

**Development of A Decision Support System For Flood Forecasting  
and Warning – A Case Study on The Maribyrnong River**

by

**Jin Wang**

P.Grad.Dip. in Computer Science (VUT, Australia)

M.Sc. in Eng. Hydrology (Galway, Ireland)

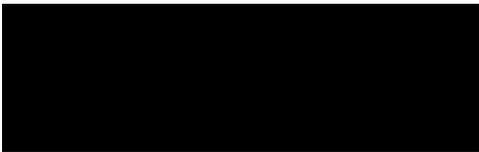
B.Eng. and M.Eng. (Hohai, China)

**This thesis is presented in fulfillment of  
the requirements of the degree of  
Doctor of Philosophy**

**School of Architectural, Civil and Mechanical Engineering  
Faculty of Health, Engineering and Science  
Victoria University  
Melbourne, Australia  
January 2007**

## **DECLARATION**

I declare that this thesis is less than 100,000 words in length, exclusive of tables, figures, appendices and references. This thesis contains no material, which has been accepted for the award of any other degree or diploma. To the best of my knowledge and belief, it contains no material previously published by another person, except where due reference is made in the text.



-----  
Jin WANG

To my parents, who passed away during my study, with love and appreciation

## **ACKNOWLEDGEMENTS**

First and foremost, I am especially indebted to my very patient and enthusiastic Principal Supervisor, Associate Professor Chris Perera without whose constant support this thesis could not be completed. I would like to thank him for his in-depth and creative comments, which were a constant source of my academic inspiration.

My thanks also go to Dr Andrews Takyi (Canada) for his contribution to my thesis in early stages as the Principal Supervisor.

I would like to thank Victoria University (VU) for offering me a Postgraduate Research Scholarship to do my PhD studies, and allowing me to use VU facilities for my research. I also pay my sincere thanks to all fellow postgraduate students, technical staff and administrative staff of the School of Architectural, Civil and Mechanical Engineering and the research office staff for their friendliness and willingness to help.

My enormous debt of gratitude also goes to Professor Brain Button at University of Canberra for his consistent assistance during the latter of my PhD study, during which time I have also been working for him.

Finally, I am indebted to my family. Without their support, tolerance and encouragement, I would not have completed this thesis. I would memorize respectfully my parents who taught me to respect learning. In particular, I would specially like to thank my loving wife Martha for her continuous support and also thank my children Mandy and Angela for their emotional support and tolerance. I extend my thanks to my parents-in-law Professors Yu Soulin and Zhu AiJuan, my sister and my brother whose encouragement were continuous inspirational sources for me to pursue this doctoral program.

## ABSTRACT

Floods are one of the most costly types of natural disasters in Australia and other parts of the world. It was reported that the average annual cost of flood damage in Australia was about \$300 million as at 1994. However, the effects of flooding can be mitigated, and thereby reduce the loss of life and damage to property. Flood mitigation measures can be categorised into two groups. The first group, the structural measures, involves civil works in the flood plain and/or catchment. The second group, the non-structural measures, includes flood forecasting, flood warning and emergency planning, planning controls and acquisition of flood prone land within the catchment, and providing flood insurance to affected people. The flood damage mitigation in the catchment or basin depends on complex social, economical and environmental conditions.

It is not always feasible to completely control or manage flood damage through structural measures due to economic, technological, environmental and social constraints. Therefore, non-structural measures such as flood forecasting and warning often play an important role in minimizing flood damage, especially, when there are no feasible structural measures that can be implemented. While planning, design, construction and operation of most structural measures can be done using definite mechanisms, the decisions of non-structural measures, especially flood forecasting and warning, are complex and are not uniquely defined. Therefore, such decisions require the aid of mathematical model results, and require both quantitative and qualitative decision modelling steps. Thus, these decisions can be effectively obtained through the use of a Decision Support System.

The Decision Support Systems (DSSs) have recently become popular in making decisions related to complex water resource problems. However, the design and the development of some of these applications do not contain all essential elements of a modern-day DSS, such as effective databases and file management facilities, user-friendly interfaces, appropriate simulation models, spatial and graphical data display and analysis modules, and facilities for effective decision making. Moreover, the theory of DSS and computer science has developed rapidly since the initial development of some of these applications. Furthermore, only a few applications of DSS in flood control and warning exists in the literature. These applications cited in the literature mostly deal with planning aspects of flood control, and not real-time flood forecasting and warning.

Therefore, considering the above facts, it is timely and necessary to develop an effective DSS to facilitate decision making of flood warning using all recent advances in DSS theory and computer science, and combining all necessary and desirable elements of a DSS into one system.

The Maribyrnong River basin is a medium size catchment located in the northwest of Melbourne in Victoria, Australia. Its low-lying flood plains along the lower sections of the river have been frequently being inundated by floods. A flood warning system has been established in 1975 after a major flood in 1974 to minimise flood damage in the lower part of the catchment. This system uses several numerical models such as the RORB model and the HEC-2 model for flood forecasting. However, there is no single computer-based system that integrates these models to facilitate analysis of different scenarios in controlling and managing the flood damage, and in making objective and effective decisions. Furthermore, the use of these separate models is time consuming and can lead to errors in transferring information from one model to another. Therefore, a computer-based DSS for flood forecasting and warning in the Maribyrnong River basin would enhance the effectiveness of flood warning in this catchment.

As part of this research, the author has defined the DSS as an interactive computer-based system that helps decision-makers to use data and models to solve semi-structured problems effectively. This DSS should allow the user to participate in principal steps of the decision making process, to simulate many steps in the process of decision making, to investigate alternative scenarios, to seek the overall goal for decision, and to improve the effectiveness of decision making. The author also suggested a DSS in water resources, which in most cases deals with spatial data display and analysis, should include five essential components: a database subsystem, a modelbase subsystem, an interface subsystem, a decision support subsystem, and a spatial and graphic data display and analysis subsystem.

Most previous research work on DSS development, especially in the area of water resources do not give details of the conceptual system design and details of the subsystems. This thesis provides the details of the conceptual system designs of all subsystems and their major functions. These approaches will help further system development of the DSS of this thesis. The general concept used in this thesis can be used for DSS studies in other water resource studies and in other fields.

Based on well-designed system, a unique decision support system, DSSFCMR (Decision Support System for Flood Control in the Maribyrnong River basin) was developed in this thesis to help decision making in flood forecasting and warning from data entry to search of final decisions. The DSSFCMR consists of five subsystems, namely Database Management System (DBMS), Modelbase, Spatial and Graphic Data Display and Analysis (SGDDA), Decision Support, and Interface. The DSSFCMR can consider various forecast rainfall depths in three different forecast periods. The developed Database subsystem can perform various tasks for database management related to flood warning. The URBS hydrological and HEC-RAS hydraulic models in the Modelbase subsystem are used to calculate flood hydrographs and corresponding flood water levels along the flood prone area respectively. Based on the calculated water levels, the shapefile for flood inundated area is instantly created, which is then used for spatial analysis of the flood inundated area through the developed interactive map interface. Two separate methods were developed in the SGDDA subsystem to perform spatial data display and analysis of the flood inundated area for use by different users (with different computer skills) and/or for organizations with different levels of resources. The process of complicated data transfer within DSSFCMR (e.g. the peak discharge to the flood water level, then flood water level to the shapefile of flood area) is automated by the developed system functions. The technology developed for decision choice support in this study helps to locate the required scenarios from many scenario results using the database technology. All functions are properly integrated together for the benefit of the user to make the decisions effectively.

The use of DSSFCMR to provide decision support for flood forecasting and warning in the Maribyrnong River basin was illustrated. The application was on the flood event that occurred on 04 October 1983, but under 1997 topographical conditions. Essentially, the application concentrated on flood forecasting and warning decisions at a particular time during the event. The system effectively performed calibration of the URBS and HEC-RAS models, forecasting of flood hydrographs, calculation of flood water levels, spatial data display of flood inundated areas and decision selection support for flood warning at this particular time. Generally, the developed system DSSFCMR can efficiently forecast flood hydrographs and calculate the flood water levels; the process of complex data transfer is done automatically and quickly; the data can be displayed flexibly in various formats; the system is easy to use by different users with different computer skills; the user can use DSSFCMR to investigate decision making variables related to flood warning (e.g. people relocation) conveniently and quickly. In summary, this system helps

the decision maker to make the decisions in relation to flood forecasting and warning in the Maribyrnong River basin effectively.

# TABLE OF CONTENTS

DECLARATION.....	II
ACKNOWLEDGEMENTS .....	IV
ABSTRACT .....	V
TABLE OF CONTENTS .....	IX
LIST OF FIGURES.....	XV
LIST OF TABLES .....	XXIII
CHAPTER 1 INTRODUCTION.....	1
1.1 BACKGROUND .....	1
1.2 DECISION SUPPORT SYSTEM (DSS).....	2
1.2.1 GENERAL .....	2
1.2.2 WHY DSS? .....	4
1.2.3 ADVANTAGES AND DISADVANTAGES OF A DSS FOR FLOOD FORECASTING AND WARNING.....	6
1.3 AIM OF THE STUDY .....	7
1.4 LAYOUT OF THE THESIS .....	7
CHAPTER 2 DECISION SUPPORT SYSTEMS – A REVIEW .....	9
2.1 INTRODUCTION .....	9
2.2 DECISION SUPPORT SYSTEMS.....	9
2.2.1 HISTORY .....	9
2.2.2 DECISION MAKING .....	10
2.2.3 DSS DEFINITION AND COMPONENTS .....	12
2.2.3.1 DSS DEFINITION .....	12
2.2.3.2 COMPONENTS (OR SUBSYSTEMS) OF A DSS.....	13
2.2.4 DSS DEVELOPMENT .....	14
2.2.4.1 PHASES (MODELS) OF DSS DEVOLVEMENT .....	14
2.2.4.2 DSS PLANNING AND ANALYSIS.....	16
2.2.4.3 DSS DESIGN .....	19

2.2.4.4	DSS DEVELOPMENT AND EVALUATION.....	22
2.2.4.5	DSS MAINTENANCE AND SERVICE .....	26
2.2.4.6	RECENT DSS APPLICATIONS OTHER THAN WATER RESOURCES .....	26
2.3	DSS IN WATER RESOURCES .....	27
2.3.1	GENERAL .....	27
2.3.2	WATER QUALITY AND ENVIRONMENT .....	28
2.3.3	WATER POLICY AND RESERVOIR OPERATION .....	29
2.3.4	FLOOD CONTROL.....	31
2.4	HYDROLOGICAL, HYDRAULIC AND ECONOMIC MODELS FOR FLOOD CONTROL .....	33
2.4.1	GENERAL .....	33
2.4.2	FLOOD FORECASTING .....	35
2.4.2.1	RAINFALL FORECASTING.....	35
2.4.2.2	WEATHER RADAR AND REMOTE SENSING FOR FLOOD FORECASTING.....	38
2.4.2.3	LARGE SCALE FORECASTING WEATHER FOR FLOOD FORECASTING IN REAL-TIME.....	40
2.4.2.4	SOME RELEVANT ASPECTS OF RAINFALL AND RUNOFF MODELS.....	41
2.4.3	FLOOD AREAS AND FLOOD LEVELS.....	44
2.5	SPATIAL AND GRAPHIC DATA DISPLAY AND ANALYSIS AND GIS APPLICATION .....	46
2.5.1	GIS APPLICATIONS .....	47
2.5.2	SGDDA IN DSS.....	50
2.6	DECISION SUPPORT AND DECISION CHOICE SUPPORT .....	52
2.6.1	DECISION SUPPORT.....	52
2.6.2	FLOOD WARNING .....	53
2.6.3	DECISION CHOICE SUPPORT .....	54
2.7	SUMMARY .....	55
CHAPTER 3 FOUNDATION THEORY OF DSSFCMR.....		58
3.1	DECISION SUPPORT SYSTEM .....	58

3.1.1	DESIGN ASPECTS .....	60
3.1.2	DEVELOPMENT ASPECTS .....	62
3.2	HYDROLOGICAL MODEL .....	63
3.2.1	URBS MODEL .....	63
3.2.2	INTEGRATION OF URBS MODEL .....	65
3.3	HYDRAULIC MODEL .....	70
3.3.1	BASIC THEORY OF HEC-RAS.....	72
3.3.2	INTEGRATION OF HEC-RAS MODEL.....	75
3.4	SPATIAL AND GRAPHICAL DATA DISPLAY AND ANALYSIS TECHNOLOGY	79
3.4.1	DXF FILE.....	80
3.4.2	SHAPEFILE .....	85
3.4.3	MAPOBJECTS.....	87
3.5	DECISION SUPPORT TECHNOLOGY.....	88
3.6	SUMMARY .....	91
CHAPTER 4 CONCEPTUAL DESIGN OF DSSFCMR .....		92
4.1	MARIBYRNONG RIVER BASIN AND ITS FLOOD MITIGATION.....	92
4.1.1	PLUVIOMETER AND STREAMFLOW GAUGING STATIONS.....	95
4.1.2	SUBCATCHMENT DATA FOR URBS MODEL .....	98
4.1.3	CROSS SECTION DATA FOR HEC-RAS MODEL .....	100
4.2	STRUCTURE OF DSSFCMR .....	101
4.3	DATABASE SUBSYSTEM (DBMS) .....	102
4.3.1	GENERAL .....	102
4.3.2	DETAILS OF CONCEPTUAL DESIGN .....	106
4.3.2.1	DATA INPUT .....	106
4.3.2.2	DATA DELETE AND UPDATE FUNCTIONS .....	107
4.3.2.3	DATA QUERY FUNCTION .....	107
4.3.2.4	OUTPUT FUNCTION .....	109
4.4	MODELBASE SUBSYSTEM .....	111
4.4.1	URBS HYDROLOGICAL MODEL.....	112
4.4.1.1	USE OF ACQUIRED KNOWLEDGE AND KNOWLEDGE LEARNING.....	112
4.4.1.2	MODEL DEFINITION AND PARAMETERS .....	113

4.4.1.3	CALIBRATION .....	115
4.4.2	HEC-RAS HYDRAULIC MODEL .....	115
4.5	SPATIAL AND GRAPHIC DATA DISPLAY AND ANALYSIS (SGDDA) SUBSYSTEM.....	118
4.5.1	GIS DATA.....	118
4.5.2	SGDDA METHODS IN DSSFCMR .....	120
4.6	DECISION SUPPORT SUBSYSTEM .....	123
4.7	INTERFACE SUBSYSTEM.....	123
4.8	DECISION MAKING IN REAL-TIME FLOOD FORECASTING AND WARNING	125
4.9	SUMMARY .....	129
CHAPTER 5 DSSFCMR SYSTEM DEVELOPMENT .....		131
5.1	MAIN MENU OF DSSFCMR .....	131
5.2	DATABASE AND SGDDA SUBSYSTEMS.....	132
5.2.1	MODEL PARAMETERS .....	134
5.2.1.1	PHYSICAL DATABASE TABLE DEVELOPMENT .....	134
5.2.1.2	FUNCTIONS AND INTERFACE DEVELOPMENT .....	135
5.2.1.3	ERROR HANDLING AND SAFETY SYSTEMS.....	142
5.2.1.4	SYSTEM STATUS .....	144
5.2.1.5	TESTING .....	144
5.2.2	HISTORICAL FLOOD EVENTS.....	145
5.2.2.1	PHYSICAL DATABASE TABLE DEVELOPMENT .....	145
5.2.2.2	FUNCTIONS AND INTERFACE DEVELOPMENT .....	146
5.2.2.3	ERROR HANDLING.....	158
5.2.3	REAL-TIME FLOOD EVENT .....	158
5.2.4	SIMULATED FLOOD SCENARIOS .....	160
5.2.4.1	PHYSICAL DATABASE TABLE DEVELOPMENT .....	160
5.2.4.2	FUNCTIONS AND INTERFACE DEVELOPMENT - FORECAST OR CALIBRATION URBS ONLY .....	161
5.2.4.3	ERROR HANDLING.....	168
5.2.5	REAL-TIME FLOOD WARNING .....	168
5.2.6	SUMMARY .....	176
5.3	RUN-MODELS .....	176

5.3.1	FUNCTIONS AND INTERFACE.....	177
5.3.1.1	CALIBRATION OF URBS HYDROLOGICAL MODEL .....	177
5.3.1.2	CALIBRATION OF HEC-RAS HYDRAULIC MODEL .....	184
5.3.1.3	FORECASTING.....	189
5.3.2	ERROR HANDLING.....	193
5.3.3	FINAL REMARKS .....	193
5.4	DECISION SUPPORT.....	194
5.5	INSTALLATION AND SYSTEM REQUIREMENTS.....	197
5.6	SUMMARY .....	198
CHAPTER 6 USE OF DSSFCMR FOR FLOOD WARNING IN MARIBYRNONG RIVER.		201
6.1	PROBLEM DEFINITION AND DECISION MAKING PROCESS .....	201
6.2	DATA PROCESS AND DATABASE MANAGEMENT.....	203
6.2.1	DATA ENTRY IN DSSFCMR.....	204
6.2.1.1	OBSERVED DATA ENTRY USING TEXT FILE (AT ROMSEY AND MACEDON).....	205
6.2.1.2	OBSERVED DATA ENTRY USING TABLE (AT CLARKEFIELD) .....	207
6.2.1.3	DATA ENTRY USING SINGLE RECORD ENTRY FROM INTERFACE (AT DARRAWEIT GUIM) .....	208
6.2.1.4	ENTERING DATA INTO DATABASE TABLE DIRECTLY (AT BULLA) .....	209
6.2.2	DATA MANAGEMENT IN DATABASE USING DEVELOPED FUNCTIONS .....	211
6.2.2.1	CHECK AND STUDY THE ENTERED DATA BY TABULAR AND GRAPHIC VIEW .....	211
6.2.2.2	FIXING INCORRECT DATA.....	213
6.2.2.3	DELETE INCORRECT OR UNWANTED DATA.....	216
6.2.3	FINAL REMARKS .....	218
6.3	HYDROLOGICAL MODEL CALIBRATION.....	218
6.3.1	CALIBRATION AND VALIDATION USING HISTORICAL FLOOD EVENT DATA .....	219
6.3.2	CALIBRATION FOR CURRENT FLOOD EVENT .....	227

6.4	HYDRAULIC MODEL CALIBRATION .....	232
6.5	FLOOD FORECASTING .....	238
6.6	FLOOD INUNDATION AREA DISPLAY AND SPATIAL ANALYSIS.....	245
6.7	DECISION SUPPORT.....	252
6.8	SUMMARY .....	258
CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS .....		260
7.1	ACHIEVEMENTS.....	261
7.2	STRENGTHS AND LIMITATIONS OF THIS RESEARCH.....	266
7.2.1	STRENGTHS.....	266
7.2.2	LIMITATIONS .....	268
7.3	FUTURE RESEARCH AND APPLICATION.....	269
7.4	CONCLUSIONS .....	270
REFERENCES.....		271

## LIST OF FIGURES

FIGURE 3.1 EXAMPLE OF A CATCHMENT DEFINITION FILE.....	66
FIGURE 3.2 EXAMPLE OF RAINFALL FILE .....	68
FIGURE 3.3 EXAMPLE OF A RAINFALL DATA FILE.....	69
FIGURE 3.4 EXAMPLE OF AN OUTPUT HYDROGRAPH DATA FILE.....	71
FIGURE 3.5 REPRESENTATION OF TERMS IN THE ENERGY EQUATION.....	73
FIGURE 3.6 SECTION OF A GEOMETRY DATA FILE USED IN HEC-RAS MODEL .....	77
FIGURE 3.7 CROSS SECTION 46 DETAILS .....	77
FIGURE 3.8 FLOW DATA FILE IN HEC-RAS MODEL .....	78
FIGURE 3.9 SEGMENT OF FLOW DATA FILE SHOWING PEAK DISCHARGE AND DOWNSTREAM WATER LEVEL.....	78
FIGURE 3.10 AN EXAMPLE OF A PART OF AN OUTPUT FILE OF HEC-RAS MODEL ..	79
FIGURE 3.11 RESULTS RELATED TO CROSS SECTION 46 .....	79
FIGURE 3.12 GROUP CODE RANGES .....	81
FIGURE 3.13 AN EXAMPLE OF A DXF FILE.....	83
FIGURE 3.14 SECTION DESCRIBING THE ONE POINT IN FIGURE 3.13 .....	84
FIGURE 3.15 FIELDS IN THE FILE HEADER IN MAIN FILE .....	86
FIGURE 3.16 VALUE FOR SHAPE TYPE.....	86
FIGURE 4.1 MARIBYRNONG RIVER BASIN .....	93
FIGURE 4.2 FLOOD PRONE AREA .....	94
FIGURE 4.3 STREAMFLOW AND RAINFALL GAUGING STATIONS, AND SUBCATCHMENTS OF URBS MODEL .....	96
FIGURE 4.4 CROSS SECTIONS IN FLOOD PRONE AREA OF MARIBYRNONG RIVER	100
FIGURE 4.5 STRUCTURE OF DSSFCMR.....	102
FIGURE 4.6 STRUCTURE OF DBMS.....	103
FIGURE 4.7 BASIC ELEMENTS OF DATABASE.....	104

FIGURE 4.8 DATA ENTRY MODULE IN DATABASE SUBSYSTEM .....	108
FIGURE 4.9 DATA DELETE AND UPDATE MODULE IN DBMS .....	109
FIGURE 4.10 DATA QUERY MODULE IN DBMS .....	110
FIGURE 4.11 OUTPUT MODULE IN DBMS .....	111
FIGURE 4.12 HYDROLOGICAL MODEL PARAMETERS MODULE IN MODELBASE...	114
FIGURE 4.13 CALIBRATION URBS HYDROLOGICAL MODEL .....	116
FIGURE 4.14 CALIBRATION OF HEC-RAS HYDRAULIC MODEL.....	117
FIGURE 4.15 DATA FLOW IN SGDDA .....	122
FIGURE 4.16 CONCEPTUAL DESIGN DECISION SUPPORT SUBSYSTEM.....	124
FIGURE 4.17 MAIN MENU OF DSSFCMR.....	125
FIGURE 4.18 PROCESS OF DECISION MAKING WITH REAL-TIME FLOOD FORECASTING.....	128
FIGURE 5.1 WELCOME SCREEN OF DSSFCMR.....	132
FIGURE 5.2 INTERFACE OF MAIN MENU IN DSSFCMR .....	133
FIGURE 5.3 END INTERFACE OF DSSFCMR .....	133
FIGURE 5.4 SCREEN OF URBS MODEL PARAMETERS IN DATABASE MENU.....	136
FIGURE 5.5 EXAMPLE SCREEN OF ADDING OR DELETING A MODEL PARAMETER VALUE.....	137
FIGURE 5.6 EXAMPLE SCREEN OF SELECTING A SUBCATCHMENT .....	139
FIGURE 5.7 SCREEN OF HEC-RAS MODEL PARAMETERS IN DATABASE MENU .....	140
FIGURE 5.8 AN EXPECTED ERROR WARNING WINDOW .....	143
FIGURE 5.9 AN UNEXPECTED ERROR WARNING WINDOW .....	143
FIGURE 5.10 HISTORICAL FLOOD EVENTS WINDOW .....	147
FIGURE 5.11 INPUT CONFIRMATION SCREEN FOR HISTORICAL FLOOD EVENTS DATA ADDING .....	147

FIGURE 5.12 SCREEN TO CONFIRM DELETING ALL RECORDS IN DATABASE TABLE .....	147
FIGURE 5.13 TABLE FOR DIRECTLY ENTERING DATA AFTER DELETING ALL RECORDS.....	148
FIGURE 5.14 TABLE FOR DIRECTLY ENTERING DATA AFTER KEEPING ALL RECORDS IN DATABASE TABLE .....	148
FIGURE 5.15 SCREEN FOR ENTERING THE DATA FROM DATA FILE.....	149
FIGURE 5.16 SCREEN FOR BROWSING DATA FILE.....	149
FIGURE 5.17 ADDING A RECORD IN HISTORICAL FLOOD EVENTS .....	150
FIGURE 5.18A INTERFACE OF DELETING A RECORD IN HISTORICAL FLOOD EVENTS.....	151
FIGURE 5.18B INTERFACE OF FIND EXPRESSION BUILDER IN DBMS.....	151
FIGURE 5.19 DELETE CONFIRMATION SCREEN.....	152
FIGURE 5.20 QUERY BUILDER SCREEN IN DBMS.....	153
FIGURE 5.21 QUERY BUILDER SCREEN DEALING WITH AN EXAMPLE .....	153
FIGURE 5.22 QUERY RESULT SHOW SCREEN FOR QUERY STATEMENT IN FIGURE 5.21 .....	154
FIGURE 5.23 QUERY RESULT SHOW SCREEN FOR QUERY STATEMENT USING MULTIPLE:AND.....	155
FIGURE 5.24A INTERFACE OF UPDATE OF HISTORICAL FLOOD EVENTS IN DBMS	156
FIGURE 5.24B INTERFACE OF FIND EXPRESSION BUILDER IN DBMS.....	156
FIGURE 5.25 INTERFACE OF VIEW OF HISTORICAL FLOOD EVENTS IN DBMS .....	157
FIGURE 5.26 SUB MENU OF MENU ITEM ON FIGURE 5.25 .....	158
FIGURE 5.27 REAL-TIME FLOOD EVENT WINDOW .....	159
FIGURE 5.28 INTERFACE OF FORECAST OR CALIBRATION URBS ONLY.....	162
FIGURE 5.29 INTERFACE OF CONFIRMATION FOR BUTTON NEW ACTION IN FIGURE 5.28 .....	163

FIGURE 5.30 INTERFACE OF CONFIRMATION FOR BUTTON DELETE ACTION IN FIGURE 5.28.....	164
FIGURE 5.31 INTERFACE OF OBSERVED AND CALCULATED HYDROGRAPHS .....	164
FIGURE 5.32 SUB MENU OF MENU ITEM ON FIGURE 5.31 .....	164
FIGURE 5.33 INTERFACE OF IMAGE DISPLAY OF A SELECTED SIMULATED FLOOD RECORD.....	165
FIGURE 5.34 INTERFACE OF INTERACTIVE FLOOD WATER LEVEL ANALYSIS .....	166
FIGURE 5.35 INTERFACE OF REAL-TIME FLOOD WARNING .....	170
FIGURE 5.36 INTERFACE FOR SEARCHING STORED DECISIONS IN DATABASE D6RFW.....	171
FIGURE 5.37 INTERFACE OF THE HYDROGRAPH IN KEILOR IN THE PHASE OF FORECASTING.....	175
FIGURE 5.38 SUB ITEMS OF MENU ITEM ON FIGURE 5.37 .....	175
FIGURE 5.39 SUBMENU OF RUN-MODELS.....	177
FIGURE 5.40 DATA INPUT SCREEN OF CATCHMENT DEFINITION FILE IN URBS MODEL CALIBRATION.....	178
FIGURE 5.41 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE - CALIBRATION .....	180
FIGURE 5.42 WARNING SCREEN FOR USING OBSERVED RAINFALL FOR EACH SUB CATCHMENT .....	182
FIGURE 5.43 SCREEN OF RAINFALL IN EACH SUB CATCHMENT READ FROM DATABASE D4RFE.MDB .....	182
FIGURE 5.44 SCREEN SHOWING SAME RAINFALL IN EACH SUB CATCHMENT.....	183
FIGURE 5.45 SCREEN SHOWING DIFFERENT RAINFALLS IN DIFFERENT SUB CATCHMENTS .....	183
FIGURE 5.46 INTERFACE FOR CALIBRATING HEC-RAS MODEL.....	185
FIGURE 5.47 MAIN MENU OF HEC-RAS.....	186

FIGURE 5.48 STEADY FLOW ANALYSIS .....	186
FIGURE 5.49 PROCESS FOR CALCULATION .....	187
FIGURE 5.50 PROFILE OUTPUT TABLE .....	187
FIGURE 5.51 SAVE OUTPUT INTO TEXT FILE .....	187
FIGURE 5.52 RESULTS OF CALIBRATION HEC-RAS MODEL .....	188
FIGURE 5.53 DATA INPUT SCREEN OF CATCHMENT DEFINITION FILE IN URBS MODEL - FORECASTING .....	189
FIGURE 5.54 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE IN VRBS MODEL – FORECASTING.....	190
FIGURE 5.55 INTERFACE TO FIND SCENARIOS IN D5SFS.MDB TO BUILD ACCEPTABLE DECISION SCENARIOS .....	196
FIGURE 5.56 DECISION SCENARIOS CORRESPONDING TO QUERY IN FIGURE 5.55	197
FIGURE 5.57 CONTENTS OF DSSFCMR DIRECTORY .....	198
FIGURE 6.1 DECISION MAKING PROCESS FOR FLOOD FORECASTING AND WARNING.....	202
FIGURE 6.2 HISTORICAL FLOOD EVENTS WINDOW .....	205
FIGURE 6.3 SCREEN FOR ENTERING THE DATA FROM DATA FILE.....	206
FIGURE 6.4 SCREEN FOR OPENING DATA FILE .....	206
FIGURE 6.5 INTERFACE FOR TABULAR DATA ENTRY METHOD FOR CLARKEFIELD (BEFORE DATA ENTRY).....	207
FIGURE 6.6 INTERFACE FOR TABULAR DATA ENTRY METHOD FOR CLARKEFIELD (AFTER DATA ENTRY) .....	208
FIGURE 6.7 INTERFACE FOR ADDING A RECORD .....	209
FIGURE 6.8 THE INTERFACE FOR ADDING A RECORD (AFTER ENTERING THE DATA).....	209
FIGURE 6.9 INTERFACE FOR ENTERING DATA FROM DATABASE DIRECTLY FOR BULLA.....	210

FIGURE 6.10 INTERFACE SHOWING ‘NO MATCHED DATA FOUND’ FOR BULLA....	212
FIGURE 6.11 INTERFACE TO VIEW TABULAR AND GRAPHIC DATA AT BULLA ....	212
FIGURE 6.12 MENU OF ITEM OF FIGURE 6.11 .....	212
FIGURE 6.13 VIEWING DATA AT BULLA .....	213
FIGURE 6.14 INTERFACE FOR HISTORICAL FLOOD EVENTS WITH FUNCTION BUTTONS INACTIVE.....	214
FIGURE 6.15 INTERFACE FOR UPDATING DATA .....	215
FIGURE 6.16 INTERFACE FOR SEARCHING DATA FOR UPDATING.....	215
FIGURE 6.17 SEARCHING INCORRECT DATA FOR UPDATING.....	215
FIGURE 6.18 ERRONEOUS DATA RECORD WHICH REQUIRES UPDATING.....	216
FIGURE 6.19 TABULAR AND GRAPHIC DATA REVIEW FOR UPDATED RESULTS ...	217
FIGURE 6.20 LAST RECORD FOR DELETION .....	217
FIGURE 6.21 DELETE CONFIRMATION WINDOW .....	218
FIGURE 6.22 INTERFACE FOR CHECKING DELETION.....	218
FIGURE 6.23 DATA INPUT SCREEN OF CATCHMENT DEFINITION FILE IN URBS MODEL CALIBRATION.....	219
FIGURE 6.24 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE IN URBS MODEL CALIBRATION .....	220
FIGURE 6.25 SCREEN OF SIMULATED FLOOD SCENARIO FOR CALIBRATION .....	222
FIGURE 6.26 OBSERVED AND CALCULATED HYDROGRAPHS FOR CALIBRATING URBS MODEL .....	223
FIGURE 6.27 RESULTS OF SIMULATE FLOOD SCENARIOS .....	224
FIGURE 6.28 SCREEN OF URBS MODEL PARAMETERS IN DATABASE MENU.....	224
FIGURE 6.29 DERIVED PARAMETER INPUT SCREEN OF CATCHMENT DEFINITION FILE TO CHECK CALIBRATION.....	226
FIGURE 6.30 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE FOR FLOOD EVENT IN 1987 TO CHECK CALIBRATION.....	226

FIGURE 6.31 HYDROGRAPH FOR CALIBRATION IN 1987 FLOOD EVENT .....	227
FIGURE 6.32 DATA INPUT SCREEN OF CATCHMENT DEFINITION FILE IN URBS MODEL CALIBRATION.....	228
FIGURE 6.33 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE IN URBS MODEL CALIBRATION .....	229
FIGURE 6.34 SCREEN OF SIMULATED FLOOD SCENARIO FOR CALIBRATION .....	230
FIGURE 6.35 OBSERVED AND CALCULATED HYDROGRAPHS FOR CALIBRATING URBS MODEL .....	231
FIGURE 6.36 RESULTS OF SIMULATE FLOOD SCENARIOS .....	232
FIGURE 6.37 INTERFACE FOR CALIBRATING HEC-RAS MODEL.....	233
FIGURE 6.38 RESULTS OF CALIBRATION HEC-RAS MODEL.....	237
FIGURE 6.39 DATA INPUT SCREEN OF CATCHMENT DEFINITION FILE – FORECASTING.....	239
FIGURE 6.40 DATA INPUT SCREEN OF RAINFALL DEFINITION FILE – FORECASTING .....	240
FIGURE 6.41 PLUVIOMETER NAMES AND CORRESPONDING FORECAST RAINFALLS .....	242
FIGURE 6.42 RAINFALL PERCENTAGES IN FIRST, SECOND AND THIRD HOUR AT EACH STATION .....	245
FIGURE 6.43 RESULTS FOR ALL FLOOD FORECASTING SCENARIOS.....	246
FIGURE 6.44 HYDROGRAPH DISPLAY DURING FLOOD FORECASTING STAGE WITHOUT FORECASTS.....	246
FIGURE 6.45 FLOOD PRONE AREA WITHOUT FLOOD LINES .....	247
FIGURE 6.46 FLOOD AREA IMAGE FOR FORECASTING SCENARIO 12 .....	247
FIGURE 6.47 FLOOD AREA IMAGE FOR FORECASTING SCENARIO 1 .....	248
FIGURE 6.48 FLOOD AREA IMAGE FOR FORECASTING SCENARIO 11 .....	248
FIGURE 6.49 INTERFACE FOR SPATIAL ANALYSIS OF FLOODED AREA .....	249

FIGURE 6.50 FULL EXTENT OF CATCHMENT MAP .....	250
FIGURE 6.51 SELECTING A RECTANGLE AREA FOR ZOOM IN.....	250
FIGURE 6.52 ZOOM IN RESULT FOR SELECTED AREA .....	251
FIGURE 6.53 FURTHER ZOOM IN RESULTS FOR SELECTED AREA .....	251
FIGURE 6.54 RESULTS FOR DRAGGING THE MAP .....	251
FIGURE 6.55 MAP SHOWING CROSS SECTION NUMBERS .....	251
FIGURE 6.56 MAP SHOWING WATER LEVELS AT CROSS SECTIONS.....	251
FIGURE 6.57 SELECTED FLOODED AREA SHOWING INUNDATED PROPERTIES .....	251
FIGURE 6.58 WHOLE FLOOD PRONE AREA SHOWING INUNDATED PROPERTIES ..	252
FIGURE 6.59 INTERFACE OF THE FORM TO FIND SOME SOLUTIONS.....	253
FIGURE 6.60 INTERFACE OF SELECTED SCENARIOS IN DATABASE D5SFS .....	254
FIGURE 6.61 WINDOW FOR TRANSFERRING SELECTED SCENARIOS FOR DECISION MAKING.....	255
FIGURE 6.62 INTERFACE SHOWING DECISION SCENARIOS .....	256
FIGURE 6.63 FORECAST HYDROGRAPH FOR SELECTED DECISION SCENARIO 1 ...	256
FIGURE 6.64 INTERFACE FOR SEARCHING STORED DECISION IN DATABASE D6RFW.MDB .....	257

## LIST OF TABLES

TABLE 2.1 DSS DEVELOPMENT MODEL (OR PHASES) .....	17
TABLE 4.1 PLUVIOMETER AND FLOW STREAM GAUGING STATIONS.....	97
TABLE 4.2 STATION NUMBER CONFIGURATIONS FOR CASE STUDY.....	98
TABLE 4.3 SUBCATCHMENTS DETAILS USED IN URBS MODEL .....	98
TABLE 4.4 CROSS SECTIONS USED FOR HEC-RAS MODEL .....	101
TABLE 4.5 SPATIAL DATA PROCESS .....	119
TABLE 4.6 DETAILS OF MAIN MENU ITEMS .....	126
TABLE 6.1 REQUIRED WORK FOR FLOOD FORECASTING AND WARNING DECISION MAKING.....	203
TABLE 6.2 MODEL PARAMETERS USED FOR THE 1ST CALIBRATION SCENARIOS	235
TABLE 6.3 MODEL PARAMETERS USED FOR THE 2ND CALIBRATION SCENARIOS	236
TABLE 6.4 TWELVE FLOOD FORECASTING SCENARIOS USED IN THIS APPLICATION .....	239
TABLE 6.5 FORECAST 1-HOUR LOW, MEDIUM AND HIGH RAINFALLS.....	242
TABLE 6.6 FORECAST 3-HOUR LOW AND HIGH RAINFALLS .....	243

# CHAPTER 1

## INTRODUCTION

### 1.1 Background

Floods are one of the most costly types of natural disasters in Australia and other parts of the world. According to Bureau of Transport Economics (2001), floods had accounted for 29 percent of total natural disaster costs, over the past 30 years since 2001. It was reported that the average annual cost of flood damage in Australia was about \$300 million (CRC for Catchment Hydrology, 1994; Bureau of Transport and Regional Economics, 2002). However, the effects of flooding can be mitigated, and thereby reduce the loss of life and damage to property (Water Resources Council Victoria, 1978; Bureau of Transport and Regional Economics, 2002). Flood mitigation measures can be categorised into two groups. The first group, the structural measures, involves civil works in the flood plain and/or the catchment, and includes construction of dams, reservoirs, retarding basins and levee banks; channel modifications; flood-proofing of properties; catchment modifications; and schemes of drainage and flood protection works. The second group, the non-structural measures, includes flood forecasting, flood warning and emergency planning, planning controls and acquisition of flood prone areas within the catchment, and providing flood insurance to affected people. The Flood Forecasting and Warning in the catchment or basin depends on complex social, economic and environmental conditions.

