provided by weather radars and a 49 dense rain gauge network in the HYREX experiment, the Brue catchment enables an efficient evaluation of the NWP rainfall products and the improvement of numerical weather modelling by assimilating useful information from the weather radar.

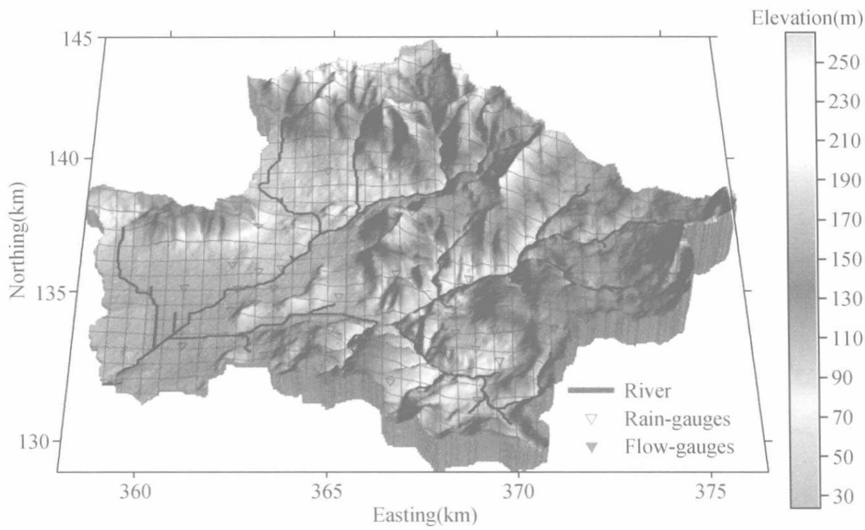

Figure 2-2 A 3D view of the Brue catchment in the NGR coordinate with the river and the locations of rainfall and flow gauges

2.2 The HYREX experiment

The HYdrological and Radar EXperiment (HYREX) was a three year research programme starting in September 1993, while data collection was continued until April 2000. HYREX aimed to advance hydrological science through gaining a better understanding of rainfall variability in space and time, as sensed by weather radar, and how this variability impacts on flow regimes at the catchment scale (Moore et al., 2000).

The experimental facilities in this experiment comprised a dense network of 49 recording rain gauges over the 135 km^2 catchment, with river flows measured at Lovington, and scanned by three weather radars: a conventional C-band radar at Wardon Hill, a new Doppler C-band radar at Cobbacombe Cross and an experimental Doppler dual-polarisation S-band radar at

Chilbolton, as shown in Figure 2-3. The Wardon Hill radar is highlighted in red, which is about 30 km to the south and gives a whole coverage of the Brue catchment. Additional facilities included a mobile vertical-pointing X-band radar, a line network of rapid response rain gauges aligned from Chilbolton towards the Brue, automatic weather and soil moisture stations, a disdrometer, radiosonde ascents from various locations and access to the Met Office Research Flight C130 aircraft. Support for this infrastructure came from the National River Authority (now the Environment Agency), the Met Office, the Ministry of Agriculture Fisheries and Food and a water utility (North West Water).

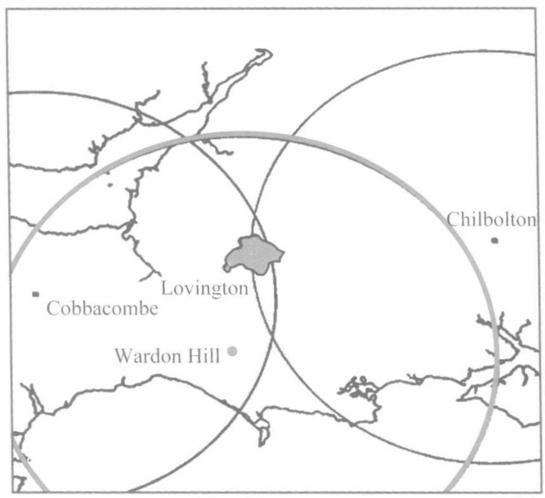

Figure 2-3 Radar coverage over the Brue catchment in the HYREX experiment

Much research has been generated from the HYREX dataset, producing many interesting findings, particularly during the HYREX experiment itself (e. g. , Bell and Moore, 2000; Moore et al. , 2000; Pedder et al. , 2000; Cluckie et al. , 2000). The rainfall-runoff observations used throughout the work discussed in this book, including the rainfall measurements from the dense rain gauge network and the weather radar, and also the observed flows at Lovington, are totally based on the HYREX experiment, which are available at the HYREX data archive at the BADC (British Atmospheric Data Centre) website (http://www. badc. nerc. ac. uk).

2. 3 Weather radar and rain gauge network

An overview of the weather radar and the rain gauge network in the HYREX experiment is given in this section. The radar measurements are assimilated into the WRF model for the improvement of the rainfall forecasting in Chapter 8; while the gauge rainfall observations are used for the data mining studies of the rainfall-runoff model in Chapter 3 and Chapter 4 together with the observed flows; meanwhile the gauge observed rainfall is also treated as the 'ground