In general, it is not always feasible to completely control or manage flood damage through structural measures due to economic, technological, environmental and social constraints. Therefore, non-structural measures such as flood forecasting and warning often play an important role in minimizing flood damage, especially when there are no possible structural measures to be completed in the near future. While planning, design, construction and operation of most structural measures can be done using definite mechanisms, the decisions of non-structural measures, especially flood forecasting and warning, are complex and are not uniquely defined. Therefore, such decisions require the aid of mathematical model results, and require both quantitative and qualitative decision modelling steps. Thus, these decisions can be effectively obtained through the use of a Decision Support System (DSS). The development of such a DSS is the focus of this thesis with specific reference to Flood Forecasting and Warning in the Maribyrnong River basin, in Victoria, Australia.

The Maribyrnong River basin is a medium size catchment located in the northwest of Melbourne in Victoria. Its low-lying flood plains along the lower sections of the river have been frequently inundated by floods. A flood warning system was established in 1975 after a major flood in 1974 (Melbourne and Metropolitan Board of Works, 1988) to minimise flood damage in the lower part of the catchment. The system uses several numerical models such as RORB (Laurenson and Mein, 1995) model, HEC-2 model (USACE, 1982a) for flood forecasting. However, there is no single computer-based system that integrates these models to facilitate analysis of different scenarios in controlling and managing the flood damage, and in making objective and effective decisions. Furthermore, the use of these separate models is time consuming and can lead to errors in transferring information from one model to another. Therefore, a computer-based DSS for Flood Forecasting and Warning in the Maribyrnong River would enhance the effectiveness of flood warning in this catchment.

## **1.2 Decision Support System (DSS)**

### **1.2.1 General**

The decision making process for solving a complex problem such as Flood Forecasting and Warning generally consists of four phases as follows (McLeod, 1995).

- searching the environment for conditions calling for a solution,
- investigating, developing and analysing the possible courses of action,
- selecting a particular course of action from the above actions, and
- assessing the selected course of action.

If it is possible to specify algorithms for the first three phases of the above decision making process of a complex problem, then the problem is said to be structured. An unstructured problem, on other hand, is one in which none of the above first three phases is structured. A semi-structured problem is one in which one or two of the above three phases are structured. Many water resource problems are semi-structured.

The DSS, which is a computer-based system for solving semi-structured problems; allows the decision-maker to simulate many steps of the process of decision making, investigate the alternative decision scenarios, and to improve the decision making effectiveness. Although there is no unique definition or standard components of a decision support system, the

purpose of a DSS is to increase both the efficiency and effectiveness (Power, 2002). However, McLeod (1995) showed that a DSS significantly increases the effectiveness of decision-making, but does not improve the efficiency. Therefore, a well-designed and developed DSS can improve effectiveness of the flood forecasting and flood warning.

A DSS in general uses recent advances in computer science and decision making theory. Based on the advances in computer technology, a modern-day DSS could include five subsystems: Database, Modelbase, Spatial and Graphic Data Display and Analysis (SGDDA), Decision Support, and Interface.

The Decision Support Systems (DSSs) have recently become popular in making decisions related to complex water resource problems (e.g. Srinivasan and Engel, 1994; Loucks, 1995; Dunn et al., 1996; Jamieson and Fedra, 1996a,b; and Fedra and Jamieson, 1996; Simonovic, 1998; Ito et al., 2001; Makropoulos et al., 2003). However, the design and the development of some of these applications do not contain all essential items of a modern-day DSS, such as effective databases and file management facilities, user-friendly interfaces, appropriate simulation models, spatial and graphical data display and analysis modules, and facilities for effective decision making. Moreover, the theories of DSS and computer science have developed rapidly since the time of the development of some of these applications.

In spite of recent popularity of DSSs in water resources, only a few applications of DSS in flood control and warning exists in the literature. Some examples are the work of Ford (2001), Shim et al. (2002) and Ford and Killen (1995). These few applications that exist in flood control and warning, mostly deal with planning aspects of flood control, and not real-time flood forecasting and warning. However, there are some applications dealing with specific areas of flood warning. For example, Cock and Elliott (1989) and Kelly and Krzysztofowicz (1994a) concentrated their work only on flood warning, while Lardet and Obled (1994), Camara et al. (2000) and Sun et al. (2000) studied rainfall forecasts for flood warning.

Considering the above facts, it is therefore necessary to develop an effective DSS to facilitate decision making of flood warning using all recent advances in DSS theory and computer science, and combining all necessary elements of a DSS into one system.

## 1.2.2 Why DSS?

There exists a number of reasons that show why a DSS can benefit the flood forecasting and warning decision making process, and some of them are listed below under two categories, namely why we can use a DSS and why we should use a DSS.

- Why can we use a DSS?
  - Semi-structured nature of the decision making process for flood forecasting and warning. There is no doubt that many steps in decision making process for flood forecasting and warning are structured (i.e. the algorithms can be found for each specific step). For example, the rainfall forecasting model can predict the future rainfall, the hydrological model can calculate the inflow flood hydrograph, and the hydraulic model can estimate the flood water levels. However, with many possible future flood water levels forecasted from various models under various uncertain parameters and variables (such as potential rainfall and unexpected flood volume in or out of the affected area), there is no single algorithm that directly produces a unique quantitative flood warning decision that exactly matches the future flood condition. The DSS can be used to analyse these multiple solutions in making the decision.
  - Improved theory and practice in application related areas such as hydrology, meteorology, decision support systems, computer science and spatial analysis. For example, there are many hydrological theories that have matured in the recent past such as the distributed and/or semi-distributed catchment representation method commonly used in Australian runoff routing models - RAFTS (Goyen, 1987), RORB (Laurenson and Mein, 1995), URBS (Carroll, 1995) and WBNM (Boyd et al., 1996). At the same time, the computer models that use these hydrologic theories are well developed and are accepted by the potential users. Another example is that the programming tools such as Microsoft Visual Studio by Microsoft (<http://www.microsoft.com>) and Java by Sun (<http://java.sun.com>) have become more convenient and powerful. All these theories and practices provide vigorous tools or vendors in DSS development.
  - Popular computer use. More and more managers and decision makers use computer technology with less anxiety. In fact, a study estimated that among 500 companies, about 10 percent of Chief Executive Officers (CEOs) and about 33 percent of high-

level managers use computers regularly in their decision making process (Sauter, 1997). As a computer based system, the DSS is becoming popular among the decision makers.

- Lower costs of development of DSS. The costs of tools for developing DSSs are dramatically reducing with recent advances in computer and information technology. For example, the prices of hardware, software including operation systems, programming tools and databases are becoming less expensive while their functions are becoming more advanced. At the same time, the developers with many different skills (which are necessary for development of an effective DSS) are being trained through proper education. Furthermore, the decision makers realize that the cost of not using the technology in decision making is becoming very high.
  
- Why should we use a DSS?
  - Complexity of the decision making process. The quantitative decision making in flood forecasting and warning determines the potential benefits of reduced flood damage in a flood affected area. However, the process of quantitative decision making is complex, since (a) there are many uncertain factors (such as forecast rainfall) that affect the accuracy of warning time and flood levels; (b) many organizations are involved in the process of decision making and related operation; and (c) there is no unique algorithm, which produces the accurate flood warning decision. However, the DSS can include much knowledge, and many data items and models to solve the complex problem of flood forecasting and warning. It can be effectively used to investigate key issues such as flood warning time and flood affected area through a number of scenarios, to account for complexity in decision making.
  - Limitations of human information process. With comprehensive decision-making required for flood forecasting and warning and the associated large information base, many knowledge processes and models could be applied to make effective decisions. The human interaction (such as transferring results from one model to another and the results from the models to the paper for presentation) can lead to errors and is often time consuming. A DSS system can improve the work effectiveness by eliminating errors in transferring information from models (and hence reducing the time used by the decision maker in analyzing “what if“ questions). While comprehensive and optimal solutions are desirable, the human information and

interaction process makes it difficult to investigate the optimal solution for flood warning. The approach in a DSS is to start with an approximate optimal solution and allows the user to refine it using DSS tools and expertise.

- Adoption of products. It is not generally possible to transfer the benefits of a traditional flood forecasting and warning system from one site to another. However, the DSS with flood forecasting and warning capabilities can include many knowledge processes and models to adopt the system for any location with minor modifications.

### **1.2.3 Advantages and Disadvantages of a DSS for Flood Forecasting and Warning**

- Advantages

- The decision maker can easily and directly involve in the many steps of decision making process in Flood Forecasting and Warning through the DSS such as the problem definition, investigation of flood mitigation measures, etc. The decision is made by the decision makers themselves rather than the machine.
- The decision maker can conveniently and quickly access various data and knowledge that are stored in the DSS. Examples of such data and knowledge include the historical climatic data, the historical flood data, the social and economic data in flood affected area, the previous flood forecasting and warning decisions, and the policies on flood mitigation. Data can be viewed in various ways. Furthermore, data types such as flood water levels and economic data can be combined to produce complete information for flood warning.
- Many ideas about the potential flood damage and related warning can be investigated through several scenarios using models in the DSS. The data and knowledge available in DSS can be employed by the models (in the same DSS) to produce information on potential flood damage and warning. These processes in a DSS are quicker and accurate than the manual processes.
- The DSS has the facility to provide the decision support to finalize the decision.
- The interface between various elements in the DSS provides the user with an environment to work easily and quickly.
- The DSS is easily adopted for another flood control system in a different location, with slight modifications.

- Disadvantages

- The decision maker needs the basic knowledge of computers, as the DSS is a computer-based system. However, this is not a big problem, as computers become very popular now.
- When there are many functions in a DSS, the system is more complex. When the DSS is large and complex, a special operator may be required. Again this is not major issue, because of the importance of flood warning.
- Additional costs for software, hardware and development are required at the development stage. However, in the long run, an effective decision support system will cost less than that of manual processes or separate programming tools, which require manual data transfer.

### **1.3 Aim of the Study**

The general aim of this research project was to develop a computer-based DSS to help users to make effective decisions in mitigating the flood damage in the Maribyrnong River basin. This DSS is called Decision Support System for Flood Control in the Maribyrnong River Basin (DSSFCMR).

This general aim was achieved through the following specific aims:

- Review the applications of DSS, in particular in water resources, and investigate the methodology for development of a DSS for Flood Forecasting and Warning.
- Develop five subsystems (i.e. a Database subsystem, a Modelbase subsystem, a Spatial and Graphic Data Display and Analysis subsystem, a Decision Support subsystem, and an Interface subsystem), which are required for an effective DSS. Each subsystem requires detailed investigations to select its (proper) models and tools.
- Integrate all above subsystems to develop the DSS.
- Use the DSS for flood forecasting and warning in the Maribyrnong River basin.

### **1.4 Layout of the Thesis**

The thesis consists of seven chapters. Chapter 1 outlines the background with respect to development of DSSFCMR, a brief description of DSS and the aims of the study.

Chapter 2 presents a detailed literature review related to this research. The review covers five areas, namely theory, development and applications in DSS; the application of DSS in water resources; hydrological and hydraulic models for Flood Forecasting and Warning; spatial and graphic data display and analysis; and decision support.

Following from literature review, Chapter 3 describes the theories and detail technologies directly connected to the research work described in this thesis. They include DSS design and development, hydrological model, hydraulic model, Geographical Information System (GIS), spatial analysis and display technology, and decision support.

Chapter 4 presents the details of the conceptual design of DSSFCMR. It describes the Maribyrnong River basin and its aspects related to conceptual design, the structure of DSSFCMR, and the detailed conceptual designs of the five subsystems, based on the theoretical foundations developed in Chapter 3. The conceptual designs of data flow and decision making process in DSSFCMR are also described in this chapter.

Chapter 5 introduces the software development of the five subsystems. The contents cover the function and interface development, and error handling and system safety of each subsystem. Other aspects of system development such as physical database table development, system testing and status system are also described. The system installation and computer requirements are also outlined in this chapter.

Chapter 6 describes the application of DSSFCMR for decision support in flood forecasting and warning in the Maribyrnong River basin. The DSSFCMR's power was demonstrated through relevant data process and database management, hydrological and hydraulic model calibration, flood forecasting, spatial data display and analysis of flood inundated areas generated from simulated flood scenarios, and decision support for flood warning.

The conclusions arising from the relevant work in this thesis are summarised in Chapter 7 with some recommendations for future research.

# **CHAPTER 2**

## **DECISION SUPPORT SYSTEMS – A REVIEW**

### **2.1 Introduction**

As outlined in Section 1.2, a Decision Support System (DSS) is a computer system that helps the decision maker to make decisions effectively for semi-structured problems. Most water resources problems are semi-structured problems. In order to develop an effective DSS in water resources, a broad range of theory and knowledge is applied. Such theory and knowledge could include DSS theory, software engineering theory, database, modelling skills in the application domain, integration technology for various model components, and so on. Therefore, the literature on these theory and model components is reviewed with the aim of developing an effective DSS for Flood Forecasting and Warning in the Maribyrnong River basin. The DSS developed in this thesis is known as Decision Support System for Flood Control in Maribyrnong River (DSSFCMR). The literature review in this chapter focuses on five areas namely, DSS theory and practice, DSS in water resources, hydrological, hydraulic and economic models for flood control, spatial and graphic data display and analysis, and decision support.

### **2.2 Decision Support Systems**

The development of the DSS is the core part of this research project. Therefore, a detailed review is given in the following areas: DSS history; decision making theory; DSS including basic theory, design and implementation; and DSS applications other than in water resources. Such a review can help understand the DSS theory in order to develop an effective DSS.

#### **2.2.1 History**

The concept of DSS was developed from two main areas of research: the theoretical studies of organizational decision-making at Carnegie Institute of Technology in USA during 50's and early 60's, and the technical work on interactive computer systems conducted mainly at Massachusetts Institute of Technology (MIT) in USA in 60's (Keen and Morton, 1978).

The theoretical work provided by H.A. Simon from Carnegie Institute of Technology during the late 50's and early 60's (Simon, 1976) was the closest to the start of theory of decision

support (or decision support systems), and still this theoretical work remains the critical theory of DSS. According to Power (1997, 2002), Simon pointed out the need for and effectiveness of decision support systems.

Morton (1971) from MIT can be considered as the first to engage two streams of organizational decision-making and interactive computer systems into one system. Although Morton (1971) developed the main technical innovation in the computer application area, focus of the work was on the decision making and the impact of information technology on decision making.

At the beginning, DSSs were called Interactive Computer Systems (Keen and Morton, 1978; Loucks et al., 1985a,b), and then titled Decision Support Systems. Since then, DSSs have been used for modelling complex systems in various fields (e.g. Fedra and Loucks, 1985; Koch and Allen, 1986; Or, 1991).

### **2.2.2 Decision Making**

Decision-making is one of the oldest and most commonly performed human activities. People make decisions every day. The decision making process for solving complex problems (such as flood damage control) generally consists of four phases as follows (McLeod, 1995), which were also outlined in Section 1.2.1.

- searching the environment for conditions calling for a solution,
- investigating, developing and analysing the possible course of actions,
- selecting a particular course of action from the above actions, and
- assessing the selected particular course of action and/or past choice.

These phases are believed to be originated from Simon's famous model for the process of decision making (Simon, 1976; Power, 2002). The original form of Simon's model had three phases: intelligence, design and choice, which represent the above first 3 dot points. Subsequently, the (above) fourth phase, review and implementation was added to the model. This model has been widely accepted as one of the foundation models of decision making (McLeod, 1995; Srinivasan et al., 2000). However, there are many other decision making models. Although the models are similar in their outcomes, they have different intermediate

steps. For example, Philp (1985) pointed out the following steps in the decision making process, as listed below:

- Clarify objective
- Consider the factors which will influence the choice of action
- Generate options
- Compare the options and make the choice
- Present the recommendation
- Plan implementation.

If it is possible to find algorithms, or decision rules, for the above first three phases of the decision making process of a complex problem, as described by McLeod (1995), then the problem is said to be structured. A non-structured problem, on other hand, is one in which none of the above first three phases is structured. A semi-structured problem is one in which one or two of the above three phases are structured. As stated in Section 2.1, most complex water resource problems are semi-structured problems.

A good understanding of the problem in the form of structured, non-structured and semi-structured is the critical step in building an appropriate system to solve the problem. For example, a Management Information System (MIS), an Expert System (ES) and a DSS can be used for structured, non-structured and semi-structured problems respectively (e.g. Keen and Morton, 1978; McLeod, 1995; Sprague and Watson, 1996; Sauter, 1997). However, there are (some) different views on structure of the problem and what type of system should be employed to solve the problem. For example, Watkins and McKinney (1994) stated that a DSS can be developed to solve non-structured problems.

As examples of the use of these definitions in hydrological work, MIS can be used for hydrological data information search systems, as there is no decision support involved in the work. DSS can be used for flood warning as this is a decision making problem. Decision makers have strategies for flood warning and can simulate the possible floods, damage and relevant flood warning action. However, they do not have specific algorithms to select which simulated flood and its relevant flood warning action as the final decision. Therefore, this kind of problems is a semi-structured problem and DSS can be used to support the decision maker. Fedra (1993) reviewed the use of expert systems in water resources and identified three types of applications: purely knowledge driven systems, expert systems components in

an intelligent front end, and fully embedded expert systems. For above DSS example, the ES can be developed as a component in that DSS for decision choice phase.

### **2.2.3 DSS Definition and Components**

#### **2.2.3.1 DSS Definition**

A definition for a DSS is helpful to review the DSS theory and practice, and to help the developer and the user to plan, design and develop an effective DSS. However, it was found in this review that it was difficult to give a formal definition for a DSS, since different researchers have used different definitions in the past.

The earliest definitions of DSS (e.g. Gorry and Morton, 1971), defined a DSS as a system, which supports managerial decision makers in making decisions of unstructured or semi-structured decision problems. The key words used in this definition were support and unstructured (or semi-structured). Barbosa and Hirko (1980) also considered that DSS was used to solve unstructured or semi-structured problems, however, they defined any problem as unstructured if it was too costly or time consuming to define the problem structure before developing the solution, and this definition was significantly different to the definition of the non-structured problems defined above by McLeod (1995).

Ginzberg and Stohr (1982) defined the DSS as a computer-based information system, which was used to support decision making activities in situations where it was not possible or not desirable to have an automated system (performing the entire decision process). Silver (1991) defined a DSS as a computerized information system for making decisions for semi-structured problems. Sprague and Watson (1996) believed that DSSs are computer-based systems that help decision makers to confront poorly structured problems through direct interaction with data and models.

Alter (1992) thought that too much attention has been given on futile definitional issues (such as the difference between DSS and Executive Information System (EIS), DSS and Expert System (ES), etc.) and these definitional issues cannot be resolved because the systems continually absorb new features from each other and become hybrids. Alter (1996) also defined a DSS as a computer-based system that is designed to assist in solving unstructured problems. Watkins and McKinney (1994) gave the following working definition for a DSS in their review for DSSs in water resources: A DSS is an integrated, interactive computer

system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large and unstructured problems.

Simonovic (1998) defined a DSS as follows: A DSS allows decision-makers to combine personal judgment with computer output, in a user-machine interface, to produce meaningful information for support in a decision-making process. Such systems are capable of assisting in solution of all problems (structured, semi-structured and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-maker's approach to problem identification and solution.

It was found that in early stages of DSS development, the semi-structured and non-structured problems are often used together to define the DSS. However, in modern DSS theory, the Management Information Systems (MIS) are normally used for structured problems or for problems, which require no decision support, while Expert Systems (ESs) are often used for non-structured problems in decision making. DSS is used for semi-structured or poorly structured problems (Sauter, 1997).

### **2.2.3.2 Components (or Subsystems) of a DSS**

Parsaye and Chignell (1988) suggested that a typical construction process of knowledge-based systems should include the development of three rudimental subsystems: the knowledge base subsystem (knowledge representation in the computer), the inference engine (the mechanism to extract conclusions) and the user interface (how the user interacts with the program). Sprague (1980) and Sprague and Watson (1996) pointed out that the major components of a DSS include a database, models, and a software system that allows the user, via an interface, access to database and models. Johnson (1986), Labadie and Sullivan (1986) and Hopple (1988) agreed with these components.

Walsh (1993) explored the idea of the Spatial Decision Support System (SDSS) that was defined as a new class of DSSs that combines the technology of Geographic Information Systems (GISs) and DSS to aid decision makers with problems that have a spatial dimension. Walsh's SDSS included three main components: database, modelbase and interface, and GIS was used in all these components, which implied that the GIS system was the DSS's operational environment. In general, DSS may include many modern technologies such as

GIS, optimisation and simulation models, genetic algorithms, neural networks, expert and knowledge bases, and statistical and graphical packages (Loucks, 1995). Moreover, Loucks (1995) pointed out that mathematical and visual interfaces are essential for a DSS. Sauter (1997) suggested that a DSS consists of four components: three common components (i.e. Database System, Modelbase Management System and User Interface) plus the component of a Mail Management System to deal with the email messages between the users of DSS.

Srinivansan et al. (2000) described a two-layer DSS architecture: Conceptual Component layer (required technological capabilities) and Implementation Component layer (platform to deliver capabilities).

- The Conceptual Component layer is desired to have the following parts or capabilities:
  - Data part for large volume of data handling.
  - Models part for describing and maintaining models that define rules for manipulating data.
  - Solver part for transforming model specifications to system components.
  - Interface part for user interaction with system components.
  
- The Implementation Component layer is illustrated to have the following parts:
  - Relational Database Management Systems.
  - Object Relational Database Management Systems.
  - Spreadsheets.
  - Visual Interface.
  - Linking Technologies.

## **2.2.4 DSS Development**

### **2.2.4.1 Phases (Models) of DSS Devolvement**

As DSS is an interactive computer system, a brief introduction of the key elements of the general computer information system, is presented below to help understand the development of a robust DSS. Generally, a computer information system has five key elements: hardware, software, data, processes and people (Shelly et al., 2001).

- Hardware is related to the physical layer of the information system. Hardware includes computers, networks, communications equipment, scanners, digital capture devices and

other technology-based infrastructure.

- Software consists of two types: system software and application software.
  - System software manages the computer, and includes the operating system and device drivers that communicate with hardware, and handles tasks such as converting data into a different format, virus protection and backup.
  - Application software consists of programs that support users and enables the business organization to carry out business functions.
- Data can be provided as useful information for business activities of the organization by a computer information system.
- Processes, or procedures, describe the tasks that users, decision makers, and Information Technology (IT) staff members perform.
- People: The primary purpose of a computer information system is to provide valuable information to the decision maker and users within and outside the organization. The people, who interact or use a computer information system such as organization employees and customers, will decide the value of the computer information system.

The 'Structured Analysis' is a traditional computer systems development technique. The systems development life cycle (SDLC) is often used to plan and manage the development process of a computer system in Structured Analysis. The SDLC describes activities and functions that computer system developers typically perform, however these activities and functions fit into a particular methodology. The SDLC model includes the following steps: system planning, system analysis, system design, system implementation, and system operation and support (Shelly et al., 2001).

Although many articles (e.g. Ginzberg, 1978) distinguish the development of DSS from general computer system development (of which basic ideas were mentioned above), it is no doubt that as a computer system, DSS must be affected by the general computer information system development methodology. However, according to Ginzberg (1978), the general computer system development tools might not always be suitable for the more dynamic development requirements of DSS's.

There are many works (Bennett, 1983; Sauter, 1997) that investigate the theory and practice of DSS development phases. A comprehensive set of phases for DSS development were given by Loucks (1995) as follows: identification of DSS model structure, identification of DSS algorithms and interactions, identification of input data requirements and assembly of data,

design of the interface that must incorporate with data input and output, code development and testing, DSS calibration and verification, and DSS documentation and training. Several descriptions about the DSS development model (or phases) are listed in Table 2.1. It was found that most of developed DSSs, in which development phases were presented, were linear sequential models rather than interactive models.

The development phases (or models) were based on many features such as the developer's interests, project size and resources. The size of development was always an issue. The methodology used for large projects is probably not good for small projects, and vice versa. It is probably safe to say that no methodology is ever a perfect fit, as reported by Inmon (1991).

A development model (or phases) can help the developers understand the development of a DSS and hence efficiently to build a DSS. DSSFCMR in this research project was developed using four phases of DSS development: planning, design, implementation and testing, and maintenance, in a linear sequential model.

#### **2.2.4.2 DSS Planning and Analysis**

Although there are a large number of reported applications of DSS such as applications in water resources, only a few of these applications discussed planning and analysis aspects of a DSS. Davis (1979) described the overall requirements for planning and budgeting the development of a DSS using a farm program planning and budgeting example. They considered issues such as (a) social and economic importance, (b) magnitude of the programs, (c) organizational importance, (d) obsolescence of automated and manual systems, (e) management style and leadership posture, (f) fast response capability, (g) documentation of decisions and (h) upgrading of skill levels.

More generally, Sprague and Carlson (1982) believed that the DSS planning should help answer the following questions:

- How can current needs susceptible to DSS be recognized?
- How can the possible extent of their growth be measured?
- What types of DSSs are required to support the needs, now and in the future?
- What are the minimum start up capabilities required, both organizational and technical?

Table 2.1 DSS Development Model (or Phases)\*

<b>Researcher(s) (Year)</b>	<b>Number of Phases</b>	<b>Define problem (order of phase)</b>	<b>Systems analysis (order of phase)</b>	<b>Conceptual design (order of phase)</b>	<b>Implementation (order of phase)</b>	<b>Test (order of phase)</b>	<b>Maintenance (order of phase)</b>
Bennett (1983)	5		Planning (1)	Design (2)	Development (3)	Testing (4)	Application and feedback (5)
Hopple (1988)	5	Problem definition and feasibility (1)	System analysis (2)	Preliminary system design and detailed system design (3)	Implementation (4)		Maintenance and evaluation (5)
Sauter (1997)	4		Planning (1)	Design (2)	Implementation (3)		Evaluation (4)
Vassilakis et al. (2002)	4		Analysis stage: identification of the most important data and structuring the knowledge base (1)	Design stage: development of the knowledge base and design of the inference engine (2)	Construction stage: software development (3)	Benchmarking : testing the diagnostic system (4)	

\* The number in the bracket (e.g. (1)) in the table is the order of the phase

- What kind of plans can be developed to establish the long-term direction, yet respond to unanticipated developments in managerial needs and technical capabilities?

Thierauf (1982) described several perspectives for DSS planning, by posing the following questions.

- Why is the feasibility study undertaken?
- Who conducts the feasibility study?
- What is the scope of the feasibility study?
- How much time is spent on the feasibility study?

Thierauf (1982) suggested the DSS analysis should include following aspects

- The current system study
- Possible DSS alternatives
- Benefit and costs of each DSS alternatives
- Exploratory survey report to top management

Loucks and da Costa (1991) addressed some factors for DSS planning and analysis by highlighting the following questions.

- Who are the clients?
- What are their stated and real information needs?
- What are the appropriate hardware, software and interface?
- How soon do they need their decision support system?
- How much money is available to pay for it?

All these opinions could help plan and design a DSS. However, many researchers in the DSS application area (eg. in water resources) have a broad knowledge of various aspects of the application in their fields such as feasibility study, problem definition, problem analysis, application model and so on, and therefore they ignore the process of DSS planning and analysis. Note that the planning and design of a DSS also includes the important steps of possible extent of DSS growth and possible DSS alternatives. In this research, the following issues were considered to guide planning and design of DSSFCMR.

- Problem definition including existing decision making tools.
- Need for a DSS for this problem.
- How can a DSS solve this problem?
- What types of DSS required now and in the future? How about this DSS in future?
- What are the minimum startup capabilities required, both organizational and technical?

### **2.2.4.3 DSS Design**

As mentioned in Section 2.2.4.1, the DSS development can be affected by the general computer information system development model. The DSS is a computer system that is used to help making decisions, while the general computer information system is a computer system that is not specifically developed for decision making. Software engineering is the establishment and use of sound engineering principles in order to obtain economical software that is reliable and works effectively on real machines (Pressman, 1997), and used in both in general computer information systems and DSSs. Therefore, the general information system design model is introduced first in this section, followed by the theory of software engineering for DSS design. Finally, the DSS design model is reviewed.

#### **(a) Information System Design Model**

According to Shelly et al. (2001), there should be three steps for the information system design. These three steps are:

- reviewing system requirements mainly from system planning and system design point of view.
- designing the system in user interface, input processed, input and output formats and reports, data and system architecture.
- presenting the system design.

These steps are based on the SDLC in information system domain.

#### **(b) Software Engineering Design Model**

Meikle (2002) presented the MODDE (Model of Decision Support System Design and Evaluation) methodology for innovations in decision support system design. MODDE uses a

simple idea of the software engineering process to show the way of considering three qualitative extents of high-level independent decision making. These three extents are the preservation of *discretion*, the maintenance of *consistency* and the maintenance of *resolution* (which is the provision of information in an appropriate way) in MODDE, and they have come up directly from a project with the Refugee Review Tribunal (Victoria) in an applied legal domain. MODDE uses a systematic method to address these three extents based on software engineering ideas.

### **(c) DSS Design Model**

From their application of DSS for Forest Management Planning in Canada, MacLean and Porter (1994) had learnt a lot in their DSS design as follows:

- Compatibility with existing (and probable over the next 5-10 years) databases and planning procedures is key to user acceptance and adoption of new DSS tools. In other words, new and better tools will not be used if they are not compatible with the current way of doing business.
- User involvement in the development of DSS tools is critical. The chance of researchers developing something that is close, but not quite right, is extremely high. User involvement continually focuses the attention on real problems.
- A tool-based approach of developing components of an overall system will help by carving a big problem into bite-size chunks, and allows earlier use of and feedback of DSS components. This will ultimately create a "tool-kit" for other DSS developers.
- Consider the management interaction time frame, and plan to have DSS components ready when they can be used.

According to Thierauf (1982), the general steps of DSS design should include: (a) review of new system requirements, (b) incorporate human factors, (c) design the new system and (d) flowchart and document the new system. However, the information below provides more detailed design approaches for DSS design.

Several DSS design approaches were summarised by Yen (1986). These approaches are listed below:

- Carlson's representation-based approach.
- Keen's adaptive design approach.

- Courbon's evolution approach.
- Schonberger's contingency approach.
- Sprague and Carlson's quick-hit approach.

The Carlson's representation-based approach attempts to reduce the differences between requirements of decision makers and the capacities of the DSS. The Keen's adaptive design approach focuses adaptiveness in a DSS design. The Courbon's evolution approach recommends the progressive design of a DSS by using multiple, minimum-length cycles. The Schonberger's contingency approach offers design leadership. The Sprague and Carlson's quick-hit approach suggests designing a DSS quickly by taking a recognized high-payoff application area. After studying these methods, Yen (1986) made the first attempt to combine two different research areas, namely, DSS and Expert System (ES), to form a new, combined and improved system design approach (i.e. the use of an Expert System method for DSS design).

Sauter (1997) outlined three approaches to design and implement a DSS. They are (a) one-stage, complete system approach, (b) quick-hit method and (c) evolutionary development method. The latter two methods were described in Yen (1986) as the Sprague and Carlson's quick-hit approach and the Courbon's evolution approach respectively.

Generally, the one-stage, complete system approach requires building an entire DSS system and then delivering it to the user. There are no subsystems such as models, database, user interface, etc with this approach. This approach is suitable for a large-scale multi-user or unique systems such as a GIS system. A prototype of DSS is often produced with this design method. It is not often used in DSS design today as users want to replace various components with recent developments (e.g. pre-existing tools and models), which is not allowed with this approach.

Both the quick-hit method and the evolutionary development method differ from the one-stage, complete system approach in that the former two methods use the existing technology. The quick-hit method is to design the system quickly for some well-known and useful immediate need. The system is likely to work in a PC environment. The designer can use the existing technologies and other tools, and then concentrate on the analysis and user interface. The evolutionary development method also uses existing technologies, and the designer focuses on the analysis of the needs rather than on the construction of DSS. It differs from

the quick-hit approach as the system design and the system will become better as the user learns from the experience during the system design, development and information access. The immediate feedback from the user is considered in the system design and development.

The quick-hit method was used by the author for DSSFCMR in this research project. The author concentrated on analysis and construction of DSS using existing technologies.

#### **2.2.4.4 DSS Development and Evaluation**

The review in this section is categorised under three main areas: (a) general; (b) user involvement; (c) components of a DSS (such as decision making, model base, database, and interface); (e) test and evaluation.

##### **(a) General**

As Loucks and da Costa (1991) stated, the following questions should be considered in developing an effective DSS:

- What database system should be developed or purchased; how can security and control of access be achieved; how can data errors be detected and corrected; how can missing data be replaced; how can data be maintained and augmented; how can feedback be established between data providers and data users; how can data be accessed when on different computers at different locations; and how can a database system be integrated within the decision support system?
- Which models and model types are most appropriate for the client; how can the model input data be managed, checked and displayed; how can model documentation, playback files, training tutorials and user's manuals best be prepared for efficient and effective technology transfer; how can the models be used to explore and synthesize as well as analyse alternatives, their impacts, and their uncertainties; how can sensitivity analyses and model calibration be performed most effectively; and how can the model results, together with their uncertainties, be displayed for maximum understanding?
- What software language and graphics tools to use; how should different modules developed by different developers linked together; how should software testing be performed; how should model misuse be prevented; what levels of on-line help should

be provided; how much effort should be placed on the models themselves, the database, interface, and all necessary and desirable training and documentation?

- How can close cooperation and communication among the developers and the clients be established and maintained; how can the maintenance and upgrading of the decision support systems be assured for changes in needs, data, and institutional procedures?

### **(b) User Involvement**

Alter (1978) used examples from a survey of fifty-six decision support systems to illustrate each of four implementation patterns that were directly observed in the sample. Alter defined four DSS development patterns in terms of combinations of high or low degree of (1) initiation by the user and (2) participation of the user in the development process. It was found that systems initiated by high degree of users and implemented with a high degree of user involvement comprised of less than one fourth of all cases.

Barbosa and Hirko (1980) pointed out the conflict of rigid design against user's changed perception of the problem. For example, as users develop further understanding of the problem in a DSS development, their perception of underlying structure of the problem could be changed. This has brought in a conflict that the rigid framework in which the algorithm or model resides cannot easily match the user's changed perception of problem.

Through three DSS case studies, Mann and Watson (1984) indicated that the level of user involvement can vary significantly. They believed the DSS technology (i.e. DSS tools and generators), the management activities and the nature of interdependence work together to influence the level of the user involvement. A tentative contingency model, which included intermediate involvement and technician involvement as well as user involvement, was then developed and discussed in their research.

### **(c) Component of a DSS**

- Modelbase

Barbosa and Hirko (1980) discussed using algorithmic aids or models for decision making to improve interface, feedback, flexibility and integration in DSS. The specific algorithmic approaches were applied to a GEO-Data Analysis and Display System. The difficulties of

using algorithms were discussed such as obtaining the user acceptance of the assumptions underlying the model, which the algorithm supported. Two general approaches, which can overcome these general difficulties in the use of algorithms, were highlighted, and one of them was the interactive algorithm approach. The interactive algorithm approach is that the DSS designer develops a procedure by which information can be mined from the user and the user may describe his/her problem parametrically. The idea is similar to that in an interactive hydrological or hydraulic model.

Huber (1981) discussed four models characterising the organization decision making environment and presented the information requirements and analytic aids for each model when designing and developing a DSS. This article makes clear that the nature of organization decision environment will more and more be seen as a key variable in the development of DSSs.

Some factors regarding models and model management were given by Sauter (1997) as follows:

- For modelling: functionality, flexibility, appropriateness of included models and ease of use.
  - For system architecture: analysis capabilities, sensitivity analysis, what-if analysis, impact analysis, symbolic reasoning evaluation, and context-sensitive model help.
- Interface:

According to MacLean (1986), the specification in the design and development of user interface should be prepared considering the following factors: displays and controls, user-system dialog, consistency, re-entry dialog, alternative data entry methods, error routines, report capabilities, online report display, Ad Hoc query language, online report help facility, graphics display capabilities, data review and modification, bulk data maintenance tasks, external data capture, online data maintenance, etc.

Loucks and Costa (1991) believed the most important features of user interface should include: (a) user dialogues, symbolic interaction, and possibly embedded rule-based methods, (b) graphic visualization and display options, (c) integration and transparent data handling, and (d) maintenance and customisation. Sauter (1997) described user

friendliness, support of modelling and data needs, graphics, and reporting forms as user interface considerations in DSS.

- Database:

The most reported DSS applications include a database or a database subsystem. The major differences in the database part in these applications were database software, integration technologies and related functions in the database subsystem. Different database software had been used such as HEC-DSS developed by U.S. Army Corp of Engineers (Ford and Killen, 1995), Oracle by Oracle Corporation (Dunn et al., 1996), MS ACCESS by Microsoft Corporation (Shim et al., 2002), and ArcView by Environmental Systems Research Institute (ESRI) (Makropoulos et al., 2003).

- Spatial and graphic data Display and Analysis (SGDDA):

SGDDA is reviewed in detail in Section 2.5, and therefore not described here.

- Decision Support:

Brown and Jones (1998) developed a model of aided decisions that incorporated both the level of reliance on the decision aid and the agreement of decisions with the decision aid's advice. The model also included the four classes of factors that could influence the decision strategy selection: decision aid features, decision-maker characteristics, decision task characteristics and factors affecting the evaluation of decision strategies. By comparing aided and unaided decision makers (the aided decision maker received decision making support while the unaided decision maker did not), it was found that the decision aid (or decision support) had greater influence in making decisions in the harder tasks than in the easier tasks. More details on decision choice support are given in Section 2.6.

#### **(d) Test and Evaluation**

When a DSS is developed, it is necessary to test the functionality of the DSS. It was found that there is no detailed test methodology specified in published DSS applications, although some developers have discussed this issue in their evaluation sections (Mowrer, 1997). However, the test technology frequently used in computer information system domain can be

used for DSS testing. Evaluation of a DSS is more than its testing for functionality. DSSs have been evaluated in the past considering many issues. For example, Power (1997, 2002) suggested to evaluate a DSS by its (a) capabilities, (b) cost of the package, (c) ease of use, (d) ease of installation and operation, (e) performance, (f) vendor reputation and (g) reliability.

Mowrer (1997) employed seven criteria categories to evaluate the computer-aided decision support system already developed for forest ecosystem management, namely the scope of each developed DSS, the spatial capacities, the computational methods, the development status, the input and output requirements, the user support availability, and the system performance. Mowrer's evaluation work was based on the questionnaire responses from DSS developers, and these responses were presented to compare the system capabilities. Some common factors for evaluating DSS software packages such as cost of the package, vendor reputation and ease of installation were not considered in Mowrer's evaluation work.

The five subsystems, namely, Interface, Modelbase, Database, SGDDA and Decision Support were developed in DSSFCMR in this research project with many functionalities for flood forecasting and warning. The developed DSS was properly tested. The detailed test technology used in this research for development of DSSFCMR is given in Chapter 5.

#### **2.2.4.5 DSS Maintenance and Service**

The maintenance and service of a DSS is a very important part of the DSS development life cycle. However, this aspect is treated only in few applications. For example, Ginzberg (1978) identified two strategies for user training, namely "operation training" and "task context training", which are quite different to each other. In "operation training", the user is taught on the operations the DSS is designed to have and how to instruct the DSS to perform these operations. The "task context training" not only shows the user how to produce certain outputs but also shows the user how to use this output in his/her job, which is more critical.

#### **2.2.4.6 Recent DSS Applications Other than Water Resources**

The DSSs have become popular for solving complex problems. Bracke et al. (2001) reported a DSS for overall welfare assessment. Johnson (2001) described a GIS-based decision support system prototype that was proposed for use by public housing authority administrators and planners designing policy for housing mobility programs. Vassilakis et al. (2002) developed a

DSS using artificial intelligence techniques for the classification, and ultimately the diagnosis of epilepsies and epilepsy syndromes in children. Kalay and Chen (2002) studied the effects on student functioning by integrating a DSS into the school management's decision-making process in planning a teaching and learning system. These applications demonstrate the power of DSSs for solving complex problems.

## **2.3 DSS in Water Resources**

### **2.3.1 General**

In 1985, several articles (Loucks et al., 1985a,b; Kunreuther and Miller, 1985; Fedra and Loucks, 1985; and Cosgriff et al., 1985) were presented together in a special issue in *Water Resources Research* on interactive water resources and environmental management, policy, and model use. Although the term DSS was not used in these articles, these papers technically dealt with DSSs. Reviewing several articles on the application of DSSs, Labadie and Sullivan (1986) and Johnson (1986) separately discussed the design principle and the contents of DSS for water resources management, and the continued development requirements of DSSs. They agreed that a DSS should include three main components: Database, Modelbase and Interface. However, with the advancement of DSS techniques, current DSSs can include other important components such as decision support (Loucks, 1995), and spatial and graphic data display and analysis (Walsh, 1993 and Loucks, 1995). A systematic overview of the past research work in DSS in water resources was given by Loucks and da Costa (1991). Some ideas described by Loucks and da Costa (1991) are still used today for DSS development.

A DSS for analysis and use of stage-discharge rating curves was reported by DeGagne et al. (1996). Numerical model analysis was presented in detail in this paper. However, only the framework of DSS was introduced without giving details of the DSS. Cortés et al. (2001) discussed how the results of Knowledge Management could improve some types of Environmental Systems, particularly Environmental Decision Support Systems (EDSS). Knowledge Management in Environmental Decision Support Systems become essential for EDSS users for studying the system behaviour, while these methodologies are still under-explored.

As the systems such as water treatment plants, ecological systems and technical devices become more complicated, there is more and more complex reasoning that should be

considered for the tasks of situation assessment, which will assist in decision making. Heller and Struss (2002) investigated a general approach to provide computational support for these tasks, namely Consistency-based Problem Solving. Based on the research in model-based systems and more specifically, consistency-based diagnosis, they developed a revision and generalization of traditional (component-oriented) theories and techniques of analysis. The approach was applied to a water treatment problem to illustrate their theory.

Considering the importance of incorporation of sustainability assessment into decision-making for water service providers in the UK and elsewhere, Foxon et al. (2002) described the development and application of a set of sustainability criteria for decision support. These criteria were developed and tested in the UK and Romania. The work was part of the Sustainable Water Industry Asset Resource Decisions project that was intended finally to develop a multi-criteria analysis decision support system. This DSS was aimed to assist the water service providers to assess the relative sustainability of water/wastewater system asset development decisions.

### **2.3.2 Water Quality and Environment**

Grobler et al. (1987) applied a DSS for predicting the impact of alternative eutrophication strategies on water quality in reservoirs. van Walsum and Drent (1987) presented a DSS for protecting the environment in regions with intensive livestock breeding and with high-intensity land cultivation in The Netherlands. Arnold and Orlob (1989) illustrated a DSS for estuarine water quality management. Newell et al. (1990) established a Graphical DSS named OASIS for groundwater contaminant modelling. On the basis of the current DSS knowledge, all these applications are not DSSs, because they are strong in numerical modelling but weak in decision support.

Camara et al. (1990) used a DSS for estuarine water-quality management considering the pollution loading as the decision variable. The system was designed using the HyperCard. Srinivasan and Engel (1994) presented a spatial DSS for water quality in a river basin. The system was mainly consisted of Agricultural Non Point Source (AGNPS) numerical model, GRASS (a GIS software) and other tools. In these two applications, the visualized display for scenario results was stressed rather than the choice of decisions.

Lotov et al. (1997) developed a DSS for water quality planning. The DSS included six subsystems, namely the data-preparation subsystem, the subsystem for approximation of the Edgeworth Pareto hull of the feasible set in criterion space, the subsystem for visual exploration of the decision maps, the subsystem for decision computing, the subsystem for decision display, and the subsystem for preparation of output data. However, there were no details of the definitions of these subsystems or the development of these subsystems. Instead the DSS as a whole was described in the article. Chen et al. (1999) developed a DSS for estimating total maximum daily loads of various pollutants. The DSS included five tightly integrated modules, namely the engineering module, the data module, the knowledge module, the total maximum daily loads (TMDL) module, and the consensus module. All these modules were integrated through a Geographical User Interface (GUI). The article focused on the modules especially on the TMDL module without giving the details of the DSS design and development.

### **2.3.3 Water Policy and Reservoir Operation**

There are many DSS applications in this research area. Koch and Allen (1986) applied a DSS for local water management. Arnold and Sammons (1988) used a DSS to aid users in selecting inputs to SWRRB (Williams et al., 1985), a model for simulating hydrological and related processes in rural basins. Stansbury et al. (1991) investigated a DSS for water transfer evaluation. Pingry et al. (1991) discussed a DSS for water delivery design. All these applications were weak in decision support. Furthermore, they used less effective DSS tools in current standards such as using inefficient text file data managing methods.

Davis et al. (1991) established a prototype DSS for analysing the impact of catchment policy for planning, but did not give the details of DSS or its development. Dunn et al. (1996) described a DSS named NELUP, which consisted of three traditional components: a database; economic, ecological, and hydrological models; and a user interface. The hydrological model was the key issue in their article, while NELUP was only briefly explained. A detailed conceptual framework for this DSS development was reported by McClean and Watson (1995), together with the general DSS definition and theory. In the design of McClean and Watson (1995), large volumes of diverse, land use related data were brought together into a central database using geographical information systems (GRASS by U.S. Army and ArcInfo by ESRI) and relational database management system technology (ORACLE). The data, as well as economic, ecological and hydrological modelling capabilities, were made available to

the decision maker via a user-friendly graphical interface. The software engineering principles for building the DSS were described.

Andreu et al. (1996) introduced a generic DSS for water resources planning and operational management of a river basin. The system runs on the Microsoft Windows Environment. The detailed structure of the DSS, developed interface and used models in DSS were given. However, some key issues such as database vendor and integration methods of data in the database with models were also not discussed.

Taher and Labadie (1996) presented a prototype DSS, namely WADSOP for guiding water-distribution system design and analysis based on changing water demands, timing and use patterns. The system integrated a GIS (PC ArcInfo by ESRI) and an optimisation technology. The functions in GIS software were used to manage spatial data, estimate model parameters and analyse spatial network. The optimisation technology was used to simulate water distribution system operation and provided guidance in development of optimal system design. The DSS computer development work was not presented in the paper.

Jamieson and Fedra (1996a,b) and Fedra and Jamieson (1996) reported a comprehensive, but easy-to-use DSS for river basin planning. The system is a product of a collaborative research program, called Eureka Eu487. The system comprised of a GIS, a generic database management system, simulation and optimisation algorithms, export models, a set of pre- and post-processors for input and output, a user interface and a set of utility functions. This system was a pioneering work in this area. However, the papers concentrated on the conceptual design, and the functions and interface. The system development was not detailed in these papers.

Arumugam and Mohan (1997) described an integrated decision support system for a tank (small scale reservoir) irrigation system. This DSS included a data subsystem, a model subsystem, a knowledge base and a user interface. The data subsystem stored inflow, rainfall and meteorological data, and these data were used by the optimisation models in the model subsystem and also used by forecasting models, which were also in the model subsystem. The reported work focused on the numerical models and their applications, without giving details on decision support computer facilities.

Taylor et al. (1999) described the Framework for Model Integration in Spatial Decision Support (FMISDS) for designing an integrated SDSS through a problem-oriented method. Two issues in model integration, namely, syntactic and semantic issues, were analysed for a declarative description of the different models, which are needed to be embedded in a SDSS, and their conceptual relationships. A reusable toolkit was used for the integration approach. FMISDS was illustrated in a spatial decision support system for water catchment management in Sydney Water Corporation, Australia. The reported work focused on the theoretical concepts without giving details on the DSS design and development work

Ito et al. (2001) developed a DSS for supporting the testing and evaluation of water management policies. Several different numerical models were provided to simulate a variety of hydrologic processes. The user-friendly interface helped the user to use these models. The system integrated user-selected scenarios into planning strategies of the water resource system in the Chikugo River basin, Japan. Sample et al. (2001) reported a GIS based DSS for urban stormwater management at a small neighbourhood scale. The application included GIS software, a database, a template for stormwater system design, and an optimization capability for screening alternatives. Westphal et al. (2003) reported a DSS for real-time adaptive water management of a reservoir system. Makropoulos et al. (2003) described a prototype SDSS for strategic planning in water demand management. This DSS was developed using ArcView by ESRI and Matlab (Mathworks, 1999) Environments. The above paper focused on the mathematical framework of the development of the SDSS, giving also the details of the decision making process. In all above four papers, the details of the DSS design and development were not.

In Makropoulos et al (2003) SDSS work, the type-1 and type-2 inference systems were used to produce suitability maps for each individual attribute of the investigated strategies. As experimental data to train the inference systems were not available, the linguistic variables (low, medium, high), with a degree of uncertainty as to the exact design parameters were incorporated in type-2 fuzzy membership functions, and with enough rules, correctly tuned.

#### **2.3.4 Flood Control**

Literature on the application of DSS in flood control is limited. Kunreuther and Miller (1985) discussed an application of a DSS for a flood hazard problem. The system was designed for homeowners in a flood-prone community; however, no details were reported on the DSS.

Garcia and Strzepek (1987) used a DSS for design and evaluation of spillways. In this application, the adequate spillway size was determined by routing the inflow hydrograph in the reservoir; however, the use of a DSS was not really required for this case because the problem was highly structured, and can be solved by a numerical model. Ford and Killen (1995) introduced a DSS for flood prevention and control in the Trinity River Basin, Texas in USA. The flood flow was selected as the decision variable, and was computed from routing releases from the reservoir. The system consists of three main parts: a Modelbase, a Database Management System (DBMS), and an Interface. HEC-1 (USACE, 1990b) was used for flood forecasting, while HEC-5 (USACE, 1982b) was used for simulating the reservoir operation. HEC-DSS (USACE, 1990a and 1991) was used for DBMS. No detailed decision support was provided in this study.

Ackermann et al. (2000) described the development and implementation of two modelling approaches (i.e. non-linear optimisation and finite-element simulation) for control of river water levels for navigation and hydroelectric operation. These two modelling methods were incorporated into a DSS for real-time control of a section of the River Mosel in Germany.

Ford (2001) presented a flood warning system for Sacramento County, California. This system can automatically collect and transmit rainfall depth and water level data in real-time. These observed data were used to detect potential flood threat, using forecasting models. The system was developed using the flood emergency operations plan of the county, which provided flood warning. This DSS used many existing programming / software such as HEC-1 (USACE, 1990b) and these programming / software were tightly integrated in the DSS. MS ACCESS (Microsoft Corporation) was used as the database software. The flood inundated area map (an important aspect for flood warning) was produced outside the DSS.

Shim et al. (2002) reported a prototype of a spatial decision support system (SDSS) for real-time flood control in a multipurpose, multi reservoir system. The system included a database management subsystem, a real-time meteorological and hydrological data monitoring system, a Modelbase subsystem and a graphical dialog interface. The GIS software ArcView by ESRI was used for areal rainfall estimation in real-time. A real-time flood forecasting module (based on artificial neural network method) in the Modelbase subsystem was used to forecast flows. The forecast flow had spatial distribution characteristics and the forecasting was updated as the flood event progressed. Forecast flows were then used as the input to a dynamic programming module to provide optimal gate-control strategies that were also

updated in real-time. The SDSS was applied for flood control in the Han River Basin in Korea. However, this SDSS did not provide spatial analysis for model output such as the flood inundated area.

## **2.4 Hydrological, Hydraulic and Economic Models for Flood Control**

### **2.4.1 General**

The hydrological, hydraulic and economic analyses are required for planning, design and management of flood control (or Flood Forecasting and Warning) within a flood plain or a catchment. Methods or models used in these analyses are determined by the purpose of the project and the data available.

Usually, the hydrological analysis in relation to flood control and management deals with determining the peak discharge of certain probabilities of exceedance by frequency analysis, or determining the flood hydrograph through rainfall-runoff models. The hydrological frequency analysis uses statistical distributions. It also requires the use of parameter estimation procedures. Distributions of Pearson Type 3 (P3), Log-Pearson Type 3 (LP3), Extreme Value Type 1 (Gumbel or EV1), Generalized Extreme Value (GEV) and Exponential are some popular distributions used in frequency analysis. The Method of Moment (MOM), Probability Weighted Moments (PWM), Maximum Likelihood (ML), Least Squares and Graphical methods are in common use for estimating the parameters in frequency analysis (Cunnane, 1989).

HEC-1 (USACE, 1990b) and RORB (Laurenson and Mein, 1995) are two popular rainfall-runoff computer models available for computing flood hydrographs. The HEC-1 model is a catchment-runoff model and developed by the U.S. Army Corps of Engineers. It evaluates the runoff from precipitation with a spatially and temporally lumped distribution of the catchment. It provides stream discharge and time series of peaks and volume totals for decision-making. The RORB model is widely used in Australia for flood estimation studies. It is a non-linear, quasi-distributed runoff routing model for simulating flood hydrographs from rainfall and other channel inputs, and can be used for design of detention basins and flood routing in channels. Melching et al. (1991) used both RORB and HEC-1 models to estimate the peak discharge of a watershed in Central Illinois, USA and showed that these models produced similar results. The XinanJiang model (Zhao et al., 1980 and Zhao, 1992)

and Stanford Model (Crawford and Linsley, 1966) are also well known rainfall-runoff models.

WBNM (Boyd et al., 1996) is an event based rainfall-runoff routine hydrologic model, which calculates flood hydrographs from storm rainfall hyetographs for natural, part urban and fully urban catchments. The original concept of WBNM was for a simple, yet physically realistic model. However, over the years WBNM has added many features to make it more useful for engineering investigations. WBNM was one among the first to have built in design storms for Australia. It has runoff-routing algorithm similar to RORB.

URBS (Carroll, 1995) is also a non-linear rainfall-runoff catchment routing model, which computes flood hydrographs due to rainfall events, giving due consideration to catchment losses. It has been successfully used by the Australian Bureau of Meteorology in many flood forecasting applications in Australia (Malone, 1999) by linking with the Australian National Weather Service ALERT rainfall and river height database. It is also easy to vary the values of input variables in URBS, which makes the scenario analysis of various possible flood hydrographs convenient. All three models (RORB, WBNM and URBS) use similar principles for rainfall runoff modelling, but as stated earlier URBS has been widely used for real-time flood forecasting (Malone, 1999) compared with the other two models. Furthermore, the URBS software is easy to integrate with other software (or computer programming) compared with the other two models and it therefore has some advantages in DSS development for real-time forecasting and warning.

The hydraulic analysis computes the flood water levels due to flood hydrographs. There are two types of hydraulic models, namely steady and unsteady, that can be used in flood modelling. The steady models compute the flood water levels due to a steady discharge such as the peak discharge, while the unsteady models deal with the total flood hydrograph. The HEC-2 computer model developed by USACE (1982a) was claimed to be the most commonly used water surface flood profile computational model in USA. It solves one dimensional, steady gradually varied flow equation to predict water-surface elevation along natural rivers or constructed canals. However, HEC-2 has been replaced by its more recent version called HEC-RAS (USACE 1997,1998a,b). HEC-RAS can also handle unsteady flows. The Dynamic Wave Operational computer model (DWOPER), which is an unsteady flow model, was developed by the National Weather Service, USA for use in flood forecasting (Fread, 1987). DWOPER can be used for analysis of flow in a single channel, or

a dendrite or bifurcated (looped) river system. It uses a four-point implicit finite difference scheme to approximate the complete one-dimensional unsteady-flow equation. The discharge, velocity and depth at channel cross sections can be computed. It is commonly used in USA.

No popular computer models dealing with cost of flood damage are reported in the literature. One of the principle techniques used for estimating urban flood risk reduction benefits has been the Property Damage Avoid (PDA) approach (Mays, 1996), which reflects the present value of expected property damage avoided by the project or policy. The benefits that can be obtained from the flood mitigation strategies in the Maribyrnong River in Victoria (Australia) had been calculated by the PDA Approach (Melbourne and Metropolitan Board of Works, 1986).

## **2.4.2 Flood Forecasting**

The accuracy in real-time hydrological modelling and forecasting has increased in recent times because of the developments in weather prediction models, watershed modelling, remote sensing methods, methods for handling spatial and temporal variability of rainfall at various scales, and so on. The review in this section focuses on the above aspects.

### **2.4.2.1 Rainfall Forecasting**

Rainfall forecasting is an important step in flood forecasting and flood damage management. However, accurate rainfall forecasting has always been a difficult subject due to many uncertain factors such as observed rainfall sampling effect (e.g. Krajewski et al., 1991), rainfall spatial distribution (e.g. Michaud and Sorooshian, 1994a,b), rainfall intercept such as by forest canopy (e.g. Hashino et al., 2002), impact of soil moisture and so on. While many research works are still continuing on these general challenging factors, some new technologies such as weather radar (e.g. Georgakakos and Krajewski, 1991) and remote sensing (e.g. Brivio, 2002) are popularly being used for rainfall forecasting. At the same time, it is common to use the numerical weather models to forecast rainfall in different spatial scales for different forward time periods.

### **(a) General Factors**

Michaud and Sorooshian (1994a,b) studied the effect of the spatial distribution of rainfall on flood hydrographs by comparing the performance of three rainfall-runoff models: a simple lumped model; a simple distributed model and a complex distributed model. Their results showed that even a network of high density of rainfall gauges might still be insufficient to define a currently occurring rainfall event, and to calculate the rainfall and its spatial distribution. They supported the common idea that the lack of proper rainfall predictions in flood forecasting could cause the problems in the reliability and lead-time for flood warning. Arnaud et al. (2002) also studied the influence of rainfall spatial distribution. They compared the empirical distribution of the peak flows (and runoff volumes) with those from three distributed hydrological models due to different spatial rainfall patterns. Their study showed that a bias in the estimation of parameters made the interpretation of results difficult.

Stow and Dirks (1998), Dirks et al. (1998), Bradley et al. (1998), and Stow (2002) described their research work on characteristics of rainfall and data spatial patch and analysis on Norfolk Island. A dense network of rain gauges had supplied high resolution data on spatial scales of about 1.5 km and time scales of 15 sec on Norfolk Island. Based on these observed rainfall data, spatial variability of rainfall were assessed on this island. In order to incorporate some of the characteristics of spatially varying rainfall, the methods for interpolation of data were compared and the inverse-distance method was recommended for data patching using spatially dense networks. A model for rainfall redistribution was developed. The relationship between rainfall accumulations and fractional time raining was examined using the observed rainfall data. Although the mechanism in this research was helpful for rainfall prediction, there was no evidence that the results (such as the model) could be directly used in other areas. GIS techniques were also used in the study for rainfall spatial distribution (Dirks et al., 1998).

A model for spatial distribution of mean monthly precipitation in the seasonal and annual periods in a mountainous region was developed by Marquínez et al. (2003) using multiple linear regression and GIS techniques. The results showed that the approach can describe 58-68% of spatial variability in mean precipitation, the standard error was approximately 10% and the mean absolute error ranged from 8.1 to 26.1 mm, which represented 13–19% of observed precipitation.

Gallus Jr. and Segal (2000) studied the impact of soil moisture and convective parameterisation on the rainfall forecast of a small scale convective system occurring on 27 May 1997 in Texas. A series of sensitivity of precipitation were tested to examine the impact of soil moisture on the simulations. Two different convective parameterisations were used for the tests. The results showed that the area average precipitation was directly linked to soil moisture, while the peak precipitation in the regions of intense convection demonstrated more complex performance. Sensitivity of precipitation amounted to soil moisture differed significantly among simulations with different convective parameterisations. The simulation and conclusions were based on the climate data from one convective system only.

Jinno et al. (1993) developed a real-time rainfall forecasting model based on two-dimensional stochastic advection-diffusion equation. The model was used to forecast the rainfall at small space-time scales. Two different modelling approaches: Gaussian solution and Fourier series were used. However, it was reported by Jinno et al. (1993) that one common problem, over smoothness in the extreme values such as peaks of short period rainfall, was still not solved. Camara et al. (2000) evaluated three stochastic rainfall models based on their ability to accurately regenerate standard and extreme statistics. However, the forecast extreme values of rainfall such as 1 hour or 3 hour maximum rainfalls were difficult to be used directly in a deterministic hydrological model.

### **(b) Weather Radar and Remote Sensing for Rainfall Forecasting**

The radar and remote sensing data are becoming popular for rainfall forecasting and flood forecasting recently, although there are still difficulties to use remote sensing for flood forecasting directly.

Georgakakos and Krajewski (1991) investigated the potential benefit of radar reflectivity as an additional input to a physically based spatially lumped rainfall model. Their model was proposed to predict mean areal rainfall in river basins of the size from 100 to 1000 km<sup>2</sup> with 1-hour lead-time. A comparison of forecast error variances with and without radar data showed that the variance could be reduced in the range from 5% to 15%. Grecu and Krajewski (2000) studied real-time quantitative precipitation forecasting (QPF) using cloud models coupled with radar data. A simulation-based Monte Carlo methodology was used in this study to investigate the uncertainty in the model. A one-dimensional stochastic-dynamic cloud model was applied to simulate rainfall and radar reflectivity data. A deterministic

version of the model was used for forecasting. The differences between the forecasts and realizations of the stochastic cloud model were analysed to study the effect of cloud model uncertainty on forecasting.

French and Krajewski (1994) and French et al. (1994) developed a model for real-time rainfall forecasting using remote sensing, using a hourly time step for a catchment whose area was 170,000 km<sup>2</sup>. Marshall Shepherd et al. (2002) did similar work. They applied data from the Tropical Rainfall Measuring Mission (TRMM) satellite's precipitation radar to study warm-season rainfall (1998-2000) patterns around several urban areas in USA. Their results showed that the monthly rainfall rates within 30-60 km downwind of the metropolis rise were about 28% on average and 5.6% over the metropolis, and portions of the downwind area increased up to 51%. The percentage changes were linked to an upwind control area. The results also indicated that the maximum rainfall rates in the downwind impact area were higher than the mean value in the upwind control area by 48%-116%. The method was used in larger spatial scales and over longer time periods. The approach and results were difficult to be incorporated with the flood forecasting in smaller space scale and short time period directly.

#### **2.4.2.2 Weather Radar and Remote Sensing for Flood Forecasting**

James et al. (1993) reported an application of weather radar in flood forecasting. A distributed rainfall-runoff model was used to calculate the hydrograph, while three kinds of rainfall data were used as the model's input: observed rainfall from rain gauging stations, rainfall estimated from radar, and combined rain from station records and radar estimates. Their results showed that the combined rain from station records and radar estimates led to a more accurate hydrograph.

Mimikou and Baltas (1996), Sun et al. (2000), Yates et al. (2000), Terblanche et al. (2001) and Borga (2002) did similar work. Mimikou and Baltas (1996) used the rainfall-runoff model HEC-1 (USACE, 1990b) for flood-flow forecasting. Two kinds of rainfall data (a) from rain gauging stations and (b) derived from radar rainfall information and calibrated against rain gauging stations were used as input to HEC-1 model. The results showed that the rain input from the processed weather radar data led to a better model performance. Sun et al. (2000) used four different methods to estimate the rainfalls from the radar and rainfall gauge data, namely observed rainfall data from gauging station alone, kriging of the observed rainfall

data, radar data alone and co-kriging of both radar and observed rainfall data. The results indicated that the rainfall from co-kriging method improved the flood estimation.

Borga (2002) focused on the influence of errors in radar rainfall estimates on rainfall-runoff modeling through application of radar rainfall estimates in Brue catchment in South-West England. Two types of radar rainfall errors, one associated with range-related bias and the other associated with mean-field bias were investigated. The first type of error was due to the vertical profile of reflectivity, while the second of type error was due to systematic errors in the radar calibration and biased reflectivity-to-rain rate relationship.

Most results of Mimikou and Baltas (1996), Sun et al. (2000) Yates et al. (2000) and Borga (2002) were similar to those of James et al. (1993). However, there are still some work to be done for improving the radar rainfall such as ground clutter, radar antenna, bright band space-time modeling for radar rainfall fields, and so on (Terblanche et al., 2001).

Andersen et al. (2002) used remotely sensed precipitation from METEOSAT (a series of satellites operated by European Organization for the Exploitation of Meteorological Satellites) data, leaf area index (LAI) from NOAA (a series of satellites operated by National Oceanic and Atmospheric Administration, USA), and Advanced Very High Resolution Radiometer (AVHRR) data, as input data to distributed hydrological modelling in the Senegal River Basin in Africa. The root depths of annual vegetation were related to the temporal and spatial variation of LAI. The results showed that the simulated hydrographs using remotely sensed LAI were improved compared with the results based on conventional input of precipitation and vegetation characteristics. The simulated hydrographs resulted from remotely sensed precipitation had the same accuracy level as did with the observed rainfall data. A simple merging of remotely sensed precipitation and rain gauge data did not make any improvement. The research was conducted on a large river basin and there was no evidence that the approach could be applied to small catchments. The disadvantages of using such high resolution remote sensing data for real-time rainfall or flood forecasting were that the data might miss the flood (or rainfall events) due to the satellite running period, and the data were significantly depended on the current high cost data receiver equipment and technology.

### **2.4.2.3 Large Scale Forecasting Weather for Flood Forecasting in Real-time**

A limited number of studies have examined the accuracy of streamflow forecasting from hydrologic models using forecast rainfall by mesoscale atmospheric models (e.g. Westrick and Mass, 2002). The capability to produce such accurate forecasts in real time has also been studied recently (e.g. Benoit et al., 2002).

Westrick et al. (2002) described and evaluated an automated river flow forecasting system for prediction of peak flows over six watersheds in Western Washington in USA during the cool season of 1998-99. The forecasting system was based on the Pennsylvania State University - National Centre for Atmospheric Research fifth generation Mesoscale Model (MM5) and the University of Washington Distributed-Hydrology-Soil-Vegetation Model. Three sets of rainfall data (i.e. real time MM5 forecasts, corrected MM5 forecasts that reduced the long-term precipitation bias identified in the original MM5 precipitation forecast, and observations) were used as the input to the hydrologic model to simulate the peak flow. The results showed that the simulation based on the observed rainfall produced the most accurate peak flow forecasts. In most cases, the simulated peak flow using MM5 forecast rainfall performed very well, while there were several poor MM5 forecasts, which caused a significant overforecast of peak flows in one watershed. The flow simulation from the corrected MM5 forecast weather data did not give sensible results for peak flow forecasting. A real-time updating approach that incorporated meteorologic observations in hydrological forecast process led to significant reduction in error in forecasting peak flow.

Benoit et al. (2002) and Seuffert et al. (2002) did similar research. Benoit et al. (2002) used the Canadian Mesoscale Compressible Community Model - MC2 (developed by Environment Canada) and the flood forecasting model WATFLOOD (Kouwen, 1988) to perform real-time high-resolution forecasts. MC2 is a numerical model, which runs within the real-time Numerical Weather Prediction (NWP) model (<http://www.metoffice.com>). The hydrological model WATFLOOD is an integrated set of computer programs for forecast flood flows for catchments. The MC2 had been run in real time with an area covering the whole of the Alpine region in Europe during the Special Observation Period (SOP; 7 September to 15 November 1999). The large amount of model output including forecast precipitation and flow had been archived. However, several gaps between observed and calculated flows occurred during the SOP. The research indicated that many unresolved key issues in MC2, such as the optimal horizontal and vertical resolutions, the use and formulation of cloud and precipitation

microphysics, and the unknown level of predictability at these scales, needed to be investigated. The research emphasized the weather prediction rather than flood forecasting.

Seuffert et al. (2002) studied the influence of a land surface hydrologic model on the predicted local weather. An operational mesoscale weather prediction model, namely Lokal Modell (LM; German Weather Service) and the land surface hydrologic "TOPMODEL" - based Land Surface-Atmosphere Transfer Scheme (TOPLATS; Princeton University) were used to explore the influence. Three factors namely the turbulent fluxes, boundary layer structure and precipitation were used to investigate the influence. The model results were compared with ground-based observation of the above three factors. The influence of soil moisture for LM was also investigated. Compared with observed data, the results showed that the two-way coupled modelling system using TOPLATS improved the predicted energy fluxes and the rain amount in comparison with predictions from the original LM. The initialisation of LM using just soil moisture fields based on TOPLATS did not make an improvement of the local weather forecast.

#### **2.4.2.4 Some Relevant Aspects of Rainfall and Runoff Models**

There are lot of research papers published in this area. However, it is not intended to review all research approaches in this area such as neural networks, genetic algorithm (GA), etc. The review is based on few selected research papers in several interested topics, and they are summarised below.

Georgakakos and Smith (1990) applied the method of Kalman filters to improve hydrologic forecasting. This forecasting experiment implemented an extended Kalman filter that updated the system states based on discharges at the basin outlet observed up to the forecast time. The dominant sources of forecast uncertainty were assumed to be the errors in estimates of model parameters and the errors in observations of model inputs. Using these assumptions, a shortcoming of the earlier hydrologic Kalman filters (i.e. lacking a procedure for estimating the time-varying covariance matrix of errors) was improved. The results confirmed improvements both in forecasts and the model's operational viability.

Smith and Eli (1995) investigated the use of neural networks for runoff response from different rainfall patterns considering spatial and temporal distribution by a very simple  $5 \times 5$  grid cell synthetic watershed. A backpropagation neural network was trained to calculate the

peak discharge and its corresponding time from a single rainfall pattern. The neural network was also trained to map a time series of three rainfall patterns into a range of discharges over future time by replacing the entire outflow hydrograph using a discrete Fourier series fit.

Imrie et al. (2000), Chang and Chen (2001) and Sivakumar et al. (2002) did similar research in the application of neural networks. Sivakumar et al. (2002) compared the performance of artificial neural networks (ANN) approach with performance of phase-space reconstruction (PSR) approach by comparing the forecast river flows from both approaches. The daily time step was used and 1-day and 7-day ahead forecasts of daily river flows were conducted. The methods were applied to Nakhon Sawan station in Chao Phraya River basin in Thailand. The results showed that the performance of the PSR approach was consistently better than that of ANN.

Wang (1991) introduced the genetic algorithm (GA) for calibrating the conceptual rainfall-runoff model. Liong et al. (1995) also used a GA to determine the optimal values of catchment calibration parameters. The catchment model was developed using the widely used conceptual rainfall-runoff model, the storm water management model (SWMM) (Huber et al., 1982). The method was applied to a catchment in Singapore of 6.11 km<sup>2</sup> in size. Six storms were used in the study, and three of them used for calibration while the remaining three were used for validation. The results showed that GA required only a small number of catchment-model simulations and produced relatively high peak-flow prediction accuracy with a range of the prediction errors from 0.045% to 7.265%. Kumar and Douglas (1997) in their discussion of the work of Liong et al. (1995) suggested using another objective function, which is minimizing the cumulative runoff volume, instead of minimizing percentage of peak discharges used by Liong et al.

Garrote and Becchi (1997) presented a software environment for real-time flood forecasting using distributed models. The software architecture was discussed based on its database design (data file format), object organization, model inference and user interface. The software namely Real-Time Interactive Basin Simulator - RIBS included two distributed rainfall-runoff models based its object-oriented design. These two models were incorporated in the system to demonstrate the real-time flood forecasting. They were: a simple conceptual model with a light computational load – HYDBL (Becchi et al., 1989) and a complex, physically based model with more realistic representations of hydrologic processes – DBSIM (Garrote and Bras, 1995). The system included the functions of process organization and data

handling; user interaction and results visualization; and access to model structure, hydrologic process and model inference. However, the design of data flow was not described in the article and the influence of the file structure of database needed further investigation.

Jinwon et al. (1998) presented a numerical study of precipitation and river flow in two California basins, Hopland and Sierra Nevada in USA to investigate the hydro-climate, snow budget, and streamflow at different elevations. The coupled atmosphere, land surface, and hydrology in the developed Regional Climate System Model (RCSM) were used for hydroclimate simulation. The large-scale weather information was downscaled to the catchment scale using a mesoscale model in RCSM and fine-resolution geographic information data. The semi-distributed TOPMODEL (Beven and Kirkby, 1979) and two versions of the lumped Sacramento model (Burnash et al., 1973) were used to simulate streamflow. Simulated precipitation from the mesoscale model and streamflow at the Hopland basin were in good agreement with the observed data. Both Sacramento models predicted a similar response of river outflows from this basin, while TOPMODEL predicted a faster recession of river flow with less base flow after precipitation stopped.

A fuzzy conceptual rainfall-runoff (CRR) framework was introduced by Özelkan and Duckstein (2001) to determine parameter uncertainties of conceptual rainfall-runoff models. The conceptual rainfall-runoff system was first fuzzified and then different operational modes were formulated using fuzzy rules. Next, the parameter identification aspect was verified using fuzzy regression techniques. For linear conceptual rainfall-runoff models, the bi-objective and tri-objective fuzzy regression models were used, while a fuzzy least squares regression framework was used to get the model parameters in the non-linear models. Three models, linear conceptual rainfall-runoff model, an experimental two-parameter model and a simplified version of the Sacramento soil moisture accounting model, were used. The results showed that the sensitivity and uncertainty stemming from the elements of the CRR model could be obtained from the fuzzy logic framework.

Jasper et al. (2002) studied coupling of atmospheric and hydrological models for flood forecasting in complex mountain watersheds. The grid-based hydrological catchment model WaSiM-ETH was used to simulate the continuous runoff hydrographs. Two different sets of meteorological input data were used: (1) surface observation data from station measurements and from weather radar, and (2) forecast data from five different high-resolution numerical weather prediction (NWP) models with grid cell sizes between 2 and 14 km. The simulated

flood runoffs were compared. The results of sensitivity studies pointed out the limitations of high-resolution flood runoff predictions in complex mountain terrain.

There are many other research works using various approaches. Some examples are listed below. Madsen et al. (2002) studied three different automated methods for calibration of rainfall-runoff models. Niehoff et al. (2002) studied the impact of land use changes on runoff generation. Szymkiewicz (2002) reported an alternative Instantaneous Unit Hydrograph approach for both the Muskingum model and the linear reservoir model. Zhang et al. (2002) developed a runoff routing model with a linear routing structure. Schumann et al. (2000) presented three semi-distributed models to show how statistical descriptions of distributed catchment characteristics could be used to consider spatial heterogeneity within conceptual models. All these works demonstrate that the rainfall runoff process can be described using an algorithm or a numerical model or an approach with reasonable accuracy for decision making in flood warning.

### **2.4.3 Flood Areas and Flood Levels**

Bates and De Roo (2000) described a flood inundation simulation model based on a high-resolution raster Digital Elevation Model (DEM) using 100, 50 and 25 m resolution DEM data. The model consisted of a one-dimensional kinematic wave approximation for channel flow (that was solved using an explicit finite difference scheme) and a two-dimensional diffusion wave representation of floodplain flow. The air photo and Synthetic Aperture Radar (SAR) data for flood inundation extent were used to support the developed model. The results of this model were compared with those from two other inundation prediction techniques: a planar approximation to the free surface and a relatively coarse resolution two-dimensional finite element scheme. The results showed that the dynamic effects were fairly unimportant for prediction of peak inundation, and the raster-based model (of Bates and De Roo) had produced close results to the current prediction limit for this kind of problems. However, the best performance of the raster model still only reached the level of 85.5% accuracy.

Nico et al. (2000) discussed the methods of flood area detection using multipass SAR data performed via amplitude change detection techniques. A prototype application of these techniques was presented. The case study referred to a flood event of Beziers, in Southern France. Three data processing methods were considered: using only the amplitude difference

information; using the interferometric coherence; and using integration of the above two methods. The results showed that the third method was most effective because it can satisfactorily detect most of the flooded area in very regular and homogeneous contour lines without numerous spurious patches that affect the single-source data sets. The flood map was produced in a DXF vector file (which is a common GIS input file format). The process could be an effective technique for flood detection and monitoring.

Brivio et al. (2002) described the use of satellite radar images and ancillary information to identify flooded areas at their peak and evaluated this potential with mapping. The procedure was tested on a disastrous flood event in Region Piemonte in Italy in November 1994. Two ERS-1 (which is a remote sensing satellite launched by the European Space) SAR data images were processed for identifying the flooded areas. One SAR image was taken one month before the flood event, while the other image was taken three days after the flood event, and the two images could reflect the ground difference before and after flood event. Visual interpretation of images and two different thresholding techniques were used. The derived flood map showed only a small fraction (20%) of the actually flood inundated area had been detected. This could be because of the time gap between the occurrence of the flood peak and the time satellite images were taken, which meant when satellite was flying over the flooded area, the flood peak had already passed this area. A new procedure was then developed to overcome the above limitation, and to estimate the flooded area at the peak by integrating the flooded area from SAR imagery with digital topographic data from a GIS technique. The derived inundated areas by the new procedure covered 96.7% of the recorded (or observed) flooded area. This new procedure is a possible way to overcome the constraint of temporal resolution in the application of SAR imagery in hydrology. However, using remote sensing (e.g. SAR data) for flood warning decisions in small or even middle sized catchments such as the Maribyrnong River catchment in this study is still questionable, since the remote sensing data in the low resolution (e.g. the size of pixel is 1 km) cannot accurately define the flooded area for such small catchments, while the remote sensing data in the high resolution may not catch the flood event on time.

Horritt and Bates (2002) studied several 1D and 2D flood hydraulic models, namely HEC-RAS (USACE, 1997, 1998a,b), LISFLOOD-FP (Bates and De Roo, 2000) and TELEMAC-2D (LHF, 1997), on a 60 km reach of the river Severn, UK to predict the river flood inundation. Both the observed inundated area and records of downstream discharge were used to calibrate these models against floodplain and channel friction. The flood inundation area

data for flood events in 1998 and 2000 from radar remote sensing satellites were available and used in this study. The results showed that both HEC-RAS and TELEMAC-2D models were able to predict the flood inundation area well compared to LISFLOOD-FP.

## **2.5 Spatial and Graphic Data Display and Analysis and GIS Application**

Spatial and graphic data display and analysis (SGDDA) has become a very important part in the decision making process (Walsh, 1993). Geographical Information System (GIS) software, which are capable of gathering, storing, manipulating, and displaying geographically referenced information (i.e. data identified according to their locations) are popularly used in water resources problems (e.g. Zheng and Baetz, 1998). However, most such applications only use some functions in GIS software such as preparation of model parameters and mapping outputs rather than complete integration with GIS. The integration between outputs from other models (or software) and GIS components is essential for decision making process in complex problems with modern information and to develop DSSs to answer “what if” questions effectively. There is no doubt that a well-developed GIS system can be used as a DSS development environment (e.g. Chiueh and Lo, 1997). However, it is not necessary that the DSS which deals with spatial data and analysis must be developed in a commercial GIS system environment, since most GIS software are expensive, not all functions of the GIS software are required by the potential users and the integration between the GIS software and other models (or software) is still needed.

Based on the application of GIS software and technology in DSS, the SGDDA in DSS is typically achieved by the following three methods.

- The first method is that the SGDDA functions are developed through integrating other DSS components with some GIS tools such as Mapobjects (which is developed by Environmental Systems Research Institute - ESRI). The technology of GIS and some GIS tools are used in this method, while the developed DSS does not rely on the GIS environment. If the user does not have the GIS tools or do not want SGDDA functions, other functions in DSS still work after the developer removes these SGDDA functions. The main advantage of this method is ease of development, flexibility and adoptability. This method is used in some applications (e.g. Shim et al., 2002).

- The second method is that the functions are developed by the DSS developers themselves. In this case, the technology of GIS may or may not be used in DSS development, while the GIS software is not used in the DSS. The method does not require the extra resources. However, the functions rely on the developer's skills and resources (e.g. funding).
- The third method is that the whole DSS is developed in a Geographic Information System (GIS) environment and the functions in SGDDA use those provided in the GIS software. The main advantage of this method is ease of development by using (existing) GIS functions in GIS software. However, the potential users must have the same GIS software.

Due to the popular use of GIS in DSS, some applications of GIS (without linking to a DSS) are reviewed in Section 2.5.1. The relevant applications of SGDDA corresponding to the three above-mentioned methods are then reviewed in Section 2.5.2.

### **2.5.1 GIS Applications**

A detailed literature review on the use of GIS with hydrological models was reported by Goonetilleke and Jenkins (1994). Two broad approaches in the integration of GIS with hydrological models and their limitations were discussed. The methods were "Loose Coupling" and "Tight Coupling". The former uses external linkage, while the latter uses GIS toolbox to implement the key elements of the model. Loose Coupling was suggested by Goonetilleke and Jenkins (1994) for integration of GIS with hydrological models. However, there are significant advantages of Tight Coupling in DSS development such as its consistency in data transfer, eliminating data transfer errors and faster simulation. Nevertheless, the DSS environment in this case does not use the GIS environment.

See et al. (1992) used ArcInfo (ESRI, 1991) GIS software to study a selenium discharge problem. Selenium concentrations in samples were determined and evaluated. The location, concentrations and type of sample media of selenium were displayed on the map through GIS. Schoolmaster and Marr (1992) also used ArcInfo as a tool to display water use data in Texas, USA. A variety of colours corresponding to the amount of water use were used on a three-dimensional map.

GIS software is also often used to assess model inputs. Shamsi (1996) used a GIS integration to estimate the input parameters of the hydrologic model, the Penn State Runoff Model (Aron, 1987). The above GIS integration approach can display both vector and raster GIS data. The PC ArcInfo was used as the vector GIS tool, while ERDAS (by ESRI) was used as the raster GIS tool. However, no system integration technology such as computer programming was reported in this study.

GIS had also been used for suburban development from an urban hydrology perspective (Zheng and Baetz, 1997). In this case, the GIS software was used to link the spatial data and the storm water runoff simulation model QUALHYMO (Rowney and Wisner, 1984), and to perform tasks such as watershed definition, hydrologic parameter estimation, location of developable areas, and presentation of design scenario applications. QUALHYMO was used to estimate the peak flow rate and the total runoff volume of a regional storm under current and future land use conditions. Two GIS software tools (i.e. ArcInfo and ArcView) were used in their application. ArcInfo was used to create and manage geographic information, and ArcView was used to visualize, explore, query and analyze geographic information.

Vector data format in GIS has been popularly used in water resources. For example, Wong et al. (1997) developed a land-use runoff model, by coupling the ArcInfo GIS software with an empirical runoff model, for the Santa Monica Bay in California, USA. The model required simple data input. It can predict receiving-water loading on an annual basis or for single-storm events, and also optimise the location of monitoring stations. The model prediction can be used to improve the evaluation of pollutant discharge control management. The model can be further improved to incorporate non-point sources and optimisation techniques that can be integrated with the GIS, so that the cost effectiveness of water quality control measures can be analysed.

Raster data format was also often used (Chen et al., 1998; Middelkoop and Van Der Perk, 1998). Chen et al. (1998) introduced the linkage of a grid-based GIS with a three-dimensional reservoir water quality model for Arha reservoir, China. Three-dimensional reservoir quality model was used to estimate the flow field and the distribution of chemical elements Fe and Mn with cell size of 50 m. The simulated results were used to obtain the distributions of Fe and Mn in grids of 25 m cells using the GIS grid-cell kriging function. The results demonstrated the efficacy of kriging in 3D reservoir quality modelling compared with the results directly from 3D reservoir quality modelling with 25 m cells.

Middelkoop and Van Der Perk (1998) presented a GIS-based mathematical model for simulation of floodplain sedimentation. The model consisted of two components: hydrodynamic WAQUA model (ICIM, 1991) and SEDIFLUX model (Van der Perk et al., 1992). The WAQUA model was used to simulate two-dimensional water flow patterns, while the SEDIFLUX model, based on a simple mass balance concept with less model parameters, was used to estimate the deposition of sediments. The models were applied to simulate floodplain sediment deposition over river reaches of the lower River Rhine in the Netherlands. The raster maps of observed sediment deposition during the flood in December 1993 was used to calibrate and validate the SEDIFLUX model. The authors also discussed the important factors effecting spatial patterns of overbank deposition such as inundation frequency, sediment load, and floodplain topography, and its influence on the flow patterns over the floodplain.

Urbanski (1999) presented the use of GIS for evaluation of the vulnerability of coastal waters and a method for mapping their vulnerability to algal blooms. The method can incorporate the probability mapping of parameters relating coastal waters and fuzzy sets. The produced maps of vulnerability could be used to discover water sources in eutrophication.

Lehmann and Lachavanne (1999) analysed and compared the distribution of submerged macrophytes along 20 km of lake shore in Lake Geneva in Switzerland in the years of 1972, 1984 and 1995. Two methods of bioindication of water quality for macrophytes, namely saprobic index and organic pollution, were compared. The saprobic index was suggested to be a better bioindicator for this research. Geographic Information Systems (GIS) was used to map and store information of submerged vegetation, as its functions were powerful for easy interrogation, updating and plotting of spatial information at various scales, and providing a reference for future comparisons.

The remote sensing and GIS techniques sometimes were integrated together to solve spatial problems in the area of water resources such as the detection of flood hazard impacts in Southeast Florida in USA (Finkl, 2000) and the assessment of hydrologic response of a watershed due to various land use and management changes (Sharma et al., 2001).

## 2.5.2 SGDDA in DSS

The method used for SGDDA development in a DSS depends on available software, financial resources, and technical skills. Three types of applications are detailed below.

### **(a) DSS Using GIS Software or Technology Without Running on a GIS Environment**

Goulter and Forrest (1987) discussed the use of GIS in river basin management. As stated by them, GIS should not be considered as a means of providing the final answers to complex water resources planning issues, but should rather be seen as an important component of a DSS. Dunn et al. (1996) used maps to display some factors such as digital elevation, and graphics to display rainfall and river flow. The GRASS GIS software was used in this system, but the DSS was not designed to run on the GIS environment. Similar work was also done by Fredericks et al. (1998). They developed a DSS that can deal with vector and raster data formats from IDRISI (Eastman, 1992). Again, DSS was not operated on the GIS environment.

Shim et al. (2002) developed the graphical display functions from Windows environment using Visual Basic programming in a prototype of a Spatial Decision Support System (SDSS). The functions of spatial analysis and display in this SDSS were run in ArcView (by ESRI) environment using AVENUE (by ESRI) script programming. However, the tools such as AVENUE cannot conveniently handle the complicated information exchange between various systems such as information from Windows to ArcView. Makropoulos et al. (2003) also used the ArcView environment to perform the functions of spatial analysis and display in a SDSS, which was also run in a Windows environment.

### **(b) Developed Functions**

Camara et al. (1990) analysed and displayed spatial data such as sampling stations and non-point pollution loads using the maps and texts in a DSS application. They developed these functions by themselves without GIS software and technology. Similar work had been reported by others (e.g. Ford and Killen 1995; Andreu et al. 1996), where computer programs had been developed for graphic and simple map display. It is obvious that most of such functions are very simple, compared with those available in the commercial software such as ArcInfo.

### **(c) GIS Software as DSS Operation Environment**

Srinivasan and Engel (1994) developed a DSS in GRASS (U.S. Army, 1987) GIS environment. They displayed factors such as sediments, nutrients and runoff movement by text files or graphics on the GIS system. The GRASS software is currently a free software, and its computer code is also available free of charge. Many DSS components related to water resources have also been developed in GRASS environment and they are also available free of charge. This GIS software could have potential in SGDDA development in a DSS, especially for those who have strong system development skills, but with less financial resources. A framework of a DSS developed in GRASS GIS environment for flood simulation and forecasting was recently reported by Garcia (2004).

The MapInfo GIS software had sometimes been used as a DSS development environment due to its reasonable prices and suitable functions. A decision support tool was developed in MapInfo environment for managing floodplain flow in Lower Balonne river in Southern Queensland, Australia (Marr and Martin, 1999). The flow was calculated by an in-house hydraulic model, HSFR, and it was run from the MapInfo interface. The MapInfo interface, which was created using MapBasic programming, was also used for displaying the flood extent map and the simulated hydrograph. However, the mapping was for display only without further spatial analysis.

The powerful GIS software from ESRI such as ArcView, ArcInfo and ArcGIS (which is the most recent version of Arcview and ArcInfo) are common software tools that had been used as DSS development environments. For example, a prototype of SDSS was developed for soil contamination problems in ArcInfo environment (Chiueh and Lo, 1997). Gorr et al. (2001) developed a SDSS in ArcView environment for home-delivered services.

### **(d) Further Remarks**

As can be seen from (a) – (c) above, the three methods described (and reviewed) have been widely used in DSS development and application in relation to spatial and graphic data display and analysis. However, few articles presented the reasons of tools selection such as the selection of GIS software and methods used.

The method of DSS using GIS software without running on a GIS environment and the method of developed own functions were used in this research for spatial and graphic data display and analysis in developing the DSSFCMR.

## **2.6 Decision Support and Decision Choice Support**

The decision choice support defined in this research is not the same as the decision support and in fact, the decision choice support is a subset of decision support. As stated earlier, the decision support (through DSSs) is often used to answer “what if” questions and deals with models, databases, spatial and graphic data display and analysis, decision choice support etc.. Certain conditions will lead to possible decisions. For example, different flood forecasts would have different flood warnings in flood warning decision making. A DSS for flood warning should have the capacity to develop and analyse many scenarios of flood forecasting and then decisions made on flood warning based on these scenario results. The decision choice support in a DSS is used to help the decision maker to select a small number of alternative decisions to build acceptable decisions. The aim of decision choice support is finally for decision support. Therefore, the decision support will be reviewed first in this section. As this study is about the DSS development to assist decision making in flood warning area, the flood warning is then reviewed to help understand the decision making of flood warning. Finally, the decision choice support in reviewed.

### **2.6.1 Decision Support**

Decision support has been performed in the past using optimisation strategies, satisfying strategies and incrementalizing strategies (Kroenke and Hatch, 1994; Schultheis and Sumner, 1995). The optimisation strategy is to find the best solution, usually the one that will best help decision-makers to meet their goals. The optimisation methods such as Linear Programming, Non-Linear Programming and Dynamic Programming can be applied to achieve these goals (Mays, 1996). These models are widely used in water resources. Sample et al. (2001) used Linear Programming in a DSS to determine the best management practice. Dynamic Programming was used to find an optimal gate-control strategy in a Spatial Decision Support System (SDSS) (Shim et al., 2002). The optimisation models are best suited for problems that can be modelled mathematically with less uncertainty. This strategy is not suitable to select the final solution for flood control problems, especially those

involving flood forecasting and warning, since such problems have a high level of uncertainty in input information.

The satisfying strategy is to find a good but not necessarily the best solution for the problem. This strategy is usually used because modelling the problem properly to get an optimal decision would be too difficult, complex and costly. The satisfying strategy normally does not investigate all possible solutions, but consider those solutions that are likely to give good results without spending too much time and effort to investigate all alternatives. This strategy is also in common use in water resources research. For example, Krzysztofowicz (1993) used Bayesian principles to develop decision rules for issuing flood warnings. Bouchart and Goulter (1997) used a rational decision making model for irrigation reservoir management. Both applications were developed to find good results rather than an optimal decision. de Azevedo et al. (2000) used satisfying state function to evaluate the reliability of water supply.

The strategy of incrementalizing is to make small steps away from current state towards a design state, and is controlled by some rules. The goal is to find an acceptable solution and “rules of thumb” are commonly used for this purpose. This strategy is very often used in decision making in practice.

### **2.6.2 Flood Warning**

Scientific decision support approaches to flood warning systems had been explored and applied by numerous researchers since the 1970s. A review of the research work on flood forecasting and warning systems was given by Krzysztofowicz (1994). Krzysztofowicz and Davis (1983) found a decision-theoretic methodology for modelling and evaluating forecast-response systems for floods on mainstream rivers. A comprehensive set of design requirements for flash flood warning systems were presented by Georgakakos (1986). Cock and Elliott (1989) introduced the work of flood warning and real-time data collection in Australia. A weighting method in conjunction with dynamic programming was used for obtaining optimal flood warning solutions (Li et al. 1992). On the other hand, Parker and Handmer (1998) studied the use of unofficial flood warnings. They believed the unofficial flood warnings can play very important role and integrating unofficial flood warnings with official ones have significant advantages.

According to Krzysztofowicz (1993), the theory derived from Bayesian principles can be used to develop optimal decision rules for issuing flood warnings, to evaluate system performance statistically, and to compute the expected economic benefits from a flood warning system. The flood warning system was decomposed into a monitor, a forecaster, and a decider. The models of the monitor and the forecaster quantify all uncertainties associated with the operation of the warning system, from the viewpoint of the decision maker. At the heart of this quantification was the Bayesian Processor of Forecasts (BPF), which produced a posterior description of uncertainty on flood occurrence and crest height, conditional on a flood crest forecast. One of the formidable challenges in applying BPF in this context has been the modeling of likelihood functions and derivation (or computation) of the posterior distribution when the prior distribution is not a member of the conjugate family for a specified likelihood model. Aside from the convenient normal-linear BPF, there are virtually no suitable analytic models. This has been a major hurdle in applying Bayesian methods to forecasts of flood peaks whose distributions are anything but Gaussian. Kelly and Krzysztofowicz (1994a) developed a general analytic solution for the BPF.

The reliability of a flood warning system can be characterized statistically in terms of two measures: (1) the relative operating characteristic (ROC) and (2) the performance trade-off characteristic (PTC), which shows feasible trade-offs that a given system offers between the expected number of detections per year and the expected number of false warnings per year. When the floodplain extends across a range of elevations, ROC and PTC are defined for each zone of the floodplain (Krzysztofowicz, 1992). The BPF (described in the previous paragraph) has provided a framework for studying the synergistic effect of a dam and forecasts. These effects were illustrated with a case study by Kelly and Krzysztofowicz (1994b). A different case study presents ROC envelopes of warning systems for uncontrolled rivers in Pennsylvania during the 1960--1980s (Kelly and Krzysztofowicz, 1994c). Numerical procedures for computing ROC and PTC were derived and applied to flood warning systems serving three communities in Pennsylvania (Krzysztofowicz et al., 1994).

### **2.6.3 Decision Choice Support**

Two types of decision support functions in DSS for water resources problems can be found: (a) model results provided without decision choice support in DSS (e.g. Koch and Allen, 1986; Stansbury et al., 1991; Andreu et al., 1996; Ford, 2001, Shim et al., 2002; Makropoulos et al., 2003); (b) model results provided with limited decision support choice in DSS (e.g.

Wang et al. 1998, Vassilakis et al., 2002). However, there could be a third decision choice support function (i.e. a complex Expert System) for decision support for which no applications were found in the literature.

As outline in Section 2.6, the decision choice support in a DSS is used to help the decision maker to select a small number of alternative decisions to build acceptable decisions. However, there are some DSSs, which have already used optimal programming (e.g. Shim et al., 2002) to derive an optimal scenario rather than optimal final decision from many scenarios. These DSSs are considered as systems without decision choice support.

A subsystem with limited decision choice support in DSS is designed in DSSFCMR in this research to help the user to select a small number of alternative decisions to build the acceptable decision. The technology developed for decision choice support in this study is to help locate the required scenarios from many scenario results using the database technology.

## **2.7 Summary**

A Decision Support System (DSS) can be viewed as a third generation of computer based application. The bloom of research and development in this area proves its significance, shows its benefit and brings it to a new development stage. The recent amazing advances in computer science led to many powerful tools or vendors related to DSS development. However, not every developer understands the recent DSS theory and practice well. A review of the DSS including its history, definition, development and general applications was presented first in this chapter. This part of the review will help the developer to understand how multiple techniques can be integrated into a DSS, understand possibilities for computerized support of decision making and sharpen tomorrow's DSSs. The review was also focused on the need to build an effective DSS for flood warning. Therefore, the remaining part of the review in this chapter focused on the following areas: DSS theory and practice; DSS in water resources; hydrological, hydraulic and economic models for Flood Forecasting and Warning; spatial and graphic data display and analysis; and decision and decision choice support.

It was found in this review that it was difficult to give a formal definition for a DSS, since different researchers have used different definitions. The effective decision support and a computer system were generally recognised as the key aspects of a DSS. The major difference in the DSS literature was on the type of problems in terms of its structure (i.e. non-structured,

semi-structured and structure). The author believes that the reference to non-structured problems in early studies often meant poorly structured problems, which is similar to semi-structured problems. The author agrees with Alter (1992) that “improving decision making” is a more fundamental idea of a DSS and the systems (e.g. DSSs, Expert Systems - ESs, Management Information Systems - MISs) continually absorb new features from each other and become hybrids. However, an appropriate description of DSS would help its further research and development. As part of this research, the author defined the DSS and components of a DSS, are described below, based on the review of previous works (many of them are pioneering work and master pieces in this area, but still paving the way for future DSS development).

The DSS is an interactive computer-based system that helps decision-makers to use data and models to solve semi-structured problems effectively. A DSS allows the user to participate in principal steps of the decision making process, to simulate many steps in the process of decision making, to investigate alternative scenarios, to seek the overall goal for decision, and to improve the effectiveness of decision making.

The components of DSSs were often identified in the conceptual design stage of DSS development, especially for water resources problems. However, these components were depended on the DSS theory development and application domain, while the database, model and interface were considered important components of a DSS in early work of DSS. Based on modern technology and more powerful functions, the author suggests that a DSS, should include five essential components or subsystems: a database subsystem, a modelbase subsystem, an interface subsystem, a decision support subsystem, and a spatial and graphic data display and analysis (SGDDA) subsystem.

This review of theory and practice of DSS helped the author to have a clear mind of DSS development life cycle, and used this information in the development of DSSFCMR for flood forecasting and warning in the Maribyrnong River. DSSFCMR includes all five essential subsystems. The DSSFCMR can consider various forecast rainfall depths in different forecast periods. The URBS and HEC-RAS models in its modelbase can be used to calculate flood hydrographs and flood water levels along the flood prone area respectively. Methods were identified for use in DSSFCMR to perform spatial and graphic data display and analysis of the flood inundated area. The database technology was identified as the method for decision choice support in this study, to narrow down the required decision scenarios from many

scenario results. It is intended that all functions in DSSFCMR will be properly integrated with each other, so that the user can make the decision effectively.

## **CHAPTER 3**

### **FOUNDATION THEORY OF DSSFCMR**

The Decision Support System for Flood Control in the Maribyrnong River Basin (DSSFCMR) developed in this research project is a computer system that helps the user to make effective decisions in flood forecasting and warning in the Maribyrnong River basin in Victoria, Australia. The theory and knowledge required to develop such a complex decision support system (DSS) could include those of DSS, computer science, decision making, Geographical Information System (GIS), hydrology, hydraulics, etc. However, the focus of this chapter is on the foundations of theory and models related to flood forecasting and warning, and theories used in DSSFCMR rather than all aspects of the above-mentioned theories or knowledge.

The development and application aspects of DSS relevant to this research project are introduced first in Section 3.1. The theories of relevant hydrological and hydraulic models are then described in Sections 3.2 and 3.3 respectively. Section 3.4 presents the relevant theory on the spatial and graphical data display and analysis, while Section 3.5 describes the theory of decision support technology. The DSSFCMR design and development are detailed in Chapters 4 and 5, following the theories explained in this chapter.

#### **3.1 Decision Support System**

The DSS is usually defined as a computer based system, which helps decision making for semi-structured problems. The DSS design and development theory is as essential as water resources theory for an effective DSS in water resources. In order to develop a DSS to solve the flood forecasting and warning problem, it usually requires a good knowledge of computer science, hydrology, hydraulics, operations research, decision making methods, etc. The design and development of such a system itself is a research problem (e.g., Yen, 1986; Loucks, 1995; Chan et al., 2000).

There had been several DSSs developed for solving various problems in the field of hydrology and water resources. Examples are river basin planning and management (Andreu et al., 1996; Jamieson and Fedra, 1996a,b; Fedra and Jamieson, 1996), flood control (Ford, 1995, 2001; Shim et al., 2002), water resources management (Ito et al., 2001; Eschenbach et al., 2001), and so on. Most of these works emphasises on the components of DSSs and the

function of the DSS. Only a few articles described how to develop an effective computer-based DSS from software engineering viewpoint (e.g. Taylor et al., 1999).

Generally, the design and development of a DSS is mainly based on

- The function of the DSS;
- The resources available (e.g. hardware, software, human resources and funds);
- The potential users;
- The system environment (e.g. desktop version, Internet version and cross platform).

The following basic requirements were considered and available in developing DSSFCMR in this study.

- Function – To develop a DSS to help the user to make decisions effectively in flood forecasting and warning in the Maribyrnong River basin.
- Available resources at the design phase:
  - Computer Hardware: developed for PC only
  - Software:
    - Operating system: DOS, Windows
    - Available programming tools: Visual Basic, Torbal C++, Visual C++
    - Available database: MS ACCESS
    - GIS software, MapInfo, ArcView, MapObjects.
    - Hydrology modelling tools: RORB, URBS (DOS version)
    - Hydraulic modelling tools: HEC-RAS (Windows version)
- Potential users  
Melbourne Water Corporation, and other catchment authorities and local government councils in the Maribyrnong catchment.
- The Windows environment; desk top version
- No extra funds
- Data support: Victoria University, Melbourne Water Corporation

The design and development aspects of an effective DSS are explained in Sections 3.1.1 and 3.1.2 respectively.

### **3.1.1 Design Aspects**

The current design for the DSS in the water resources area is often defined by the components (or subsystems) of a DSS (Labadie and Sullivan, 1986; Johnson, 1986). This method was developed by Sprague (1980) and had become the popular DSS design method (e.g. Sauter, 1997). It is a reasonable way to describe the DSS design in the water resources area, because many existing technologies can be conveniently included in subsystems, the functions and products are clearly defined in subsystems, which can be easily built, and water resources scientists and engineers can easily follow the items in these subsystems without a deep understanding of their design procedure.

As described in Section 2.2.4.3, the quick-hit method uses the existing technologies for DSS design. This method concentrates on the final DSS product and therefore on the construction of the DSS. DSSMCMR in this research uses the quick-hit method as the author uses some existing technologies and focuses on analysis and products of DSS.

Often in the past, the DSSs in water resources has included three subsystems namely a database management subsystem (DBMS), a modelbase and an interface. However, the DSS theory has been further developed since the time of these developments and continues to develop. For example, Spatial Decision Support System was introduced (e.g. Walsh, 1993); the Group Decision Support System was developed (e.g. Hendriks and Vriens, 2000), a mail subsystem was considered as a core subsystem in a DSS (Sauter, 1997), and so on. Therefore, based on some of these recent developments, the author is of the opinion that the modern DSS in water resources should in general include five subsystems. Spatial and graphical data display and analysis (SGDDA) and Decision Support subsystems should be included in addition to the commonly used DBMS, Modelbase and Interface.

Spatial data display and analysis has become a very important component in the decision making process (Walsh, 1993) and hence in DSSs. For example, spatial data display and analysis are needed in investigating the extent of flood-inundated areas, the spatial allocation of water supply pipelines, the extent of forest cover and the collection area for non-point source pollution. These examples show that the decision variables in water resource problems are often associated with spatial data and hence the importance of spatial data display and analysis in DSSs.

Many previous DSSs in water resources either did not have functions of spatial data display and analysis (e.g. Ford, 2001) or had very simple functions (e.g. Ford and Killen 1995; Andreu et al. 1996) to meet the spatial data display and analysis. The reasons for having no or limited SGDDA functions were that the relevant technologies and software tools at that time could not easily be incorporated into the DSS. For example, the GIS software was not easy to learn, the computer programming was difficult to develop the required SGDDA functions for the developer, and the prices of software tools (both GIS and DSS development tools) were high. These reasons are no more valid today. The theory of SGDDA has improved, software tools are much more powerful with ease of use, and GIS and DSS development tools have become affordable. Therefore, the Spatial and Graphic Data Display and Analysis (SGDDA) subsystem should be a core element in a modern DSS, where the spatial data display and analysis plays a central part in the decision making.

The Modelbase subsystem in this research includes models, which are used to answer “what if” questions related to decision making in flood forecasting and warning. For example, what decisions should the decision maker take if the rainfalls for the next few hours are forecasted with several different values? In this case, the models available in the Modelbase subsystem can be used to assist the decision making. A rainfall-runoff model can be used to predict the flood flows, and a hydraulic model can be used to calculate the flood water levels. Using these models, many decision variables (such as anticipated flood water levels, houses that might be subjected to these possible floods and consequent relocation of people) can be simulated under various decision scenarios with various forecast rainfall depths for different forecast durations. All these processes related to forecast rainfall, prediction of flood flows and calculation of flood water levels can be modelled, and/or can be described by algorithms or decision rules. In other words, these processes are structured and the Modelbase subsystem was used to model the structured processes.

Several decision scenarios representing various forecast rainfall depths and periods are generated in DSSFCMR to assist decision making in flood forecasting and warning. However, there is no structured way to choose the best decision from these decision scenarios. In other words, the decision making process is non-structured and therefore a separate subsystem, the Decision Support subsystem was used for this unstructured phase (which is the decision choice phase). The Decision Support subsystem offers a search function to choose a small number of relevant decisions from many flood scenarios generated from models in the Modelbase subsystem. The search function in DSSFCMR uses database search technology.

On other hand, an Expert System (ES), which is generally used for non-structured problems, also can be used for decision choice. However, it should be noted that ES is not a DSS, but can be an effective components in a DSS to support the non-structured phase of decision making only. Due to lack of data to develop an ES for decision choice, it was not used in this study.

### **3.1.2 Development Aspects**

Ideally, all components or subsystems in a DSS (in water resources) should be developed using the same operating system, the same computer language and the same database system, and then the product can be run on any platform and have the expected complete functions within the DSS such as hydrological calculations, hydraulic calculations, decision analysis, decision making support, and DSS system functions. The design and development of such DSSs can then be easily developed and totally be managed by the developer. However, the development of such DSSs in a perfect development environment needs a strong design and development team, which includes experts in various areas such as water resources and software engineering. Since all functions and models are developed by the developer in this case, the developer also needs to promote their developed application models (such as the hydrological model) for the user to accept the DSS and use confidently. Such development also needs lot more thinking and funding. Alternatively, the developer of the DSS may borrow the source code for some of these application models from other developers, which enables the DSS developer to develop the DSS in the above perfect development environment.

In practical terms, it is impossible to have the above perfect development environment due to limitations of technology, resources and deadlines. The developer often uses the software tools and models that are developed by others and are well known to the potential user. Such software tools and models are called vendors in DSS design and development theory. The advantage of using vendors to solve these problems is that the potential user (of such vendors) is confident of qualities and attributes of these vendors. The disadvantage of using such vendors is that they have been developed as standard alone tools and often developed for the general user (of the vendor) rather than for the DSS developer. They often do not interact effectively with other vendors. The earlier software engineering theory had considered only "perfect" vendors for linking with other software. However, the nature of DSS development

in water resources is such that DSSs are required to be developed with “imperfect” vendors (which are difficult to link with other software) through innovative integration technologies.

### **3.2 Hydrological Model**

The Modelbase should include a hydrological model, which can be used to calculate the forecast flood hydrographs for use in flood forecasting and warning. As stated in Sections 1.2.2 and 2.4.1, there are several hydrological models widely used in Australia such as RAFTS (Goyen, 1987), RORB (Laurenson and Mein, 1995), URBS (Carroll, 1995) and WBNM (Boyd et al., 1996). All these models share the same runoff routing principle in modelling catchment rainfall and runoff. Since the URBS model can be used for real-time flood forecasting with reasonable accuracy (Malone, 1999; Srikanthan et al, 2000) and its programming is easy to integrate with other programming, it was decided to use URBS in DSSFCMR. Given below are some features of URBS that were additionally considered in selecting URBS as the hydrological model in DSSFCMR.

The URBS modelling software tool that was received at the time of the initial development was a DOS version that was able to embed in DSSFCMR (and integrate with other software tools) easily without its source code. URBS has three different alternative routing methods, which seems to be more comprehensive than the other routing models. There are also some supplementary computer programs to support the URBS model for many extra functions such as linking the URBS model to Australian National Weather Service ALERT software.

Some aspects of theory of the URBS model that are useful in integrating URBS with other software tools are described below.

#### **3.2.1 URBS Model**

URBS is a catchment runoff routing model which can be used to generate flood hydrographs due to rainfall events, giving due consideration to catchment losses. The model requires the study catchment to be sub-divided into a number of sub-catchments. Each sub-catchment is considered as a conceptual reservoir. Three routing methods are available in URBS to describe subcatchment and channel routing behaviour. They are the Basic method, the Combined method and the Split routing method. The use of the Combined method is no longer recommended by its developer. It was reported by Malone (1999) that the Split

method, which includes more parameters for channel routing, gives better results than the Basic method.

DSSFCMR offers the facility for calibration and forecasting during a flood event. It is easy to calibrate the URBS model using the Basic method because of less parameters involved in the Basic method. Furthermore, there is a very low percentage of the shallow channels in the upper part in the study river basin where channel routing is not effective and therefore the Basic method can consider the effect of channel routing in this area. Therefore, the Basic method was used in DSSFCMR.

The Basic method is similar to the routing method in RORB (Laurenson and Mein, 1995) which is widely used in Australia (especially in Victoria) for flood estimation work. It assumes that the catchment and channel storage for each subcatchment is lumped together and represented as a single non-linear reservoir. Each conceptual non-linear reservoir is described by the storage–discharge relationship, as described below,

$$S = \frac{\alpha f L n (1+F)^2}{\sqrt{S_c} (1+U)^2} Q^m \quad (3-1)$$

- Where
- $S$  = catchment and channel storage (m<sup>3</sup>h/s)
  - $\alpha$  = storage lag parameter
  - $f$  = Reach length factor: a parameter, which modifies the reach length due to storage characteristics such as overland flow paths and steep terrain. When only the terrain conditions are considered, its value is from 0 (steepest) to 1 (normal).
  - $L$  = Length of main river reach within the current subcatchment (km).
  - $U$  = Fraction urbanization of the current subcatchment (1 for fully urbanized; 0 for fully rural).
  - $F$  = Fraction of forest of the current subcatchment (0 for no forest, 1 for complete forest).
  - $n$  = channel roughness or Manning's n
  - $S_c$  = channel slope (m/m)
  - $Q$  = Outflow of the subcatchment (m<sup>3</sup>/s)
  - $m$  = catchment non-linearity parameter

For each subcatchment, the rainfall on the subcatchment and inflow from upstream subcatchments are considered as inflow, and the outflow from the subcatchment is calculated using Equation (3-1).

Although the URBS model is suitable for flood forecasting, the model itself does not perform any adaptive parameter modifications. Development of DSSFCMR using the URBS model with other functions (such as adaptive parameter modification) in DSSFCMR would make the URBS model more powerful.

### 3.2.2 Integration of URBS Model

There are several text files in the URBS software modelling tool for catchment definition, rainfall input and output results. These files offer a way that can be used to integrate the URBS model with Windows interfaces in DSSFCMR. Details of the integration with the URBS model in DSSFCMR are given in Chapters 4 and 5. Only the structure of URBS model input and output files used in DSSFCMR are described below to help understand the integration of URBS with DSSFCMR through these files.

Figure 3.1 shows an example of the Catchment Definition file used in the URBS model. Note that although the contents of the file are given in two columns in Figure 3.1, it is a one-column file. The default value of parameter  $n$  (of channel roughness) is used in Figure 3.1. Most lines in the file are self-explained and therefore they are not described below. However, the other lines are explained as follows:

- mr0001: the file name of the Catchment Definition file with the extension *urb*. In this case, this catchment file is *mr0001.urb* stored in the URBS home directory (e.g. *c:\dssfcmr\modelbase\urbs\mr0001.urb*).
- Model: BASIC: the basic method of routing is used.
- USES: L,U,F : The catchment variables  $L$ ,  $U$  and  $F$  in Equation (3-1) are used in the model.
- alpha and m : parameters  $\alpha$  and  $m$  in Equation (3-1).
- Factor : parameter  $f$  in Equation (3-1)..
- Rain # i means only the rainfall in subcatchment  $i$  is routed through the conceptual storage using Equation (3-1) and computes the hydrograph at the downstream end of the

reach of this subcatchment. It is used when there is no subcatchment upstream of subcatchment *i*.

```

mr0001
MODEL: BASIC
USES: L,U,F
DEFAULT PARAMETERS: alpha= 1.2          m= 0.8
18 SUB-CATCHMENTS OF AREA :
114.4      86.9      67.5      81.7
62.5       75.6      70       64.9
65.5       168      44.9     15
80         68       124.1    75.9
44.9       54.3
FACTOR=0.5
RAIN # 1   L=11.7      U=0       F=0
FACTOR=1
ADD RAIN # 2   L=16      U=0       F=0
FACTOR=1
ADD RAIN # 3   L=18.9    U=0       F=0
FACTOR=1
ADD RAIN # 4   L=26.4    U=0       F=0
STORE.
FACTOR=0.5
RAIN # 5     L=7        U=0       F=0
FACTOR=0.5
ADD RAIN # 6   L=3       U=0       F=0
GET.
ROUTE        L=14.1     U=0       F=0
FACTOR=1
ADD RAIN # 7   L=27.35   U=0       F=0
STORE.
FACTOR=0.5
RAIN # 8     L=6.55     U=0       F=0
GET.
ROUTE        L=12.65    U=0       F=0
FACTOR=1
ADD RAIN # 9   L=15.2    U=0       F=0
STORE.
FACTOR=0.5
RAIN # 10    L=14.9     U=0       F=0
FACTOR=0.5
ADD RAIN # 11  L=14.4    U=0       F=0
GET.
ROUTE        L=3.3      U=0       F=0
FACTOR=1
ADD RAIN # 12  L=5.1     U=0       F=0
STORE.
FACTOR=0.5
RAIN # 13    L=9.4      U=0       F=0
DAM ROUTE VBF=24670      NUMBER = 14
24670      0
24820      2.63
25305      16
25870      39.47
26470      67.89
27070      99.47
27625      131.58
27950      160.53
28170      173.68
28710      226
29250      268
29790      315
30010      343
30350      375

FACTOR=1
ADD RAIN # 14  L=10.5    U=0       F=0
STORE.
FACTOR=0.5
RAIN # 15    L=15.8     U=0       F=0
GET.
ROUTE        L=11.1     U=0       F=0
FACTOR=1
ADD RAIN # 16  L=11.35   U=0       F=0
FACTOR=1
ADD RAIN # 17  L=18.35   U=0       F=0
GET.
ROUTE        L=12       U=0       F=0
FACTOR=1
ADD RAIN # 18  L=16      U=0       F=0
PRINT. Keilor
BASEFLOW = 0
END OF CATCHMENT DATA.
5 PLUVIOGRAPHS:
LOCATION. Romsey
3          SUB-CATCHMENTS:
1          2          3
LOCATION. Bulla
4          SUB-CATCHMENTS:
11         12         17         18
LOCATION. Macedon
3          SUB-CATCHMENTS:
13         14         15
LOCATION. Dguim
4          SUB-CATCHMENTS:
4          5          6          7
LOCATION. Cfield
4          SUB-CATCHMENTS:
8          9          10         16
END OF PLUVIOGRAPH DATA.
3 GAUGING STATIONS:
LOCATION. bulla
LOCATION. sunbury
LOCATION. keilor
END OF GAUGING STATION DATA.
0 RATING CURVE:
END OF RATING CURVE DATA.

```

Figure 3.1 Example of a Catchment Definition File

- ADD Rain # i: It is similar to Rain # i, but is used when there is a subcatchment upstream of the subcatchment *i*. The rainfall of the subcatchment *i* is added to the runoff

hydrograph of the upstream subcatchment and routed using Equation (3-1) to provide the outflow hydrograph at the downstream end of the reach of this subcatchment.

- STORE: the hydrograph before this command is stored and no further routing is done to this hydrograph until a GET command is executed. This is used at river / tributary confluences.
- GET: the previously stored hydrograph is accessed and is added to the current hydrograph. This gives the hydrograph just below the river / tributary confluences.
- ROUTE: the current hydrograph is routed through a conceptual storage along the specified reach using Equation (3-1). This action is used when there are no additional rainfall inputs.
- DAM ROUTE VBF=24670 NUMBER = 14: this line and the next 14 lines dictated by *NUMBER*, indicates that there is a dam, and the current hydrograph is routed through this dam. VBF value (i.e. is 24670 in this case) is the storage volume above which outflow from the dam occurs. The *NUMBER 14* indicates 14 pairs of storage-discharge curve values used for this dam, which are given the next 14 lines.
- PRINT. Keilor: the hydrograph at a specified location (in this case, *Keilor*) is written to an output file. This location is used as the output filename.
- BASEFLOW = 0: it sets the baseflow in cumecs ( in this case, zero baseflow).

- 5 PLUVIOGRAPHS:

LOCATION. Romsey

3 SUB-CATCHMENTS:

1 2 3

These commands define the pluviograph sites until the line END OF PLUVIOGRAPH DATA.

The first line indicates that 5 pluviometers are used for estimating the hydrograph. The second line LOCATION. Romsey shows Romsey as one of the 5 pluviometers. The third line shows that 3 subcatchments use the rainfall data in Romsey for rainfall-runoff routing. The next line shows the subcatchments, which use Romsey rainfall data, are subcatchments 1, 2 and 3.

For each pluviometer, similar information is provided.

- 3 GAUGING STATIONS:

LOCATION. bulla

LOCATION. sunbury

LOCATION. keilor

END OF GAUGING STATION DATA

These lines define the gauging stations until the line END OF GAUGING STATION DATA. The gauging stations can be used to store recorded data for calibrating a model. The first line indicates that 3 gauging stations are used for this application. The next line LOCATION. bulla indicates that one of the gauging stations is *bullla*. The other lines are similar.

- 0 RATING CURVE:

END OF RATING CURVE DATA.

These lines define the Rating Curves until the line END OF RATING CURVE DATA. In this application, no rating curves are used.

Figure 3.2 shows an example of a rainfall file used in the URBS model. This file describes the pluviograph stations used in the application and rainfall on the subcatchments for the storm event. The items in the file are described below:

```

10/14/1983 PLUVIOGRAPHS
FORECAST RUN
TIME INCREMENT: 1 HOURS
RUN DURATION: 50 HOURS
STORM DURATION: 38 HOURS
PLUVIOGRAPH. Romsey
PLUVIOGRAPH. Bulla
PLUVIOGRAPH. Macedon
PLUVIOGRAPH. Dguim
PLUVIOGRAPH. Cfield
RAIN ON SUB-CATCHMENTS:
61          61          61          78.4          78.4
78.4        78.4        83.8        83.8          83.8
104         104         76.8        76.8          76.8
83.8        104         104
LOSS: UNIFORM CONTINUING

```

Figure 3.2 Example of Rainfall File

- The first line 10/14/1983 PLUVIOGRAPHS is the heading.
- The line FORECAST RUN indicates that the type of run is FORECAST RUN model. This type of run can be used either to calibrate a model using historical rainfall data or to forecast streamflow during a rainfall event. The DESIGN RUN and MATCHING RUN are the other choices of this line.
- The line TIME INCREMENT: 1 HOURS indicates that the time step used in this application is 1 hour, and this time step will be used by the model for calculating and outputting the results.
- The line RUN DURATION: 50 HOURS indicates that the model will run for 50 hours.

- The line STORM DURATION: 38 HOURS indicates that 38 hours of pluviometer data will be used for generating the runoff hydrograph (and the data after 38 hours will be ignored). This value should be always less than the value of RUN DURATION.
- PLUVIOGRAPH. Romsey indicates that the pluviometer data at Romsey are used for this application. The pluviometer data are stored in a file called romsey.r for the Romsey pluviometer. Similar line exists for other pluviometers. The data in these pluviometers are used for the subcatchments listed in the Catchment Definition file (Figure 3.1).

- RAIN ON SUB-CATCHMENTS:

61	61	61	78.4	78.4
78.4	78.4	83.8	83.8	83.8
104	104	76.8	76.8	76.8
83.8	104	104		

These lines show the total rainfall for the storm in the 18 subcatchments defined in the Catchment Definition file.

- LOSS: UNIFORM CONTINUING indicates that the uniform continuing loss model is used for this application.

Figure 3.3 shows an example of the rainfall data file. This file contains data at the Romsey pluviometer for the storm defined in the rainfall file (Figure 3.2). The file is called romsey.r. The items in the file are described below:



Figure 3.3 Example of a Rainfall Data File

- The first line Romsey Pluviograph is the heading.
- The next 3 lines are comment lines, which describe the data file for user to identify the file.
- 0 3600 38

0.8	0.4	2.2	1.8	1
0.4	0.4	0.2	0	1.8
0.6	2.2	3	4.6	0.2
0	0	0	0	0
1.2	3.6	5.6	8.2	7.8
1.6	0	0.4	2	1.2
0.2	0.8	0.8	1.6	2.2
2.6	1.2	0.4		

The first line includes three important parameters, which define the pluviometer data at this station for this storm event. 0 is the time in seconds from the starting time of the URBS run (a parameter called URBS\_TIME) to the time when the first pluviometer data item is used; 3600 is the time step in seconds of the pluviometer data; and 38 is the total number of pluviometer data items. The 38 rainfall data items in Romsey are then followed in the next 8 lines (i.e. 5 data items in each line, with last line having 3 data items).

Figure 3.4 shows an example of an output hydrograph data file. In this case, the hydrograph details are shown for Keilor. The output file is Keilor.q. Almost all contents in the file are self-explanatory. The column Calc shows the calculated flow, while the column Recd shows the observed flow data.

An good understanding of the URBS model data input and output format, the data file structure and the contents of the data file is essential for development of an integrated system and user-friendly interfaces, which allow the user effectively to interact with the URBS model to perform calibration and forecasting functions.

### 3.3 Hydraulic Model

Similar to the hydrological model, the Modelbase should include a hydraulic model, which can be used to calculate the flood water levels in the flood prone area due to forecast flood hydrographs. There are two types of hydraulic models, namely steady and unsteady, that can be used for this purpose. The steady models compute the flood levels due to a steady discharge such as the peak discharge, while the unsteady models deal with the complete flood hydrograph. In essence, if the steady models are used with the peak discharge, they provide slightly conservative flood water levels in the flood prone area, since these models do not account for the storage in the flood prone area. This is considered to be satisfactory for flood forecasting and warning applications due to other uncertainties involved in the process of

flood warning such as in forecast rainfall values, and therefore it was decided to use a steady model.

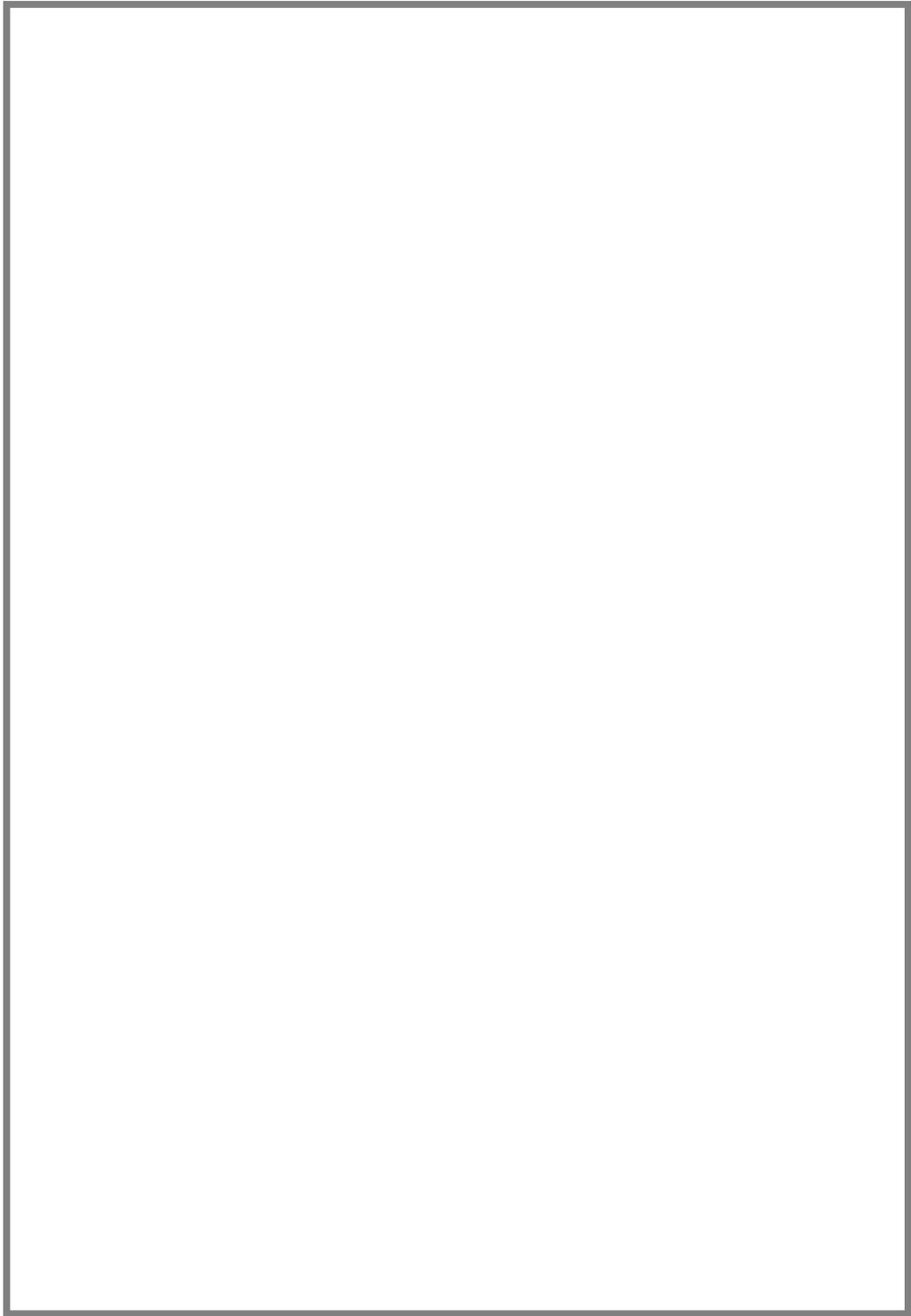


Figure 3.4 Example of an Output Hydrograph Data File

The HEC-2 computer model developed by the USACE (1982a) is a steady flow model. This model had been previously used for flood mitigation in the Maribyrnong River basin and is also well accepted by water engineering professionals in Australia. HEC-RAS (USACE, 1998) is a recent upgrade of HEC-2. However, the user who is familiar with HEC-2 could adopt the previous work from HEC-2 to HEC-RAS easily. Therefore, it was decided to use the HAS-RAS computer software in DSSFCMR to calculate the flood water levels in the flood prone areas of the catchment. Although HEC-RAS is capable in modelling unsteady flows, the steady flow option of HEC-RAS was used in DSSFCMR.

### 3.3.1 Basic Theory of HEC-RAS

HEC-RAS is designed to perform one-dimensional hydraulic calculations. The basic computational procedure is based on the solution of the one-dimensional energy equation. The energy losses due to friction and contraction/expansion of river/channel sections are included in the energy equation. They are modelled through Manning's equation and contraction/expansion coefficients respectively. The momentum equation is utilized in situations where the water surface profiles are rapidly varied. The software can consider the effect of various obstructions such as bridges, culverts, weirs and constrictions. Typically, the river/channel cross section is subdivided into left overbank, main channel and right overbank with their cross section details and roughness characteristics.

The energy equation in HEC-RAS is given below:

$$Y_2 + Z_2 + \frac{\alpha_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \quad (3-2)$$

- where:
- $Y_1, Y_2$  = Depths (m) of water at cross sections 1 and 2 respectively.
  - $Z_1, Z_2$  = Elevations (m) of the bottom of the river channel at cross sections 1 and 2 respectively.
  - $V_1, V_2$  = average velocities (m/s: total discharge / total flow area) at cross sections 1 and 2 respectively.
  - $\alpha_1, \alpha_2$  = velocity weighting coefficients at cross sections 1 and 2 respectively.
  - $g$  = gravitational acceleration (m/s<sup>2</sup>).
  - $h_e$  = energy head loss (m).

A sketch showing the terms in the energy equation (3-2) is shown in Figure 3.5

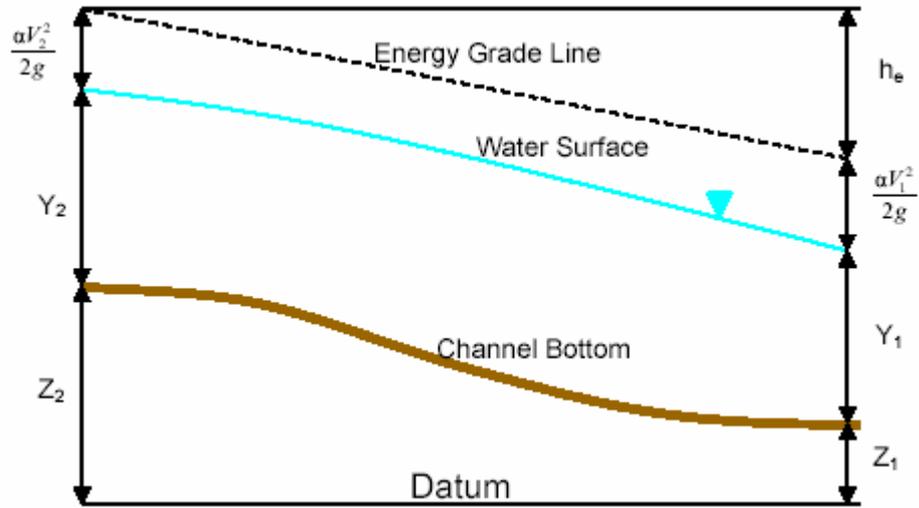


Figure 3.5 Representation of Terms in the Energy Equation

The energy head loss  $h_e$  in Equation (3.2) is calculated by following equation:

$$h_e = L \bar{S}_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \quad (3-3)$$

- where:  $L$  = discharge weighted reach length (m), as computed by Equation (3-4).  
 $\bar{S}_f$  = representative friction slope (m/m) between the two cross sections.  
 $C$  = expansion or contraction loss coefficient.

The variable  $L$  in Equation (3-3) is calculated by Equation (3-4)

$$L = \frac{L_{lob} \bar{Q}_{lob} + L_{ch} \bar{Q}_{ch} + L_{rob} \bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \quad (3-4)$$

- where:  $L_{lob}, L_{ch}, L_{rob}$  = reach lengths (m) between the two cross sections along the left overbank, main channel, and right overbank respectively.  
 $\bar{Q}_{lob}, \bar{Q}_{ch}, \bar{Q}_{rob}$  = arithmetic average of the flows ( $m^3/s$ ) between the two cross sections ( i.e. upstream and downstream ends of the reach) in the left

overbank, main channel, and right overbank respectively.

The total conveyance (and flow) for the whole cross section is computed by summing up the three subdivision conveyances (and flow) in the left overbank, the channel and the right overbank. The flow and conveyance for each subdivision  $i$  can be computed by Equations (3-5) and (3-6) respectively.

$$Q_i = K_i S_f^{1/2} \quad (3-5)$$

$$K_i = \frac{1}{n_i} A_i R_i^{2/3} \quad (3-6)$$

where:  $Q_i$  = flow discharge of each subdivision  $i$  ( $m^3/s$ ).  
 $K_i$  = Conveyance of each subdivision  $i$  ( $m^3/s$ ).  
 $n_i$  = Manning's roughness coefficient of each subdivision  $i$   
 $A_i$  = flow area of each subdivision  $i$  ( $m^2$ ).  
 $R_i$  = hydraulic radius (area/wetted perimeter) of each subdivision  $i$  ( $m$ ).

The flood water levels are computed using Equations (3-2) – (3-6) considering known values of total discharge, Manning's roughness coefficients, expansion/contraction coefficients, and topographical data of the flood prone area such as cross section details and the value of  $L_{lob}$ ,  $L_{ch}$  and  $L_{rob}$ . The reader is referred to USACE (1997,1998a,b) for more details of the HEC-RAS model.

In developing a DSS for Flood Forecasting and Warning such as DSSFCMR, it is necessary that the above topographical details are available for the DSS and this was the case of DSSFCMR. However, the Manning's roughness coefficients and the expansion and contraction coefficients at each cross section are considered as model parameters, which can be obtained from model calibration, and used in flood forecasting. Therefore DSSFCMR was designed to interact with these parameters.

### 3.3.2 Integration of HEC-RAS Model

The HEC-RAS model is a Windows based software tool. There is no a direct way to interact its programming from DSSFCMR's programming as HEC-RAS is not designed for this purpose and also it was not possible to get the original source code of HEC-RAS. The interaction through the relevant Windows forms to access relevant HEC-RAS input and output files is the only choice for integration. However, this integration was not convenient and easy for the DSSFCMR developer as the integration of the URBS model, since the integration with the HEC-RAS model required handling of Windows interfaces of HEC-RAS.

There are five major steps to build a hydraulic model using HEC-RAS:

- Create a new project
- Enter geometric data
- Enter flow data and boundary conditions
- Complete hydraulic computations
- Output results

The DSSFCMR in this research project is designed for a single user in one computer. The project filename always uses the default HEC-RAS project filename, and the DSSFCMR automatically modifies the contents in this project file. Since the default project file is used, its details are not included here, since the understanding of this file is not necessary for integration of HEC-RAS with DSSFCMR.

The geometric data, flow data and boundary conditions can be entered through several ways:

- Entering from the interface of HEC-RAS.
- Building the data files directly.
- Converting from HEC-2 (the geometric data file only)

The geometric data file, which was previously used for the Maribyrnong River basin in HEC-2 format, was first converted to HEC-RAS format. The DSSFCMR was then developed to interact with the geometric data in this HEC-RAS geometric file. Although HEC-RAS allows the user to enter the model parameter values (i.e. Manning's roughness coefficients and the expansion / contraction coefficients) through its Windows interface, the entered parameter

values are finally stored in text files. The results in the HEC-RAS model also can be viewed and printed through the HEC-RAS interface. However, these viewing and printing results through HEC-RAS interface are not suitable for DSSFCMR as DSSFCMR could not manage the HEC-RAS model to perform these activities within DSSFCMR. HEC-RAS also can output the results alternatively in a text file. This output file was used to integrate HEC-RAS results with DSSFCMR. The process of running the HEC-RAS model, calculating the flood water levels, outputting the results into the text file is done within HEC-RAS and therefore interaction between HEC-RAS and DSSFCMR was completed through the Windows interface through input and output text files of HEC-RAS. Therefore, the structure and contents of these files are described below.

Figure 3.6 shows a section of the geometric data file used in this study. Only the information of Figure 3.6 relevant to integration of HEC-RAS with DSSFCMR is described below. This information is related to the model parameter values (i.e. Manning's roughness coefficients and the expansion / contraction coefficients) at each cross section. This is explained through details of one cross section (i.e. cross section 46), which is extracted from Figure 3.6 and reproduced as Figure 3.7. The first line in Figure 3.7 indicates that the identification number of the cross section is 46, which is the most upstream cross section in the study area. Its Manning's roughness coefficient in the left overbank, the main channel and the right overbank are 0.06, 0.03 and 0.06 respectively. The main channel is defined by the lateral coordinates of 58.4 and 102.68 m, which also indicates that the left bank is between 0 m and 58.4 m, the main channel is between 58.4 m and 102.68 m, and the right bank is between 102.68 m and 133.68 m. The expansion and contraction loss coefficients are 0.3 and 0.1 respectively. The model parameters (i.e. Manning's roughness coefficients and expansion / contraction coefficients) can be modified through the DSSFCMR interfaces, which has integration links to the geometric data file.

Figure 3.8 is an example of the flow data file used in this study. The peak discharge of the forecast flood hydrograph and the water level of the most downstream cross section of the flood prone area of this file are used for calculating flood water levels in the flood prone area. The section related to these parameters are extracted from Figure 3.8 and reproduced as Figure 3.9. These parameters can be modified through the DSSFCMR interface, which has integration links to the flow data file.

```

Geom Title=Imported Geom 02
Version=September 1998 Version 2.2
Viewing Rectangle= 0.027650403311877 , 0.945650378993182 , 0.958999987840653 ,
4.10000121593475E-02

River Reach=RIVER-1 ,Reach-1
Junct Up Dn= ,
Reach XY= 2
.5 .95 .5 .05
Rch Text X Y=0.5,0.725
Reverse River Text= 0

Type RM Length L Ch R = 1 ,46 ,200,225,225
BEGIN DESCRIPTION:
SECTION AT PSM 6834

END DESCRIPTION:
#Sta/Elev= 13
0 6.03 10.28 2.9 21.03 1.79 51.3 1.93 53.48 1.25
58.4 .91 59.57 -.12 66.17 -2.27 74.57 -4.07 94.53 -1.62
99.53 -.09 102.68 1.13 133.55 6.11
#Mann= 3 , 0 , 0
0 0.06 0 58.4 0.03 0 102.68 0.06 0
Bank Sta=58.4,102.68
Exp/Cntr=0.3,0.1

Type RM Length L Ch R = 1 ,45 ,90,188,240
BEGIN DESCRIPTION:
SECTION AT POINT F

END DESCRIPTION:
#Sta/Elev= 13
0 8.07 13.31 2.74 18.07 2.34 26.35 1.85 46.81 .82
50.19 -.02 54.69 -1.93 69.68 -2.53 83.2 -2.03 87.7 .36
93.55 1.27 98.2 3.9 106.24 9.2
#Mann= 3 , 0 , 0
0 0.06 0 46.81 0.03 0 93.55 0.06 0
Bank Sta=46.81,93.55
Exp/Cntr=0.3,0.1

```

Figure 3.6 Section of a Geometry Data File Used in HEC-RAS Model

```

Type RM Length L Ch R = 1 ,46 ,200,225,225
BEGIN DESCRIPTION:
SECTION AT PSM 6834

END DESCRIPTION:
#Sta/Elev= 13
0 6.03 10.28 2.9 21.03 1.79 51.3 1.93 53.48 1.25
58.4 .91 59.57 -.12 66.17 -2.27 74.57 -4.07 94.53 -1.62
99.53 -.09 102.68 1.13 133.55 6.11
#Mann= 3 , 0 , 0
0 0.06 0 58.4 0.03 0 102.68 0.06 0
Bank Sta=58.4,102.68
Exp/Cntr=0.3,0.1

```

Figure 3.7 Cross Section 46 Details

The first line of Figure 3.9 shows that the cross section No. 46 is the upstream cross section. The second line indicates the discharge in  $m^3/s$  is 569.70 (This is usually the peak discharge of the forecast flood hydrograph). The water level at the downstream cross section (i.e. the cross section No. 1) is shown to be 1.5 m.



Figure 3.8 Flow Data File in HEC-RAS Model

```
River Rch & RM=RIVER-1,Reach-1      ,46
569.70
Boundary for River Rch & Prof#=RIVER-1,Reach-1      , 1
Up Type= 0
Dn Type= 1
Dn Known WS=1.5
```

Figure 3.9 Segment of Flow Data File Showing Peak Discharge and Downstream Water Level

Figure 3.10 is an example of the HEC-RAS output file and it includes the part of output file only. The results related to cross section 46 are extracted from Figure 3.10 and reproduced as Figure 3.11 to illustrate the data structure of output file.

The first part in Figure 3.11 shows the names of each output variable, while the second part shows the values of each variable for cross section No. 46. The flood water level in this cross section is 4.25 m. These flood water levels in each cross section will be accessed and used in DSSFCMR for spatial analysis and display of flood inundation area.

As can be seen from the above description, the integration with HEC-RAS can only be done through the input and output text files. An understanding of relevant data files including data contents and file structure is necessary to develop such an interactive system with the HEC-RAS model. The details of integration of the HEC-RAS model with DSSFCMR are discussed in Chapter 4.

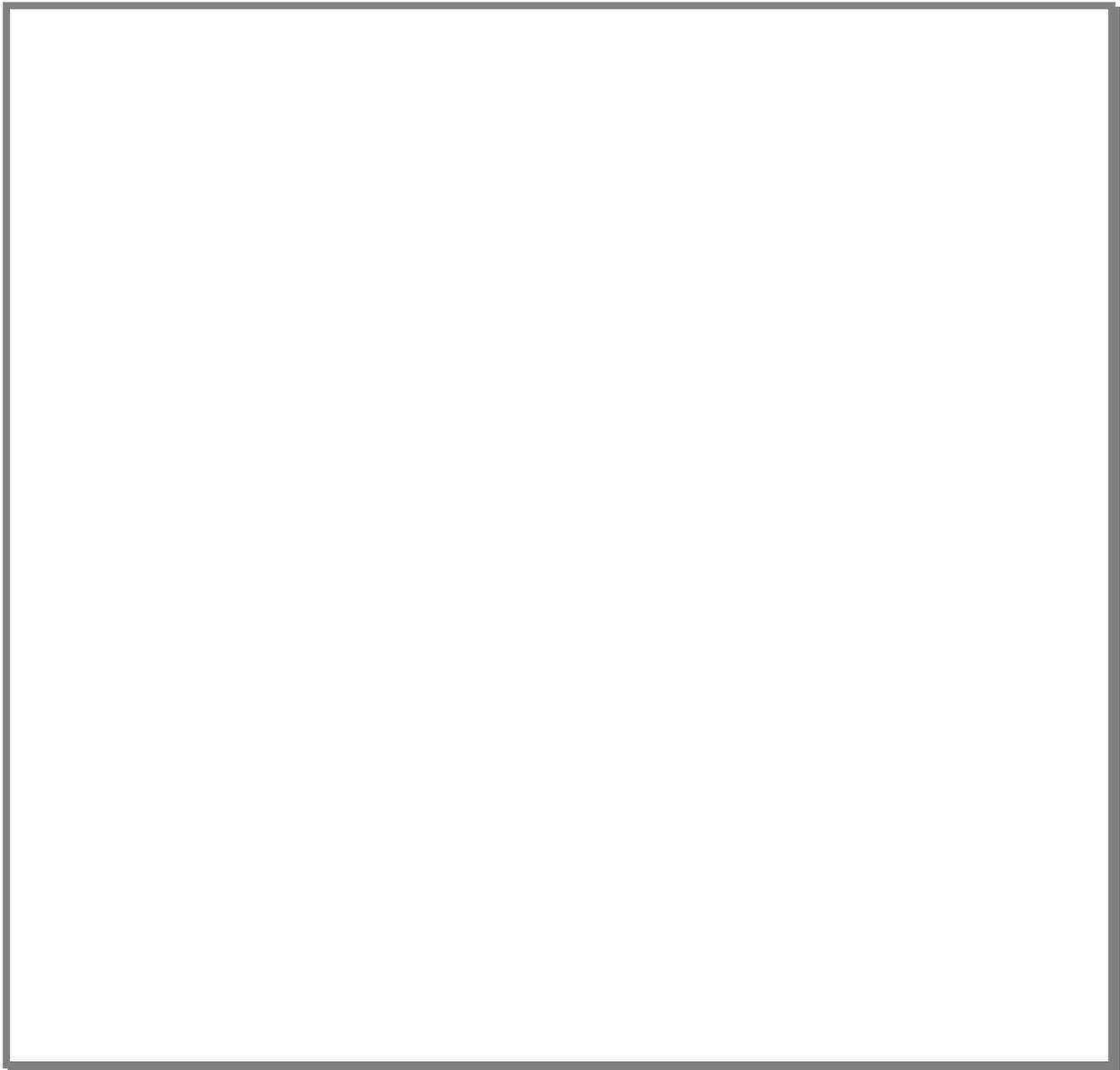


Figure 3.10 An Example of a Part of an Output File of HEC-RAS Model

Reach	River Sta	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev
E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude #	Chl	
(m/m)	(m/s)	(m <sup>2</sup> )	(m)	(m <sup>3</sup> /s)	(m)	(m)
Reach-1	46	569.70	-4.07	4.25	0.38	4.39
0.000258	1.80	428.72	116.15	0.23		

Figure 3.11 Results Related to Cross Section 46

### 3.4 Spatial and Graphical Data Display and Analysis Technology

The spatial data display and analysis technology assembles, stores, manipulates and displays the geographically referenced information. As discussed in Section 3.1.1, the Spatial and

Graphic Data Display and Analysis (SGDDA) should be a subsystem of a DSS especially in the water resources area, where the decision making process involves spatial data and analysis. An effective SGDDA subsystem would improve organizational integration, make visual maps and geographic analysis, and finally help the user to make better decisions. The SGDDA in a DSS is typically achieved by three methods. Although these methods were described in detail in Section 2.5, they are listed below for easy reference.

- The first method is that the SGDDA functions are developed through integrating other DSS components with some GIS tools such as MapObjects (by ESRI). The technology of GIS and some GIS tools are used in this method, while the developed DSS does not rely on the GIS environment. The second method is that the relevant functions are developed by the DSS developers. In this case, the development of these functions is based on the developer's skills and resources. The third method is that the whole DSS is developed in a GIS environment. The potential users then must have the same GIS software to use the DSS. The above methods when considered individually have certain problems such as the lack of involvement of the potential user in the system development, the lack of suitable functions, and the difficulty in integration of model outputs with spatial attributes. The approach used in this research is a combination of the first two methods.

To develop a DSS with spatial data display and analysis capabilities, a good understating of the GIS data format and GIS software tools (e.g. MapObjects in this study) is essential especially if the integration between the GIS software and other models (or software) is needed. Two common GIS system data files namely, DXF and shapefile were used in the DSSFCMR development. Therefore, these two GIS data files, and MapObjects are introduced in this section. Further details can be found from relevant documents (Autodesk, 2003 for DXF, and ESRI, 1998 for shapefile). All available GIS data in this study were originally in the DXF data format.

### **3.4.1 DXF File**

A DXF file is a standard interchange vector GIS data format and is widely used in MapInfo as a data file format. It is also recognized by other GIS vendors (ESRI, 2003). The DXF files can be either in ASCII or binary format. The ASCII DXF files are more common than the binary

DXF and therefore, the term DXF file is normally used to refer to the ASCII DXF files, while the term binary DXF is used for the binary format.

A DXF file is composed of pairs of codes (known as group codes), and associated values. The code specifies the type of the value, which is followed by the code. For example, a code between 60-79 shows that a 16-bit integer value is followed by this code. Using these pairs of group code and value, a DXF file is structured into sections, and each section is composed of records, which are made up by a group code and a data item in two consecutive lines. The details of group code ranges are presented in Figure 3.12, An example of a DXF file using group codes is described later in Figure 3.13. A detailed description of DXF file format and contents can be found in Autodesk (2003).



Figure 3.12 Group Code Ranges

Each section starts with a group code 0 followed by the string, SECTION. This is followed by a group code 2 and a string indicating the name of the section (for example, HEADER). A section ends with a 0 followed by the string ENDSEC.

The overall organization of a DXF file is as follows:

- HEADER section. Contains general information about the drawing. It could consist of an AutoCAD database version number and a number of system variables. Each parameter contains a variable name and its associated value.
- CLASSES section. Holds the information for application-defined classes, whose instances appear in the BLOCKS, ENTITIES, and OBJECTS sections of the database. A class definition is permanently fixed in class hierarchy.
- TABLES section. Contains definitions for the following symbol tables.
  - APPID (application identification table)
  - BLOCK\_RECORD (block reference table)
  - DIMSTYLE (dimension style table)
  - LAYER (layer table)
  - LTYPE (linetype table)
  - STYLE (text style table)
  - UCS (User Coordinate System table)
  - VIEW (view table)
  - VPORT (viewport configuration table)
- BLOCKS section. Contains block definition and drawing entities that make up each block reference in the drawing.
- ENTITIES section. Contains the graphical objects (or entities) in the drawing, including block references (insert entities).
- OBJECTS section. Contains the non graphical objects in the drawing. All objects that are not entities or symbol table records or symbol tables are stored in this section. Examples of entries in the OBJECTS section are dictionaries that contain line styles and groups.
- THUMBNAILIMAGE section. Contains the preview image data for of the drawing. This section is optional.

0	0
SECTION	SECTION
2	2
HEADER	BLOCKS
9	0
SEXTMAX	ENDSEC
10	0
315764.827272577	SECTION
20	0
5813584.989374440	ENTITIES
9	0
SEXTMIN	POLYLINE
10	8
315564.983602819	Graph9_shp
20	62
5813524.084636990	256.000000000
9	66
SLUPREC	1
70	10
8	0.0
0	20
ENDSEC	0.0
0	30
SECTION	0.000000000
2	39
TABLES	0.000000000
0	0
TABLE	VERTEX
2	8
LAYER	Graph9_shp
70	10
2	315564.983602819
0	20
LAYER	5813584.989374440
2	30
0	0.000000000
70	39
0	0.000000000
62	0
7	VERTEX
6	8
CONTINUOUS	Graph9_shp
0	10
LAYER	315764.827272577
2	20
Graph9_shp	5813524.084636990
70	30
64	0.000000000
62	39
7	0.000000000
6	0
CONTINUOUS	SEQEND
0	8
ENDTAB	0
0	0
ENDSEC	ENDSEC
	0
	EOF

Figure 3.13 An Example of a DXF File

Figure 3.13 shows an example of a DXF file, which describes a line connected by two points. Note that although the contents of the file are given in two columns in Figure 3.13, it is a one-column file. The following lines that describe the one location of the point (of the two points describing the line) are extracted from Figure 3.13 (for illustration purposes) and reproduced in Figure 3.14. The column of *Line Number* is added for explanation.

Line Number	Contents in the Line
1	0
2	ENTITIES
3	0
4	POLYLINE
5	8
6	Graph9_shp
7	62
8	256.000000000
9	66
10	1
11	10
12	0.0
13	20
14	0.0
15	30
16	0.000000000
17	39
18	0.000000000
19	0
20	VERTEX
21	8
22	Graph9_shp
23	10
24	315564.983602819
25	20
26	5813584.989374440
27	30
28	0.000000000
29	39

Figure 3.14 Section Describing the One Point in Figure 3.13

The line 2 in the above section (Figure 3.14) indicates that the details below defines a graphical object (entity); the line 4 shows that this object is polyline; the line 20 indicates the following part is the vertex of the polyline; the line 23 with line 24, and the line 25 with line 26 are pairs of codes known as group codes and associated values, define the point by its coordinates. The line 23 with value 10 (see Figure 3.12) and line 24 show that the point is a double precision 3D point and its first coordinate is 315564.983602819. Similar information is given in lines 25 and 26 to define the second coordinate. Therefore, Figure 3.14 defines the point by its coordinates (315564.983602819, 5813584.989374440).

Familiarization with the DXF file structure will help the developer to develop a DSS that includes DXF data input and output files. This is especially important when the related GIS software tools are not available for the potential user or these GIS software tools are not allowed to be embedded DSS. In these cases, the end user of the DSS still can use the GIS functions using DXF format through developed functions without using the commercial GIS software tools.

### 3.4.2 Shapefile

The shapefile is a spatial data format developed by ESRI. The shapefile stores non-topological geometry and attribute information of the spatial features in the data set. The shapefile can be created with the following four general ways:

- **Export:** Shapefiles can be created by exporting any data source using ARC/INFO, PC ARC/INFO, Spatial Database Engine (SDE™), ArcView GIS, or Business MAP software.
- **Digitize:** Shapefiles can be created directly by digitizing shapes using ArcView GIS feature creation tools.
- **Programming:** Using Avenue in ArcView GIS, MapObjects, ARC Macro Language (AML) in ArcInfo or Simple Macro Language (SML) in PC ArcInfo software, the developer can create shapefiles within their programs.
- **Programming directly by the developer** who has a good understanding of the shapefile structure. This method was used in DSSFCMR development.

A shapefile consists of at least a main file, an index file and a dBASE file. The main file and index file store the feature geometry and the index of the feature geometry respectively. Attributes of geometric data (e.g. house) are held in the dBASE file. Each attribute record has a one-to-one relationship with the associated shape record. The main file (with the extension “shp”) is a direct access, variable-record-length file in which each record describes a shape with a list of its vertices. In the index file (with the extension “shx”), each record contains the offset of the corresponding main file record from the beginning of the main file. The dBASE table (with the extension “dbf”) contains feature attributes (e.g. elevation of a house) with one record per feature. Attribute records in the dBASE file must be in the same order as records in the main file.

Each file in a shapefile has a specific data structure. For example, the main file (\*.shp) contains a fixed-length file header followed by variable-length records. Each variable-length record is made up of a fixed-length record header followed by variable-length record contents. The main file header is 100 bytes long. Figure 3.15 lists the fields in the file header with their byte position, value, type and byte order.

Position	Field	Value	Type	Order
Byte 0	File Code	9994	Integer	Big
Byte 4	Unused	0	Integer	Big
Byte 8	Unused	0	Integer	Big
Byte 12	Unused	0	Integer	Big
Byte 16	Unused	0	Integer	Big
Byte 20	Unused	0	Integer	Big
Byte 24	File Length	File Length	Integer	Big
Byte 28	Version	1000	Integer	Little
Byte 32	Shape Type	Shape Type	Integer	Little
Byte 36	Bounding Box	Xmin	Double	Little
Byte 44	Bounding Box	Ymin	Double	Little
Byte 52	Bounding Box	Xmax	Double	Little
Byte 60	Bounding Box	Ymax	Double	Little
Byte 68*	Bounding Box	Zmin	Double	Little
Byte 76*	Bounding Box	Zmax	Double	Little
Byte 84*	Bounding Box	Mmin	Double	Little
Byte 92*	Bounding Box	Mmax	Double	Little

**\* Unused, with value 0.0, if not Measured or Z type**

Figure 3.15 Fields in the File Header in Main File

In Figure 3.15, the byte position is with respect to the start of the file. The values for shape type are given in Figure 3.16. More details of the shapefile can be found in ESRI documents (ESRI, 1998). As the shapefiles are binary files, the listings of example files are not given in this thesis.

Value	Shape Type
0	Null Shape
1	Point
3	PolyLine
5	Polygon
8	MultiPoint
11	PointZ
13	PolyLineZ
15	PolygonZ
18	MultiPointZ
21	PointM
23	PolyLineM
25	PolygonM
28	MultiPointM
31	MultiPatch

Figure 3.16 Value for Shape Type

After familiarizing with the structure of the shapefiles, the developer can write her/his own programming to integrate various elements of the DSS with ESRI desktop GIS products, without using any commercial software tools.

### 3.4.3 MapObjects

MapObjects is developed by ESRI for software development work and is a set of mapping software components that allow the developer to add/delete maps to their DSS applications. MapObjects consist of an ActiveX Control (also known as the Map control), which is one of the family of Microsoft COM technologies that enables software components to communicate, and a set of over twenty ActiveX Automation objects. MapObjects is ideal for use in industry standard Window programming environments, such as the DSSFCMR development environment. The developer of applications can connect MapObjects with components from other vendors, such as graphs and database objects to build DSSs using Window programming languages such as Visual Basic (used for development in DSSFCMR) and Visual C++. It can use ESRI shapefiles or ArcInfo coverage as the basic spatial data. The applications using MapObjects can be developed for the user-specific requirements in spatial data analysis and display.

Programs built with MapObjects will run on Windows 95 and 98, Windows NT and Windows 2000 and higher. Many spatial analysis functions in a DSS can be achieved using MapObjects by computer programming. Some of them are listed below (based on Version 2.0 of MapObjects)

- Display a map on the screen with multiple map layers, such as streams, reservoirs, lakes, dams, roads, streams and property boundaries.
- Pan and zoom throughout a map on the screen.
- Draw graphic features such as points (e.g. gauging stations), lines (e.g. river and road), ellipses, rectangles (e.g. some property boundaries) and polygons (e.g. lakes).
- Draw descriptive text (e.g. water level at a specific location).
- Identify features on a map by pointing at them such as the water level in a house.
- Select features along lines, and inside of boxes, areas, polygons and circles.
- Select features within a specified distance of other features such as the house 100 meters from the bank.
- Select features with a Structured Query Language (SQL) expression. For example, the number of houses inundated by a flood can be obtained by specifying the values of the elevation attribute. The details of SQL are given in Section 3.5.
- Calculate basic statistics on selected features such as the average water depth.

- Render features with thematic methods such as value maps, class breaks, dot density, and charts.
- Label features with text such as the river name.
- Draw images from aerial photography or satellite imagery.

MapObjects can co-operate with the development tools (used in this research project) such as Visual Basic and MS ACCESS very well. It is not necessary to run DSSFCMR (which uses MapObjects) in a GIS environment, but should run on a Windows environment. The shapefile of the flood inundated area corresponding each simulated flood scenario can be created instantly in DSSFCMR, which then integrates with other spatial data to perform spatial analysis of flood area using MapObjects. The details of this integration are given in Chapters 4 and 5.

### **3.5 Decision Support Technology**

As outlined in Section 3.1, the decision-making in a DSS is very complex when any phase of decision-making is non-structured, which causes the final decision choosing process uncertain. This is quite common in decision making in water resource management problems. Decision support can be carried out either simply by searching results from likely decision scenarios to answer the “what if “ question related to the problem, or by developing a large and complex Expert System. The Decision Support subsystem in DSSFCMR was developed to provide decision support through data searching of the simulated flood scenarios stored in the database. The data in DSSFCMR is the collection of decision variables such as the peak discharges, the water levels and so on. Some information on database and data search support are introduced in this section.

To define and understand exactly what is meant by the database, first the data should be described. Data are the facts about an object or a concept. Data can be a person or an organization (e.g. the decision maker for flood warning or an user of a DSS), a place (e.g. catchment, house), an event (e.g. a flood event), an action (e.g. flood forecasting and warning) and many others, or they can be any combination of above facts. A single fact could be considered as an element of data. Information is data that are organized, refined and presented in a form that can be used to aid the decision-making process or alos perform other activities such as identifying the flood-inundated houses and drawing the flooded area. Often data

considered as a unit of information. The difference between the two definitions of data and information can become uncertain and unclear.

A database is a shared collection of logically related data and their description. The data in the database is designed to meet information requirements of an organization or a project. A database management system (DBMS) is a system that allows the users to define, create, and maintain the database, and offers controlled access to this database. The advantages of database management systems include control of data redundancy; data consistency; extracting more information from the same amount of data; sharing of data; improved data integrity; improved data security; enforcement of data standards; improved data accessibility and responsiveness; increased productivity and more. However, there are also some disadvantages such as complexity, cost of developing and maintaining DBMSs, additional hardware costs, cost of maintenance and so on.

DBMS in general consists of several databases (each having several tables), which are represented by data models. The data model is an integrated collection of concepts of expressing data, relationships between data and constraints on the data in an organization. The relational data model, which is widely used in MS ACCESS, is based on the concept of mathematical relations. In a relational data model, data and relationships are represented as database tables, and each database table has a number of columns with unique names. These can be considered as the parameters of the database. A primary key, which consists of one or several parameters, uniquely identifies a record in a database table, which can help to locate the data. The relational data model is very popular and is most widely used in Personal Computers (PCs). It has become the de-facto standard for the design of both large and small databases. The relational database model was used in DSSFCMR in DBMS.

The decision making support in this research project was developed through information search, and such information includes the peak discharge and flood water levels along the flood inundated area, stored in the database. Data search was developed based on the Structured Query Language or SQL as it is commonly called (Connolly et al., 1999). The SQL language is a particular language that has emerged from the development of the relational model. It is a non-procedural language and is relatively easy to learn. SQL is essentially free-format which means that the statements do not have to be typed at particular locations on the screen. SQL has two major components:

- A Data Definition Language (DDL) for defining the database structure.
- A Data Manipulation Language (DML) for retrieving and updating data.

The Data Definition Language (DDL) was used in this research project to define the database structure (e.g. create a database table). The Data Manipulation Language (DML) was used to develop the Windows interface to help the user to locate the primary key for the decision support. Therefore, the basic idea of DML is introduced here:

The SQL DML statements have four types of command functions as described below:

- SELECT: To find data in the database
- INSERT: To add data to a table in the database
- UPDATE: To modify the data in a table in the database
- DELETE: To delete data from a table in the database

For example, a SQL statement is required to be written to find all scenarios with minimum of 1.05 for *Alpha*, a minimum value of 0.8 for *m*, a minimum of 1 mm/h for *continuing loss* and a maximum value of 20 cumecs for *base flow* in the URBS model, with 3 hours of forecast rainfall with the forecast greater than 0 mm and the forecast in the first hour of 20% of the total, and the decision made at 01 January 1983. The data of all scenarios are stored in database table RtFw1 for Real- Time Flood Warning. The SQL statement for this example is given below:

```
Select * from RtFw1 where Alpha >= 1.05 and m >= 0.8 and ContLoss >= 1 and
BaseFlow <= 20 and ForecastStormPeriod = 3 and ForecastStormQty01 >= 0 and
ForecastStorm01P1 >=20 and Year = 1983 and Month = 1 and Day = 1
```

Through the developed user-friendly Windows interface in DSSFCMR, the decision maker can find the likely decision scenarios from many scenarios produced by the models (in the Modelbase), using the database search technology and SQL statements. Using these likely decision scenarios coupled with the decision maker's own experience, the decision maker can finalize the decision for flood warning. The system does not demand the decision maker to require the database and SQL knowledge to run the DSSFCMR for decision making.

The design and development of the Decision Support subsystem will be detailed in Chapters 4 and 5.

### **3.6 Summary**

The relevant concepts, theory and models in DSS design and development, the hydrological model, the hydraulic model, the spatial and graphical data display and analysis (SGDDA), and the decision support are introduced in this chapter. The purpose of the chapter was not to introduce all theory and practices, but to describe the relevant and sufficient theory and knowledge, which will assist further design and development, which will be described in Chapters 4 and 5.

In the sections of DSS design and development, the hydrological model, the hydraulic model and the decision search support, only the selected method or model is detailed. These particular methods or models have been selected after careful examination of their reputation, easy integration, and the support of supplementary software tools for the potential user. However, there is no doubt that DSSFCMR can co-operate with other models if they are found to be more suitable. For example, the RORB (or WBNM) hydrological model can be used instead of the URBS model, but this requires certain integration works for linking RORB (or WBNM) within DSSFCMR, which are different to linking URBS (but on similar principles).

The SGDDA was a significant development in integration of outputs of hydrological and hydraulic models with GIS software tools, and in performance of spatial analysis for flood scenario decisions in DSSFCMR, which requires handling of DXF files, creation of shapefiles and use of MapObjects software.

The theory and knowledge presented in this chapter can also be used and extended in future for further system design and development of DSSFCMR (and other DSSs).

## **CHAPTER 4**

### **CONCEPTUAL DESIGN OF DSSFCMR**

The conceptual design of DSSFCMR is presented in this chapter, with its system development described in detail in Chapter 5. Although it is not intended to describe the conceptual design in detail showing algorithms used for each subsystem, it will give sufficient details so that the information can be used to guide the implementation of each subsystem of DSSFCMR.

The DSSFCMR was specifically designed for the Maribyrnong River basin and hence the conceptual design (as well as the detailed design) has incorporated some hydrological and hydraulic details of this catchment and river. Therefore the Maribyrnong river catchment, river itself and relevant physical attributes such as subcatchment definitions of the catchment (for use in the URBS hydrological model) and river cross section data of the flood prone area (for use in the HEC-RAS hydraulic model) are described first.

The structure of the DSSFCMR is then outlined. After outlining the structure of DSSFCMR, the conceptual design of each subsystem is presented. As stated in Sections 2.2.4.3, the quick-hit method was used to design the DSSFCMR, as it was decided to use existing technologies with extensions and enhancements as the tools for the project. This method was used in the development of all subsystems of DSSFCMR, which essentially meant tools such as MS ACCESS and MapInfo, were used in the project.

It should be noted that although DSSFCMR is specifically developed for the Maribyrnong River basin, the general concept and the design of the system can be used for other Decision Support System (DSS) studies in water resources and other fields, in particular in flood forecasting and warning.

#### **4.1 Maribyrnong River Basin and Its Flood Mitigation**

The Maribyrnong River basin is located in the Northwest of Melbourne, in Victoria, Australia (Figure 4.1). Its catchment area is 1,433 square kilometres, which is also covered by 470 km of waterways. Main tributaries of the Maribyrnong River include Riddells Creek, Emu Creek, Jacksons Creek, Boyds Creek and Deep Creek. Most of the basin consist of dissected, upland volcanic plains, with deeply entrenched waterways. However, the northern border and a strip

stretching down Deep Creek are composed of sedimentary rocks with areas of granite and gneiss.

The annual rainfall in the north of the river basin varies between 700 - 1,500 mm. However, in the central and southern part of the river basin, the rainfall is between 600 and 700 mm, reducing to 500 - 600 mm at Keilor. About 80% of the basin is cleared for grazing and broad acre cropping with the remainder being remnant, low, mixed-species forest. The upper part of the catchment is rural, while the lower 15 km of the Maribyrnong River flows through urban areas. Floods have frequently inundated the low-lying flood plains along the lower sections of the river (Melbourne and Metropolitan Board of Works, 1986).

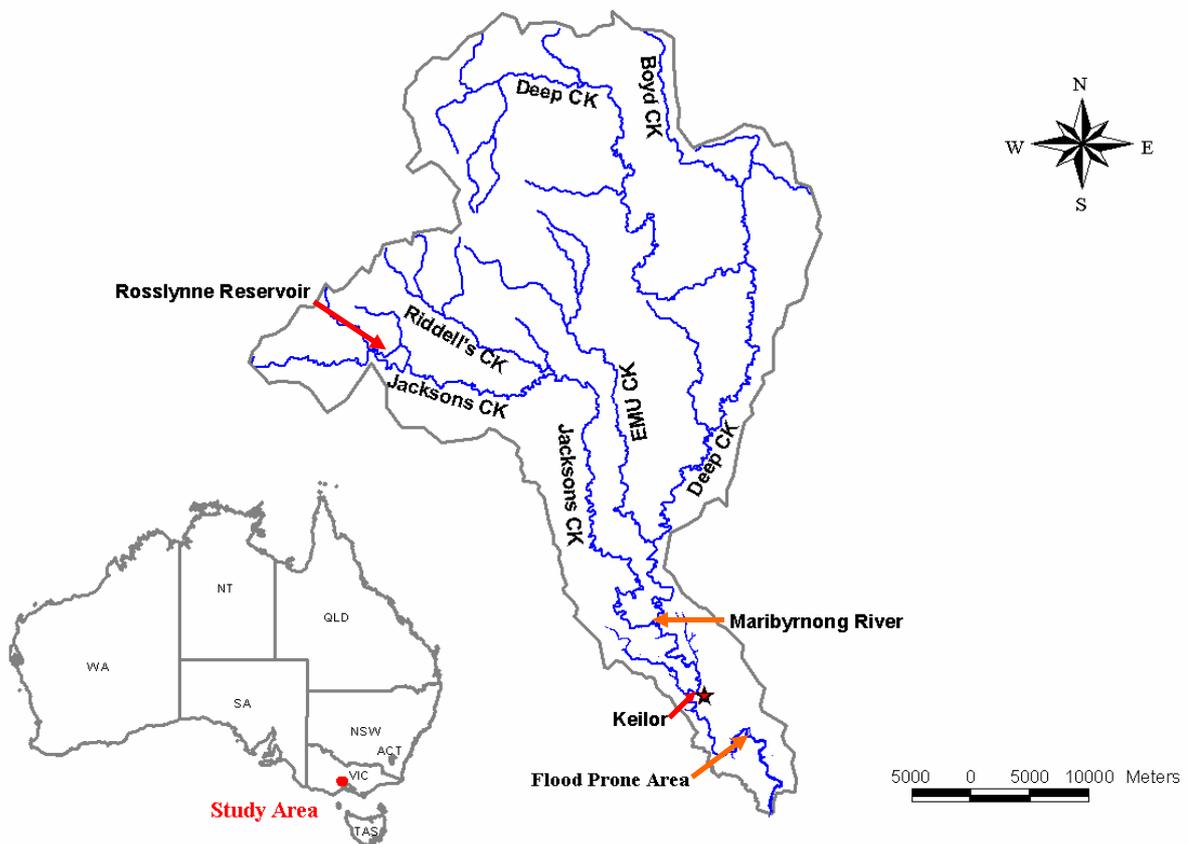


Figure 4.1 Maribyrnong River Basin

A more detailed map of the flood prone area is shown in Figure 4.2. The major part of flood prone area is the area to the south of Raleigh Road due to the relative low ground elevation of properties and high flood water level during the flood period. There are several bridges in this area. At the end of the river is the narrow channel connecting to the ocean, which causes backwater effects in the flood prone area.

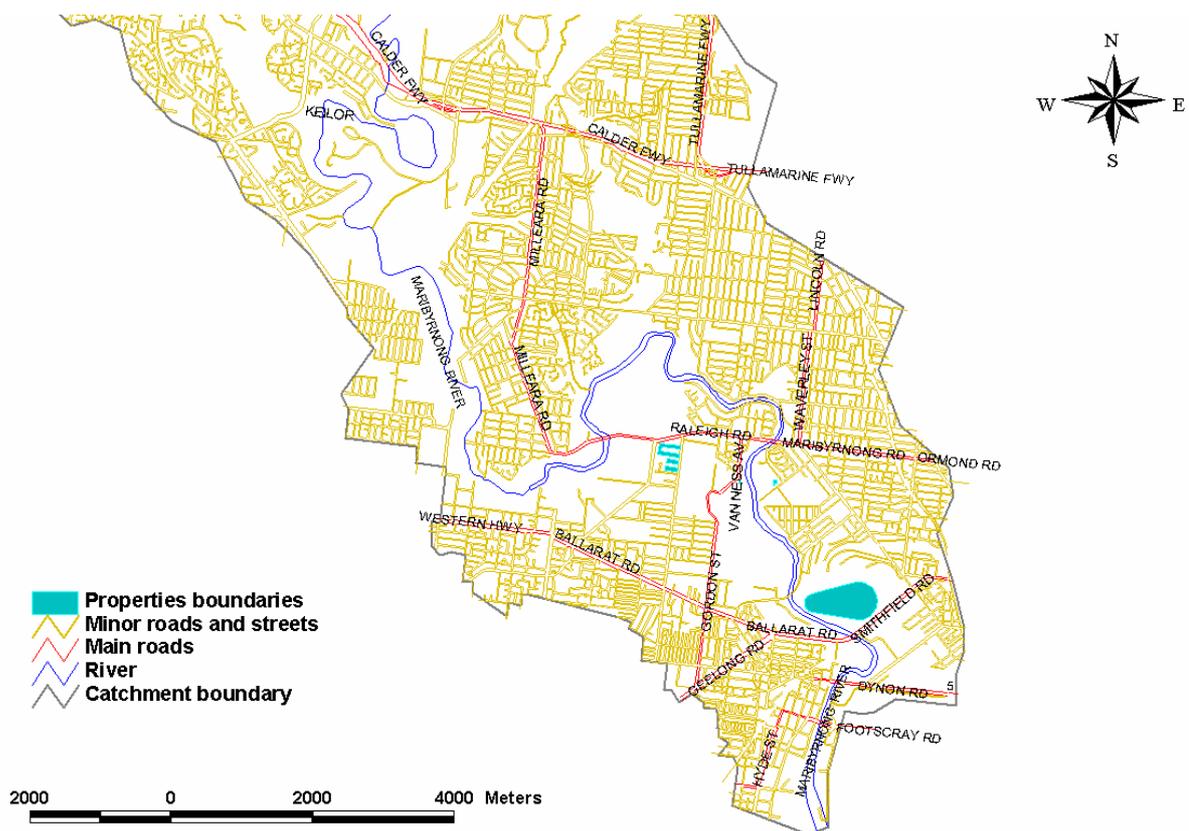


Figure 4.2 Flood Prone Area

Rosslynne Reservoir is located on the Jacksons Creek. Rosslynne Dam was built to provide water supplies to the townships of Sunbury and Gisborne, and to support agricultural irrigation development by diverters along the Maribyrnong River. Rosslynne Dam impounds a storage of 24,700 - ML with a small catchment area of 83 km<sup>2</sup>. It is an earth and rock-fill embankment 36.6 m high. A concrete lined spillway with discharge capacity 29,100 ML/d passes floods downstream of the embankment. However, the reservoir does not have a significant role in reducing the flood damage in the lower section of the Maribyrnong River due to its limited capacity.

There are no significant tributaries between Keilor and the flood prone area (which is the case study area studied in this thesis for flood forecasting and warning), and therefore the flow in Keilor can be considered as the flow entering the flood prone area. Hence, Keilor is modelled as the outlet of the catchment and the flow at Keilor obtained from the hydrological model under forecast rainfall conditions is considered as the forecast inflow to the flood prone area.

Several studies have been conducted by the former Melbourne and Metropolitan Board of Works – now Melbourne Water Corporation (1975, 1976, 1984, 1986 and 1988) with the aim of reducing social and economic impacts of flooding in this catchment. Several flood control

measures were investigated in these studies. They include the structural measures such as construction of retarding basins and levee banks, channel improvements, and flood proofing of properties; and the non-structural measures such as flood forecasting and warning, providing flood insurance, and acquisition and control of planning permits of properties within the catchment. A flood warning system was established in 1975 after a major flood in 1974 (Melbourne and Metropolitan Board of Works, 1984, 1986 and 1988).

In the flood warning system, the RORB (Laurenson and Mein, 1995) hydrological model was used for real-time hydrological forecasting for flood warning and the HEC-2 hydraulic model (USACE, 1982a) was used to calculate the flood water levels in the flood prone area of the lower part of the Maribyrnong River (personal communication with G. Crapper of Melbourne Water Corporation, 1997). However, the decision making process for flood forecasting and warning has been achieved by using separate models (i.e. RORB and HEC-2), and there has not been a single computer model linking these models. If the models are not properly linked, the use of separate models can lead to errors in transferring information from one model to the other. Furthermore, the user has to spend considerable time in analysing the problem by using various scenarios because the models have to run separately by the user.

#### **4.1.1 Pluviometer and Streamflow Gauging Stations**

There are 12 gauging stations scattered throughout the catchment, as shown in Figure 4.3, all measuring rainfall with some measuring streamflows as well. Table 4.1 presents details of these stations. All 12 gauging stations were used in the initial system design and development of DSSFCMR.

The recorded data of the flood event of 14 October 1983 was used in the case study of this thesis. Although the DSSFCMR design was built around all 12 gauging stations, only the rainfall data at stations Macedon (1), Clarkefield (3), Romsey (6), Darraweit Guim (7) and Bulla (9), and flow data at stations Sunbury (4), Bulla (9) and Keilor (10) were available for the case study event. However, the flow data at Bulla and Sunbury were not used in the case study, since the focus of the study was on flood warning with respect to flooding of the lower part of the catchment, which is close to Keilor. Flow data at Keilor was used only for the calibration of the URBS model. Therefore, it was necessary to devise a procedure to use the hydrological data of the above 5 rainfall gauging stations without corrupting the output file structure that was developed for the original design and without modifying the computer code

of DSSFCMR. This is considered to be necessary, since real-time flood events may not have data at all gauging stations at all times. The devised procedure consists of a conversion table and is explained below for the case study event.

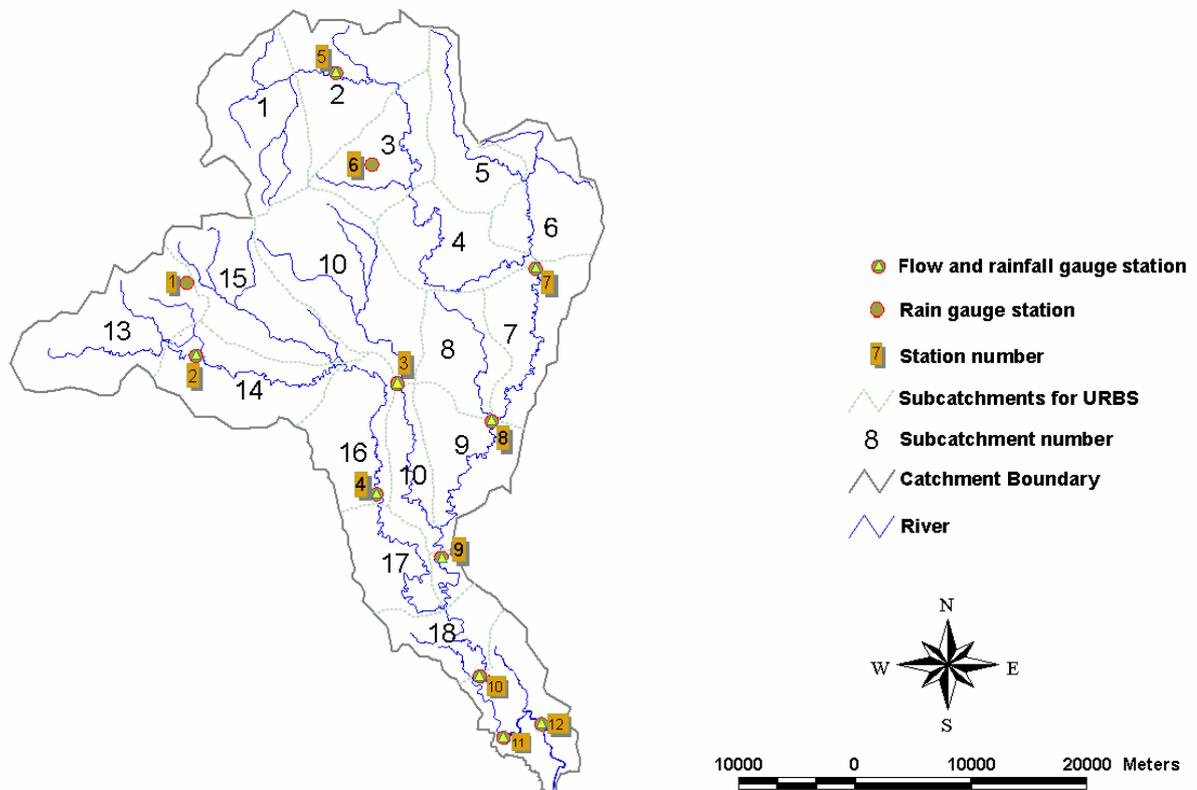


Figure 4.3 Streamflow and Rainfall Gauging Stations, and Subcatchments of URBS Model

As stated above, since there are 5 gauging stations involved in the case study flood event, it is necessary to input observed rainfall, streamflow and other data only for these 5 stations and produce output corresponding to these stations. In order to access the databases involving these stations only, they need to be prepared in a certain way, since the databases are accessed sequentially based on the alphanumeric values of the database names. Five database tables starting with station numbers with the lowest first-digit and then the second lowest first-digit and so on, are considered to represent the data for these five stations. When there are several stations with the lowest first-digit as in this case, the stations with the second digit are also considered. Using the above procedure, the database tables 1, 10, 11, 12 and 2 are used for this case study flood event. This will also allow the output summary table for simulated flood scenarios to have the data related to the rainfall gauging stations of the case study flood event in the first five columns. The conversion table for the case study flood event is given in Table 4.2 and this table shows the station number used in the original design, the station name, and the station number used for the case study flood event.

If the original design was used without conversion, the output summary table for simulated flood scenarios would have used the first five columns for the five stations defined by station numbers 1, 10, 11, 12 and 2 (i.e. Macedon, Keilor, Maribyrnong 1, Maribyrnong and Rosslynne Reservoir), and then the user will get incorrect information for the case study flood event.

According to the procedure described above on the station numbers defined by their digits, Macedon, Clarkefield, Romsey and Darraweit Guim should have 1, 10, 11 and 12 respectively. However, since all these station numbers are used in the case study, order is not important. Therefore as seen from Table 4.2, data for Macedon will be stored in database table station12, Clarkefield in database table station11, etc.

This procedure allows the use of DSSFCMR with any number of gauging stations without modifying the code. However, it has the disadvantage that new station number does not show any relationship to their actual location. For example, Macedon's new station number is 12, which has the physical location of Maribyrnong. This disadvantage is considered to be negligible compared to required modifications of DSSFCMR code to accommodate different gauging stations, whenever DSSFCMR is used with different flood forecasting events with varying number of gauging stations. If the data in all 12 stations are available, the conversion is not necessary.

Table 4.1 Pluviometer and Flow Stream Gauging Stations

<b>Station</b>	<b>Station Name</b>	<b>Function</b>
1	Macedon	Pluviometer
2	Rosslynne Reservoir	Streamflow and Pluviometer
3	Clarkefield	Streamflow and Pluviometer
4	Sunbury	Streamflow and Pluviometer
5	Lancefield	Streamflow and Pluviometer
6	Romsey	Pluviometer
7	Darraweit Guim	Streamflow and Pluviometer
8	Kongaderra	Streamflow and Pluviometer
9	Bulla	Streamflow and Pluviometer
10	Keilor	Streamflow and Pluviometer
11	Maribyrnong 1	Streamflow and Pluviometer
12	Maribyrnong	Streamflow and Pluviometer

Table 4.2 Station Number Configurations for Case Study

Station Name	Station Number in Original Design	Display Name	Station Number For Case Study
Macedon	1	Macedon	12
Clarkefield	3	Cfield	11
Romsey	6	Romsey	1
Darraweit Guim	7	DGuim	10
Bulla	9	Bulla	2

#### 4.1.2 Subcatchment Data for URBS Model

As stated in Section 3.2, the URBS software requires the study catchment to be divided into a number of smaller subcatchments. Each subcatchment is then considered as a conceptual reservoir in URBS. Based on the previous work at Victoria University (Perera and Shipton, 2005), a total of 18 subcatchments were considered in this study, as shown in Figure 4.3. The details of each subcatchment as required by URBS are given in Table 4.3. The 18 subcatchments do not include the catchment area downstream of Keilor. The catchment area above Keilor is considered to be predominantly rural.

Table 4.3 Subcatchments Details used in URBS Model

Catch No	Area (km <sup>2</sup> )	Factor	L	U	F	Up Catch	Down Catch	Down Comb	Printing	VBF	File Name	Route L	Route U	Route F	Route Factor
1	114.4	0.5	11.7	0	0	0	2	N	NO			0	0	0	1
2	86.9	1	16	0	0	1	3	N	No			0	0	0	1
3	67.5	1	18.9	0	0	2	4	N	No			0	0	0	1
4	81.7	1	26.4	0	0	3	7	STORE	NO			0	0	0	1
5	62.5	0.5	7	0	0	0	6	N	NO			0	0	0	1
6	75.6	0.5	3	0	0	5	7	GET	NO			14.1	0	0	1
7	70	1	27.35	0	0	4	9	STORE	NO			0	0	0	1
8	64.9	0.5	6.55	0	0	0	9	GET	NO			12.65	0	0	1
9	65.5	1	15.2	0	0	7	12	STORE	NO			0	0	0	1
10	168	0.5	14.9	0	0	0	11	N	NO			0	0	0	1
11	44.9	0.5	14.4	0	0	10	12	GET	NO			3.3	0	0	1
12	15	1	5.1	0	0	12	18	STORE	NO			0	0	0	1
13	80	0.5	9.4	0	0	0	14	DAM	NO	24670	rosslynn	10.7	0	0	1
14	68	1	10.5	0	0	13	16	STORE	NO			0	0	0	1
15	124.1	0.5	15.8	0	0	0	16	GET	NO			11.1	0	0	1
16	75.9	1	11.35	0	0	14	17	N	NO			0	0	0	1
17	44.9	1	18.35	0	0	16	18	GET	NO			12	0	0	1
18	54.3	1	16	0	0	12	0	N	Keilor			0	0	0	1

Note that the total subcatchment area in Table 4.3 is less than the catchment area stated in Section 4.1, since only the catchment above Keilor is considered in Table 4.3. Note that U, F, Route U and Route F are 0 in Table 4.3, since the subcatchments are considered to be predominantly rural with no forest cover.

The items of *Factor*, *L*, *U* and *F* are similar to those in Equation (3-1) . Other items in Table 4.3 are described below:

Catch No	Identification number of the subcatchment.
Area	Area of the subcatchment (km <sup>2</sup> )
UpCatch	Identification number of the subcatchment upstream of the current subcatchment along the main stream.
DownCatch	Identification number of the subcatchment downstream of the current subcatchment along the main stream.
DownComb	Type of the confluence at the outlet of the current subcatchment. Four types (i.e. 'N' GET, STOTE, Dam) are available. 'N' means that there is no tributary at the outlet. 'GET' and 'STORE' are described in Section 3.2.2. 'DAM' means the outlet of the current subcatchment is a dam.
Printing	Whether printing of the hydrograph is required at the outlet of the subcatchment.
VBF	Volume available in a storage reservoir at the outlet of the subcatchment, which must be filled before any discharge occur.
File Name	The name of storage-discharge file related to the storage reservoir described by above VBF.
Route L	Length of a river reach where the current hydrograph is routed without any additional rainfall from a subcatchment.
Route U	Fraction urbanization of Route L reach where the current hydrograph is routed without any rainfall from a subcatchment (1 for fully urbanized; 0 for fully rural).
Route F	Fraction of forest of Route L reach where the current hydrograph is routed without any rainfall from a subcatchment (0 for no forest; 1 for complete forest).
Route Factor	A parameter, which modifies Route L reach due to slope of the reach. Its value varies from 0 (steepest) to 1 (normal).

### 4.1.3 Cross Section Data for HEC-RAS Model

The cross section data are essential to build the geometric file of the HEC-RAS model. The cross section data for the flood prone area of the lower part of Maribyrnong River were supplied by the Melbourne Water Corporation for use in the HEC-RAS model. These data were originally in HEC-2 file format, and were first converted to the HEC-RAS format. Cross sections used in this application are shown in Figure 4.4, with the description of each cross section is given in Table 4.4.

The contraction coefficient, expansion coefficient, Manning roughness coefficients in each three parts of the river cross sections (i.e. left bank, channel and right bank) are the calibration parameters used in HEC-RAS and they change from one cross section to another. DSSFCMR offers functions to calibrate these HEC-RAS model parameters.

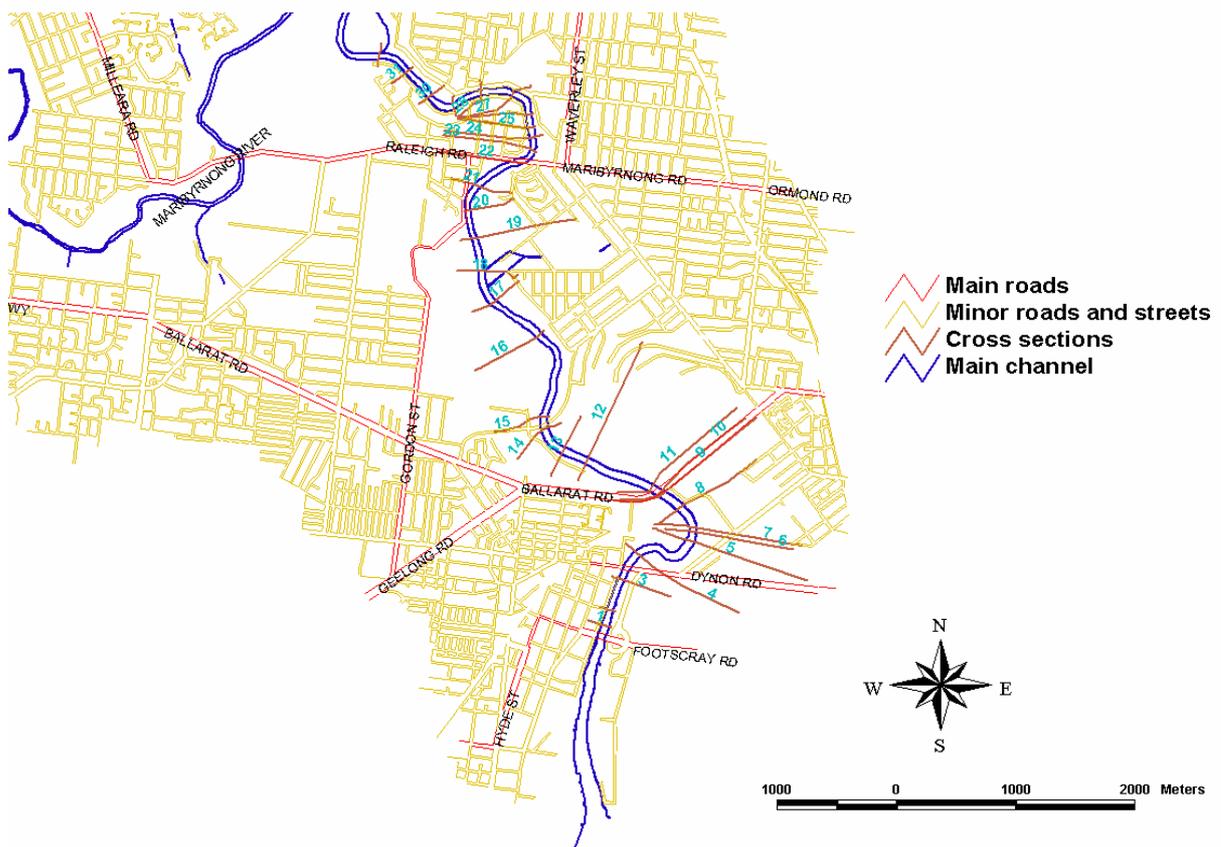


Figure 4.4 Cross Sections in Flood Prone Area of Maribyrnong River

Table 4.4 Cross Sections Used for HEC-RAS Model

<b>Cross Section ID</b>	<b>Description</b>
1	150 m downstream of Dynon Road bridge
3	Just downstream of Dynon Road bridge
4	120 m upstream of Dynon Road bridge
5	150 m downstream of Railway bridge
6	Just downstream of Railway bridge
7	Just upstream of Railway bridge
8	5m downstream of Stock bridge
9	50 m downstream of Ballarat Road bridge
10	Just downstream of Ballarat Road bridge
11	50 m upstream of Ballarat Road bridge
12	600/ upstream of Ballarat Road bridge
13	320 m downstream of Fisher Parade bridge
14	10 m downstream of Fisher Parade bridge
15	50 m upstream of Fisher Parade bridge
16	Charles street
17	250 m downstream of Newson street
18	Newson street
19	250 m upstream of Newson street
20	Just downstream of Hillside crescent
21	430 m downstream of Raleigh Road bridge
22	Just downstream of Raleigh Road bridge
	Just upstream of Raleigh Road bridge
23	Anglers arms hotel
24	Leopold street
25	Esplanade
26	Ensign street
27	Clyde street
28	Newstead street
29	Telemetry site
30	Fawkner street
31	Scenic place
32	100 m upstream of Afton road

#### 4.2 Structure of DSSFCMR

DSSFCMR consists of five main subsystems as shown in Figure 4.5. These subsystems are: Database (DBMS), Modelbase, Spatial and Graphic Data Display and Analysis (SGDDA), Decision Support, and Interface. Each subsystem has distinctive functions; however, some functions can be performed by more than one subsystem. The database subsystem is designed to access, process and manage data in a systematic and convenient manner. The Modelbase

subsystem is designed to contain some software tools and models that are used to compute the forecast flood hydrographs, the water levels at critical river sections, and the flood inundated areas. The SGDDA subsystem is designed to perform spatial data display and analysis of flood inundated areas, which also shows the inundated properties. The Decision Support subsystem is designed to assist the decision-maker to seek solutions for flood warning from the results of the analysis of many flood forecasting scenarios. The Interface subsystem is designed to exchange information between the user and the computer, and also to integrate all other subsystems.

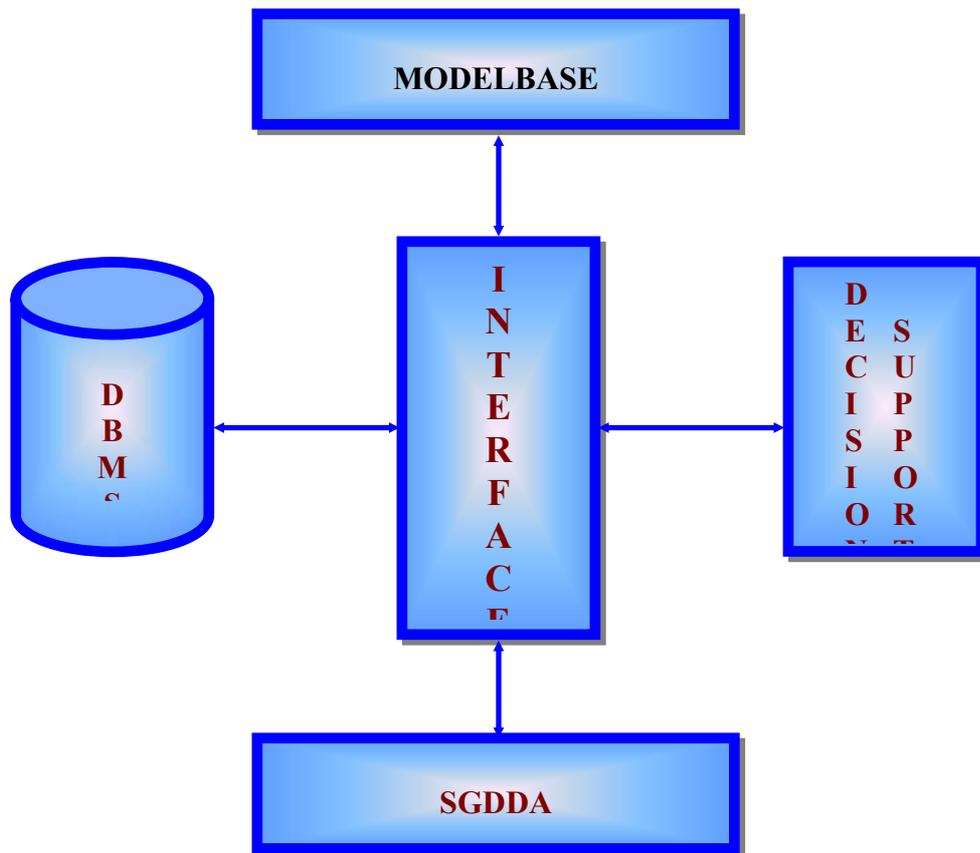


Figure 4.5 Structure of DSSFCMR

DSSFCMR is designed to run on the Window operation system. The Visual Basic software, MS ACCESS and MapObjects were used to develop DSSFCMR with features similar to a professional Windows application.

### 4.3 Database Subsystem (DBMS)

#### 4.3.1 General

The Database subsystem (DBMS) in DSSFCMR was designed to organize and manage the database systematically. It has facilities for creating an organized structure for the database and for individual data files (e.g. data entry into specific tables, editing data, sorting data into specific orders, viewing data in a variety of ways, querying data and reporting on selected data). The MS ACCESS and Visual Basic software were used as development tools for this subsystem.

The Database subsystem comprises of six groups of databases (Figure 4.6), namely: Catchment Characteristics D1; Model Parameters D2; Historical Flood Events D3; Real-Time Flood Events D4; Simulated Flood Scenarios D5; and Real-Time Flood Warning D6. These databases were described by D1CC.MDB, D2\_U\_C.MDB, D3HFE.MDB, D4RFE.MDB, D5SFS.MDB and D6RFW.MDB respectively. The contents of each group are shown in Figure 4.7. These details are essential for an effective DSS for flood forecasting and warning. The reasons for storing the data in six groups of databases rather than in six groups of tables in the same database are given below:

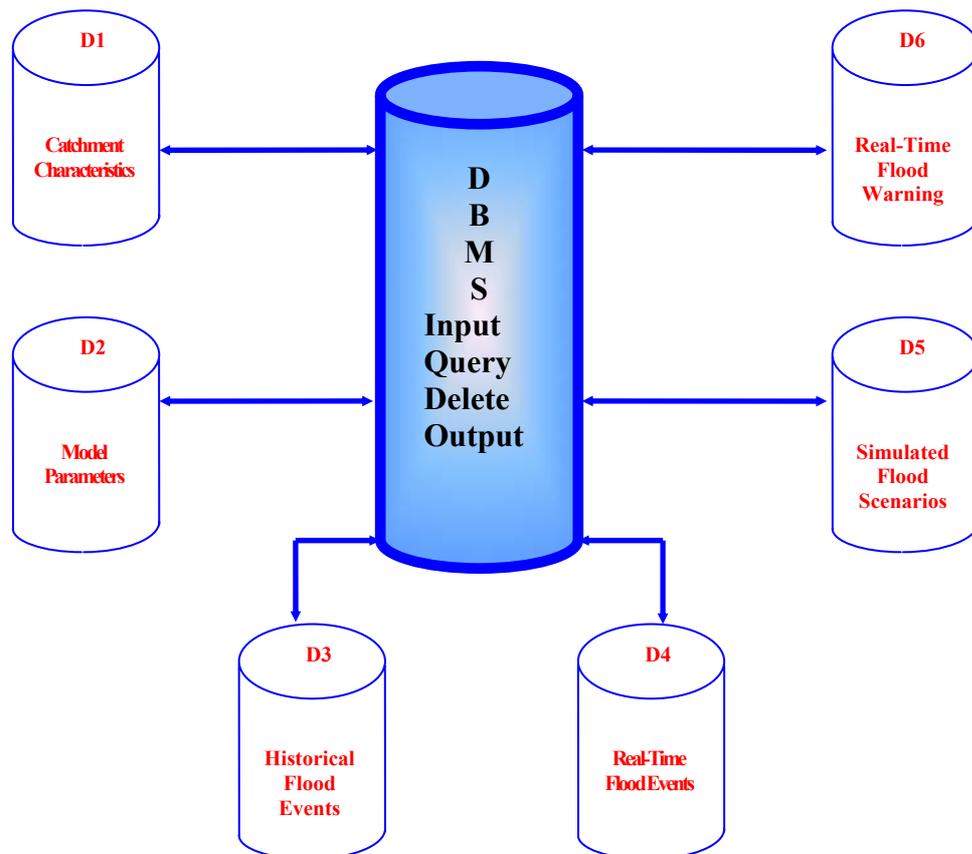


Figure 4.6 Structure of DBMS

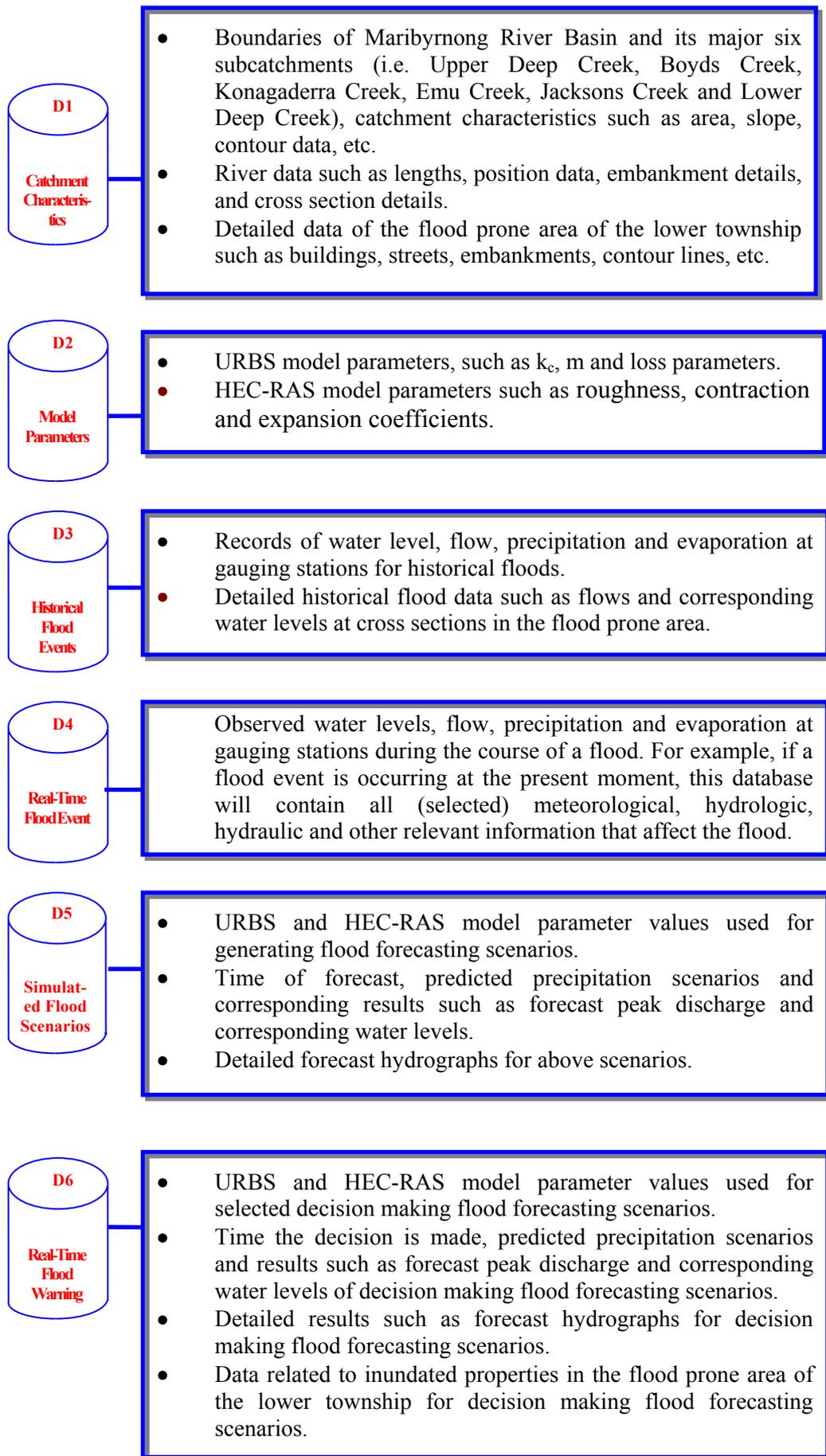


Figure 4.7 Basic Elements of Database

- Limitation of the database software: MS ACCESS was the only available database software to the author for this project. The functions of MS ACCESS database have some limitations. For example, the maximum size of the database was 1 GB (now it is 2 GB), which limits many tables in the database.
- Limitation of tool connecting the database: Data Access Objects (DAO) was the popular method to connect MS ACCESS database in Visual Basic programming at the original design stage of this project. DAO does not allow the user to access a database more than once for different data items simultaneously, which restricts the database having several database tables, which are likely to be accessed at the same time. Several databases properly designed to store their contents can significantly reduce the system run errors, since one database with several tables is not accessed simultaneously.
- Complex data structure: There are many data that were considered in the design stage of this project. Several databases properly stored by their contents make the database more professional and allow data management easy.

The structure of databases D5SFS.MDB and D6RFW.MDB in Figure 4.6 is similar. During forecasting, many flood scenarios can be considered and stored in D5SFS.MDB. From these scenarios, most likely scenarios and corresponding hydrographs relevant to the current storm are transferred to D6RFW.MDB for decision making. Because of the transfer of scenarios, most information in these two databases is similar.

The structure of databases D3HEF.MDB and D4RFE.MDB is exactly the same, compared to D5SFS.MDB and D6RFW.MDB. The data of current flood event are stored in D4RFE.MDB, while all data for historical flood events are stored in D3HFE.MDB. Furthermore, the data of the current flood event, which is stored in D4RFE.MDB, are transferred to D3HFE.MDB at the end of forecasting. Because of data transfer from D4RFE.MDB and D5SFS.MDB to D3HFE.MDB and D6RFW.MDB respectively, both D4RFE.MDB and D5SFS.MDB may become empty at the end of forecasting related to the current flood event. The advantages of such design are to save the hard disk space and to save data search time. For example, the scenarios in D5SFS.MDB can be deleted if the scenarios are no longer needed by the decision maker. Only the valuable decision making flood forecasting scenarios are stored in D6RFW.MDB for the decision maker. The decision searching in D6RFW.MDB can be done much faster than searching in a database storing all contents currently in D5SFS.MDB.

The D1CC.MDB is a database, which includes spatial data that mostly exist as spatial data files such as DXF files or ESRI shapefiles (Section 3.5). The data in this database are mostly pre-defined (or pre-existing), and they are not modified by the DSSFCMR programming.

Most tables in databases in this project are pre-defined (or pre-existing). Such design is based on the function of the project. DSSFCMR in this project is designed for real-time flood forecasting and flood warning, which requires fast data transfer that enables quick decision making for flood warning. The editing of pre-defined (or pre-existing) database tables to update data and save data is quicker than creating these database tables during the real-time flood event. Therefore, the method of pre-defined database tables is used in this project, so that quick decisions can be done for flood forecasting and warning.

#### **4.3.2 Details of Conceptual Design**

All subsystems in DSSFCMR deal with the database(s). Several database functions such as data entry, data delete, data update and data query were designed to be used in these databases. However, the user needs all these functions only for Historical Flood Events database D3HFE.MDB and Real-Time Flood Events database D4RFE.MDB, while other databases require only few functions. In some cases, DSSFCMR automatically completes some database functions as required. For example, the data in database D5SFS.MDB for Simulated Flood Scenarios are entered by DSSFCMR programming automatically, and the user does not use the input function (Section 4.3.2.1) for this database. All database functions are described below, using the databases D3HFE.MDB and D4RFE.MDB as the example, since all these functions are used in these two databases.

##### **4.3.2.1 Data Input**

Three methods were designed and developed for data entry into D3HFE.MDB and D4RFE.MDB databases as described below.

- The first method enters one record at a time through the developed interface. This method does not corrupt the other records in the database, by accidentally deleting or modifying them. This method was designed for the users with general computer skills.

- The second method was designed for the users with high-level computer knowledge and skills. The user can view all data and the database table structure, and can directly enter data records into the database tables. It is an easy way to enter several records into the database table. However, it is also possible to accidentally delete or modify other records in the database.
- The third method was designed to enter (or convert) a large number of data records from text files, where the data are stored.

The data input design was based on the consideration of the flexibility of system, the user's level of computer knowledge, and the varying hydrological data formats that are common in flood forecasting and warning applications. It was not intended to develop a universal data converting programming system in this thesis, but limited to flood forecasting and warning applications.

Figure 4.8 shows the data entry module in DSSFCMR for D3HFE.MDB and D4RFE.MDB databases. The left, middle and right segments of Figure 4.8 illustrate the first, second and third methods of data entry respectively.

#### **4.3.2.2 Data Delete and Update Functions**

Data delete and update functions for D3HFE.MDB and D4RFE.MDB databases were designed for a single record to be performed at one time. It means only one record can be deleted and updated at one time. Considering the complexity of delete and update functions and the potential damage to the database in attempting delete or update many data records simultaneously, such a design is reasonable. Two data search functions were designed to delete and update records to help the user to locate the required data record. The first search function limits the range of data records based on user's search criteria, while the second function finds the required record. The detailed design of these functions is shown in Figure 4.9.

#### **4.3.2.3 Data Query Function**

The data query function was designed to find the data record(s) for the users with all different levels of computer knowledge. The user can select a key parameter such as flow discharge, an operator such as greater than (>), and a value such as 20 m<sup>3</sup>/s to build a simple

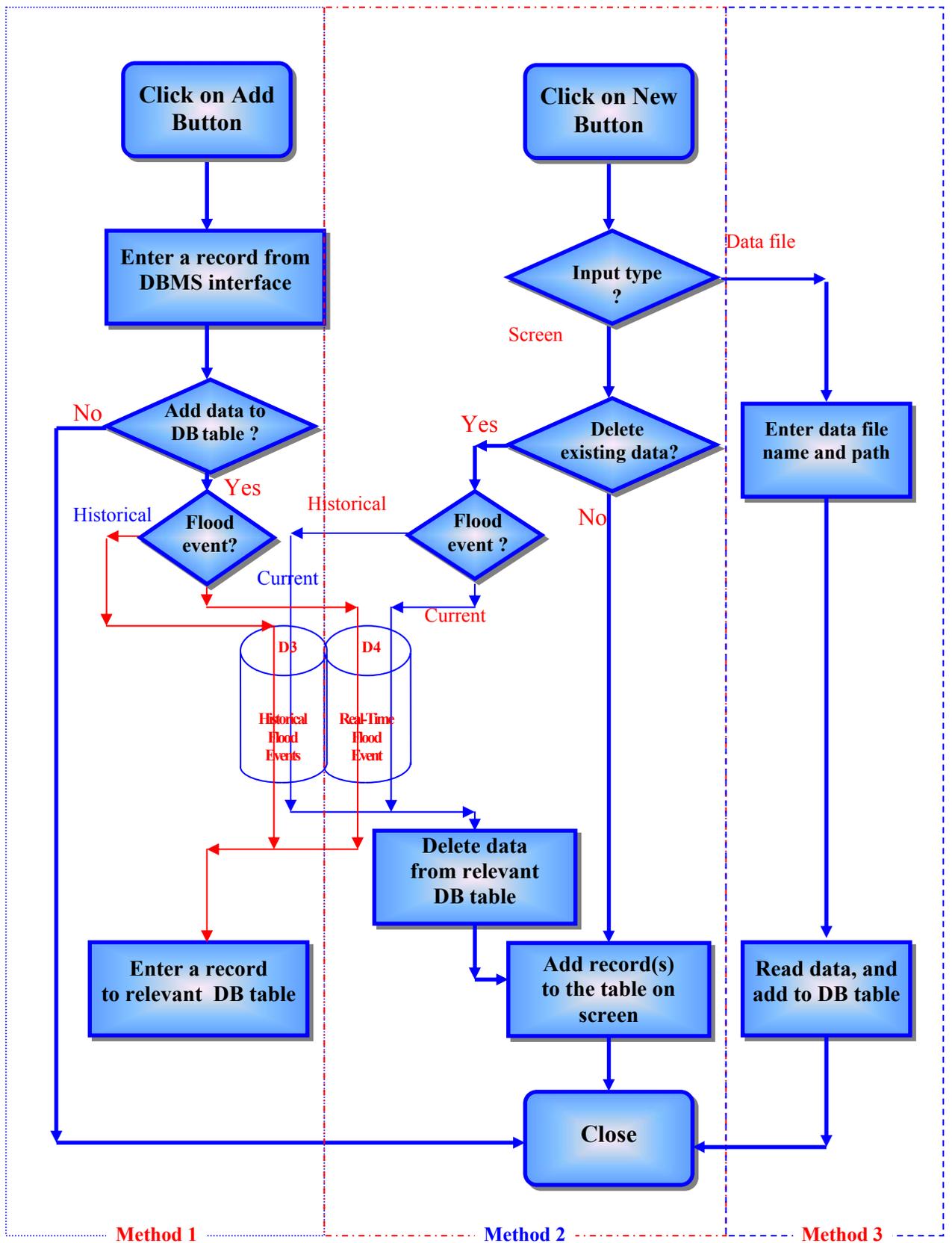


Figure 4.8 Data Entry Module in Database Subsystem

querystatement to find the required data. However, the user also can build complex Structured Query Language (SQL) statements as necessary, combining many key parameters and even

specifying sorting records in ascending or descending order based on certain key parameters. The detailed design of data query module is shown in Figure 4.10.

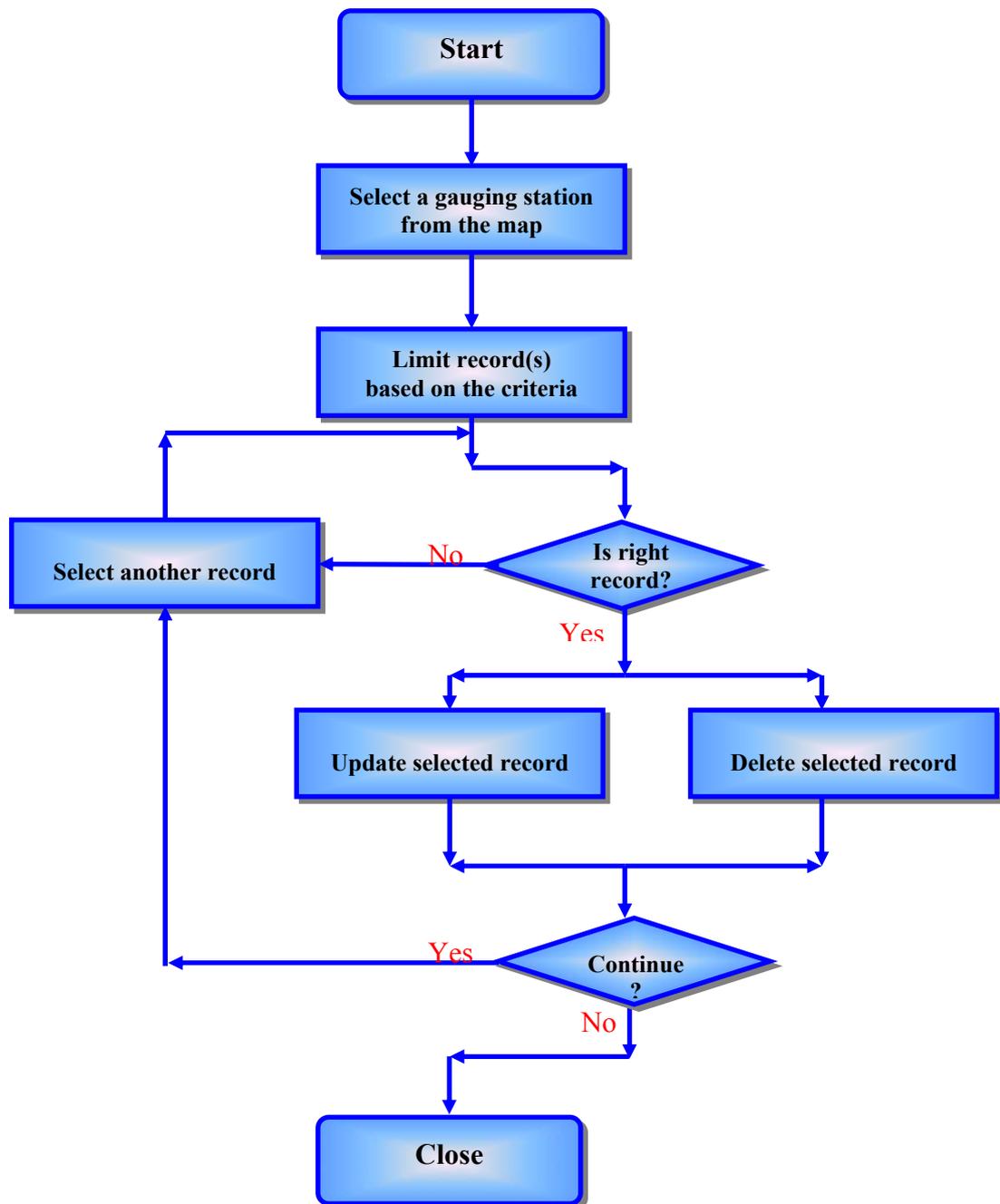


Figure 4.9 Data Delete and Update Module in DBMS

#### 4.3.2.4 Output Function

The output function is designed to provide details of flood hydrographs, flood water levels and rainfall data at the selected gauging station in graphical and tabular format. This output

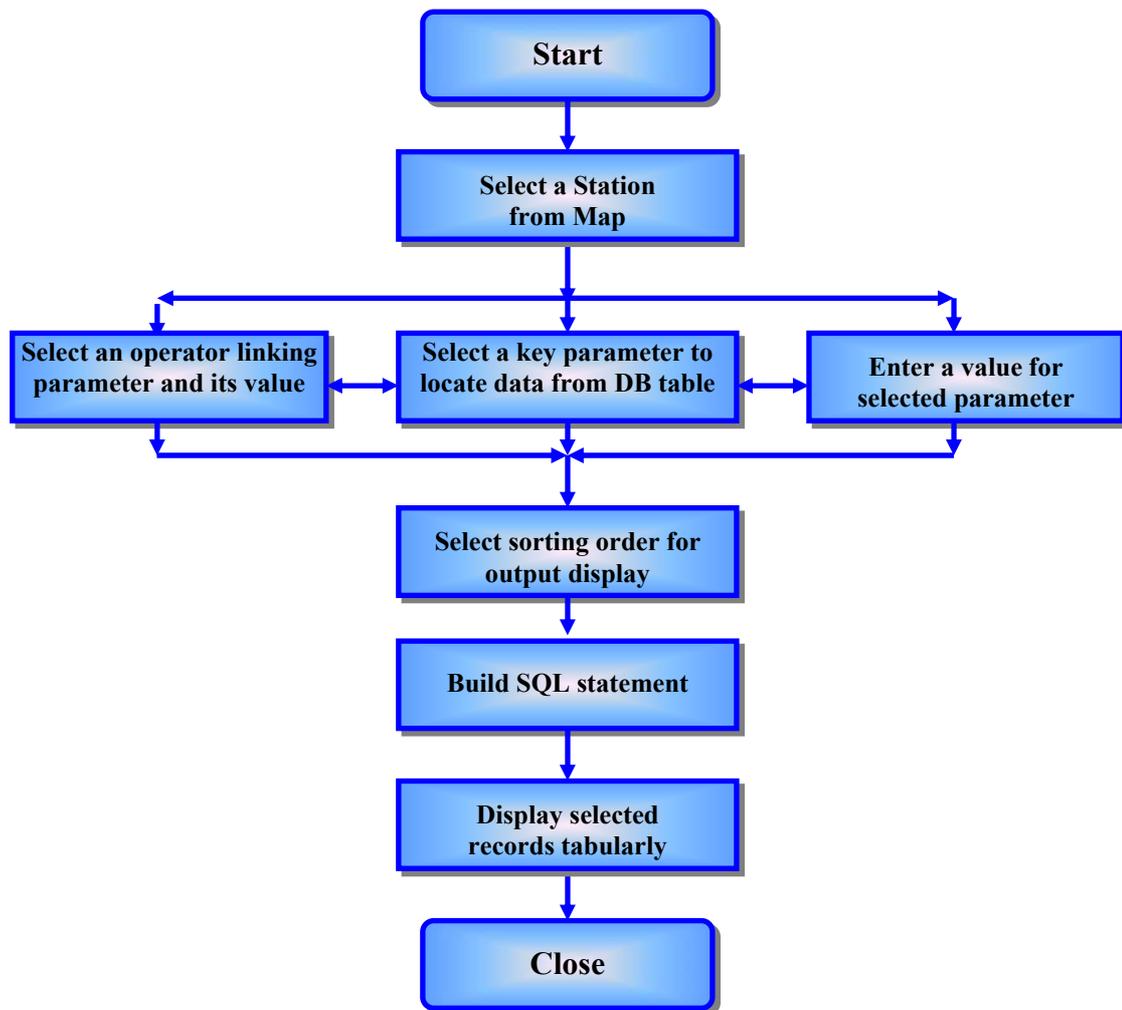


Figure 4.10 Data Query Module in DBMS

function was designed in the format of screen display only, without any printing facility. Although the original design also includes the output to other file formats such as MS EXCEL and print tables, these functions were removed during the project. This was because the design tool, the version of Crystal Report (Visual Basic 4.0, Microsoft) was not compatible with 32 bit Windows operation environment, when DSSFCMR was updated in 2001 from 16 bit Windows to 32 bit, and there was no new version of Crystal Report available, which is compatible with 32 bit Windows. Another important factor was that DSSFCMR was developed for decision making for flood forecasting and warning, and therefore the print document is relatively less important compared to the screen display, which is used for quick decision making. The detailed design of the output function is given in Figure 4.11.

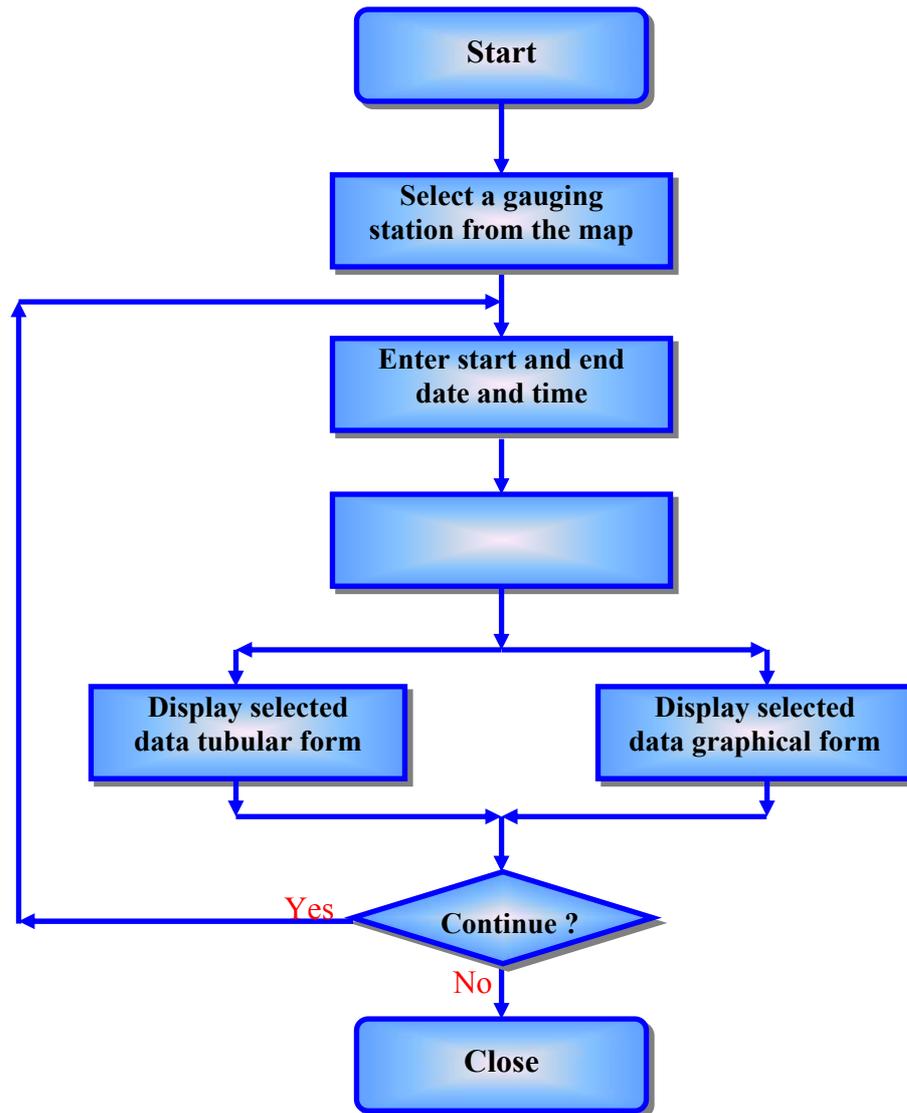


Figure 4.11 Output Module in DBMS

#### 4.4 Modelbase Subsystem

The purpose of the Modelbase subsystem is to operate and manage numerical models associated with flood forecasting and warning. Two types of numerical models are currently included in this subsystem. They are the hydrological model and the hydraulic model. The hydrological model is used to simulate the flood hydrographs due to observed or forecast rainfalls. The water levels at critical sections are determined by the hydraulic model using the peak discharges of the flood hydrographs. The results from these models are automatically transferred to other subsystems.

#### 4.4.1 URBS Hydrological Model

##### 4.4.1.1 Use of Acquired Knowledge and Knowledge Learning

The application of the knowledge from previous work and/or from experts into DSSFCMR is illustrated in this section through the system design, development and application. However, the collected knowledge on the flood mitigation in the studied river basin is limited. The reasons are: (1) there is limited knowledge available on flood forecasting and warning other than what was obtained from the current flood warning system, which was established in 1975; (2) there is some knowledge other than flood forecasting and warning, which is difficult to incorporate into this project, since this knowledge is not directly relevant to flood forecasting and warning. Therefore, the collected knowledge is not sufficient to build a knowledge base to support decision making. However, some collected was built into DSSFCMR, as described below.

Based on the collected knowledge on the flood mitigation in the study river basin, the application of knowledge for decision support are designed through two approaches: (1) application of acquired knowledge directly and (2) knowledge learning and development. The latter is obtained through the functionality developed in DSSFCMR and provides very powerful knowledge on flood events in terms of peak discharge, flood levels and flood inundated areas. The above two methods are detailed below:

- Application of acquired knowledge directly -

There is limited acquired knowledge on hydrological model parameters relevant to the Maribyrnong catchment, although it is acknowledged that such acquired knowledge could improve the power of the DSS. One such acquired knowledge was the method of *7-day mean daily Q* used as an alternative method in DSSFCMR to calculate the *Initial Loss* from the parameter of *7-day mean daily Q* (Flow). The *7-day mean daily Q* is the average daily flow over 7 days prior to the storm. This method has been used for the Maribyrnong River and the user is referred to Crapper (1989) for theory of the method. However, the equation relating the *Initial Loss* to the *7-day mean daily Q* is given below:

$$LC = 1.24 Q^2 - 23.7 Q + 133 \quad (4-1)$$

where:  $LC$  = Initial Loss(mm)

$Q$  = 7-day mean daily flow ( m<sup>3</sup>/s)

- Knowledge learning and development -

The model parameters play a very important role in the hydrological model application. They can be different for different catchments and for different storm events. The DSSFCMR allows the user to learn and accumulate the knowledge of hydrological model parameters and their effect on flood hydrographs. The user can add, update, delete or refresh these parameters in the database based on the learnt knowledge and their appropriateness for the application.

The design on model parameters is based on selecting one model parameter at a time in forming the parameter set rather than selecting a set of parameters at a time, which meant several values of each model parameter are stored in a database having different database tables for different parameters. The main advantage of this design is the flexibility of the design to build new parameters sets for the application. However, the major disadvantage is that the user has to have a good knowledge of hydrology to determine the appropriate set of parameters.

Figure 4.12 shows the design for preparing the Catchment Definition file required by the URBS hydrological model. The central and right part of the figure shows how the acquired knowledge is incorporated in the design.

#### **4.4.1.2 Model Definition and Parameters**

As outlined in Section 3.2.2, the DOS-based URBS model required the user to prepare parameter data files such as Catchment Definition file, Rainfall Definition file, and rainfall (data) files, as ASCII files, outside the URBS software tool. Therefore, the user needs to have a good knowledge of the structure and format of these data files. However, the design in DSSFCMR allows the user to easily build these data files through the developed Windows interface. The structure (or definition) of subcatchments and most physical parameters of subcatchment such as  $L$ ,  $F$ , and  $Area$  in the Catchment Definition file are fixed for a catchment and they are pre-defined and stored in the Catchment Definition file in DSSFCMR (These parameters are explained in Section 3.2.1). This means the user cannot interact with the definition of subcatchments and their physical variables from the interface. However, the design in DSSFCMR allows the user to directly view the subcatchment definition information from the interface.

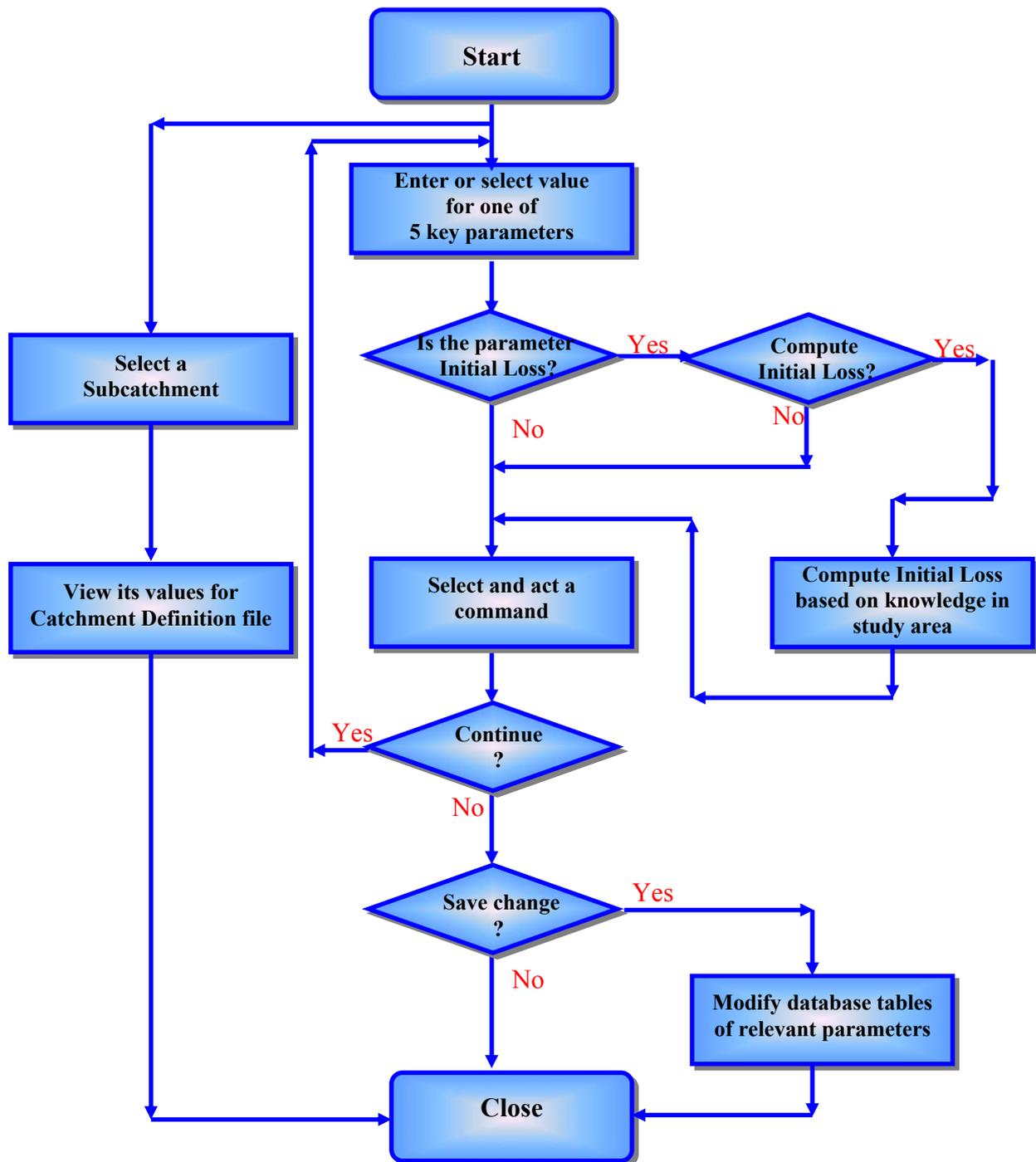


Figure 4.12 Hydrological Model Parameters Module in Modelbase

The user can edit the model parameters in the Catchment Definition file (i.e. *alpha*, *m*, *initial loss*, *continue loss* and *base flow*) through DSSFCMR interface. The parameters *alpha* and *m* are catchment specific, while *IL*, *CL* and *baseflow* are storm specific. However, *alpha* and *m* may be slightly different for different storms depending on the magnitude of storm. These parameters require calibration.

#### **4.4.1.3 Calibration**

A Windows based interface was designed to calibrate the DOS-based URBS model. The purpose of this design was to make the DSSFCMR more flexible and convenient for the user to interact with URBS. However, the user does not have to calibrate the URBS model each time during the forecasting stage and the results from a previous calibration of this event can be used instead. Figure 4.13 shows the design of the interface for interactive calibration of the URBS model.

#### **4.4.2 HEC-RAS Hydraulic Model**

The HEC-RAS hydraulic model is used in DSSFCMR to calculate the flood water levels in the flood prone area of the lower section of the study river basin. A HEC-RAS project generally consists of a project file, and corresponding relevant geometry data file, flow data file and plan file. In this study, the HEC-RAS project file was pre-defined. However, an interface was designed and developed to integrate the entered data (by the user) with corresponding parameters values stored in relevant HEC-RAS files, to calibrate the hydraulic model and finally to calculate the flood water levels corresponding to flood peak discharges computed from the URBS model. Similar to the URBS model, the calibration is not always necessary before calculating flood water levels during the forecasting stage and the results from a previous calibration can be used instead.

As in knowledge application in the URBS model, the general knowledge on HEC-RAS model parameters for the study catchment was also applied to help the user to calibrate the HEC-RAS model. The knowledge application in this case study was through storing values of the model parameters, which had been obtained from previous calibrations. These model parameters include the Manning coefficient in each three parts (i.e. left bank, channel and right bank), and contraction and expansion coefficients in each of the cross sections of the flood prone area. Figure 4.14 shows the (designed) procedure of calibration of the HEC-RAS model.

The steady flow model of HEC-RAS was used in DSSFCMR, as the unsteady HEC-RAS model was not completely developed when DSSFCMR was designed and developed. DSSFCMR uses the peak discharge during both calibration and forecasting stage. The use of peak discharge (and the steady flow model) is justified below:

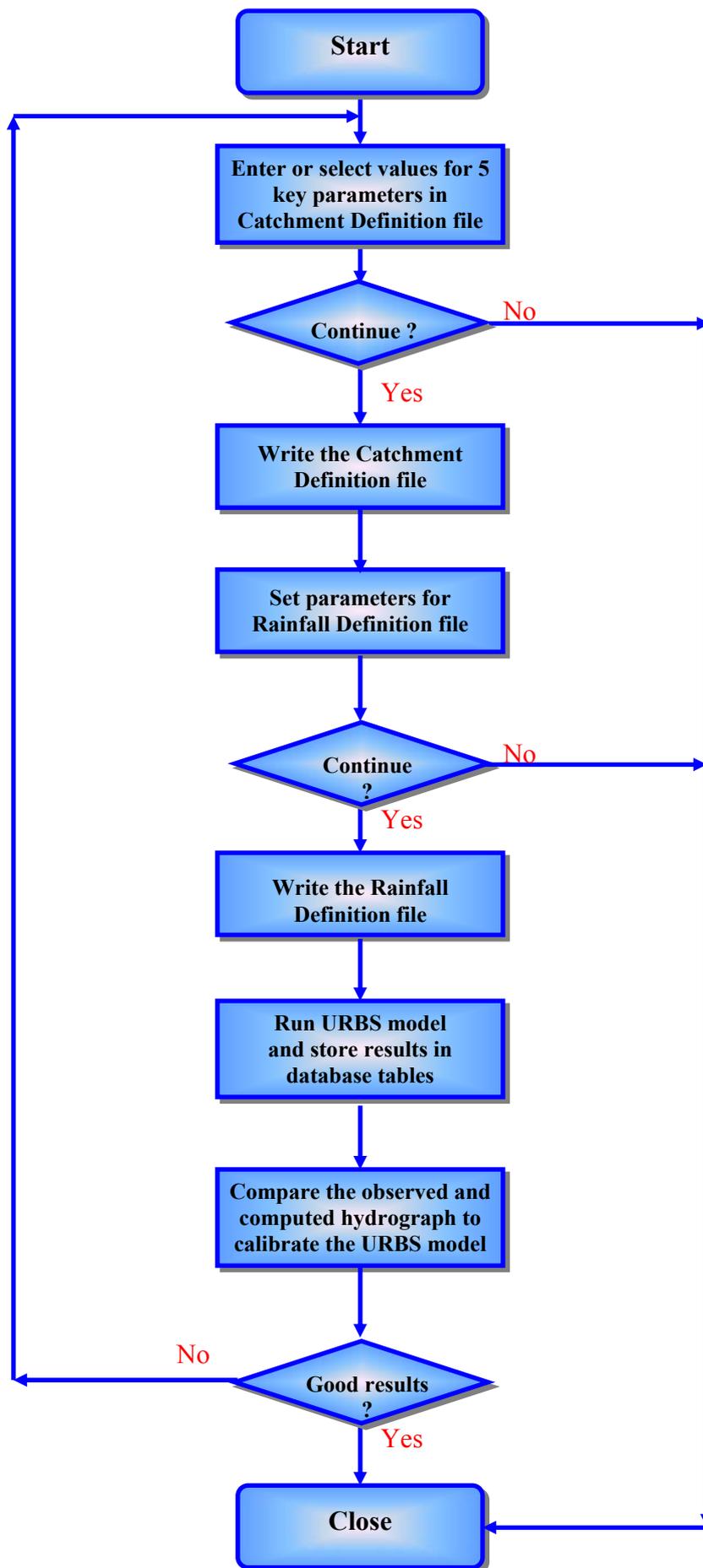


Figure 4.13 Calibration URBS Hydrological Model

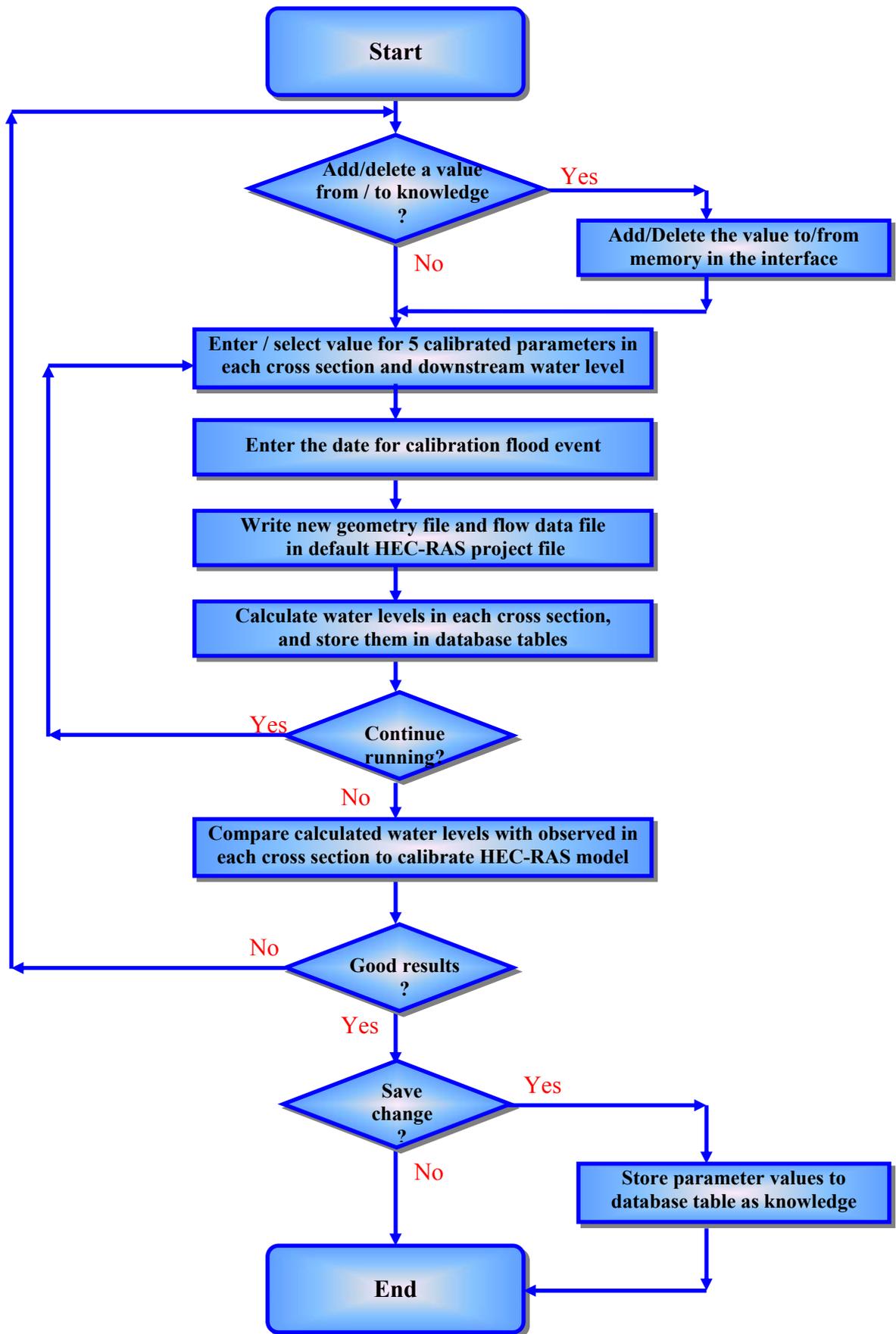


Figure 4.14 Calibration of HEC-RAS Hydraulic Model

- During calibration, the calculated water levels are compared with the observed water levels, which are generally obtained from surveying of the debris marks after the flood events had occurred that are considered to be the water levels corresponding to the maximum discharge.
- During the forecasting stage, the water levels due to maximum discharge give a conservative values for flood warning, which are the possible maximum values, and hence appropriate values for flood warning.

## **4.5 Spatial and Graphic Data Display and Analysis (SGDDA) Subsystem**

### **4.5.1 GIS Data**

GIS data of the catchment and the flood prone area were used in DSSFCMR for spatial data display and analysis corresponding to each simulated flood. In fact, the GIS data were used in DSSFCMR for three purposes.

- GIS data were used to generate the study area maps (i.e. images) for displaying the image directly. They were also used to generate the flood prone area image (to produce the flood inundation area image instantly for each simulated flood scenario by overlaying the flood line on the flood prone area image).
- GIS data were converted to ESRI shapefiles, which were then used to display these GIS data directly through MapObjects. These shapefiles were pre-generated using the MapInfo software.
- GIS data were used to produce the position data that were used by DSSFCMR. These position data were pre-generated from GIS data and saved in the format of pairs of Northing and Easting (i.e. pairs of Northing and Easting of several significant change points in each cross section). These data were then used by DSSFCMR interactively to create shapefile of the flooded area instantly. The flood line was then overlaid on the pre-generated flood prone area image, also by programming. The details about using these data interactively are given in Section 4.5.2.

Table 4.5 shows how GIS data were used for the three purposes (as described by three dot points above and abbreviated by Image Map, Directly display and Interactive). For example, the catchment boundaries were originally stored in a DXF file, when they were obtained for this research. This file was first converted into a MapInfo Table using the MapInfo software, and then generated a bmp file (which was used to display the catchment map). At the same

time, the catchment boundaries file (which are in DXF format) was also converted to the shapefile format and used by MapObjects to display the catchment boundary, river tributary and other topographical details in DSSFCMR. The river cross section data were first digitised into a shapefile, and then these data were converted into pairs of Northing and Easting for all significant change points in each cross section. DSSFCMR will use these interactively to create shapefile of flooding area instantly or the flood line.

Table 4.5 Spatial Data Process

Purpose	Original Data		Results Data	
	Contents	Format	Contents	Format
Image Map	Catchment boundaries	DXF	Catchment boundaries	Image
	River channels	DXF	River channels	Image
	Roads	DXF	Roads	Image
	Streets	DXF	Streets	Image
	Contours	DXF	Contours	Image
Directly Display	Catchment boundaries	DXF	Catchment boundaries	Shapefile
	River channels	DXF	River channels	Shapefile
	Roads	DXF	Roads	Shapefile
	Streets	DXF	Streets	Shapefile
	Contours	DXF	Contours	Shapefile
	River cross sections	Image	River cross sections	Shapefile
Interactive	Contours	DXF	Contours	ASCII text file
	River cross sections	Image	River cross sections	ASCII text file

All available GIS data were originally in DXF data format and the data did not satisfy the (specific) requirements of this development. For example, the original contour data consisted of many segments of small lines and they did not link with each other from river upstream to downstream, or vice versa. Therefore, the data processing and reproduction were necessary. A C++ program was separately developed to read vertex data from the original DXF file, then to reorganize segments in one contour line from upstream to downstream, or vice versa, and finally to output the ordered vertex data in contours into ASCII file. These data were used to derive the positions for other data such as cross section position data.

There was no property boundary shapefile of all properties available for the study area (i.e. flood prone area of the lower part of the catchment shown in Figure 4.2) during the time of this study. Because of time constraints, it was decided not to collect all property data in the study, but consider few properties in the property boundary shapefile. Six properties were considered in the property boundary shapefile to demonstrate the use of SGDDA in DSSFCMR, and to find the inundated properties from these six properties. If the user has a property boundary shapefile with 1000 property boundaries, DSSFCMR will find the inundated properties from these 1000 properties. DSSFCMR does read all property boundaries in the property boundary shapefile and such design and development make the system flexible.

#### **4.5.2 SGDDA Methods in DSSFCMR**

Two separate methods were designed and developed in DSSFCMR to perform spatial data display and analysis of the flood inundated area, for use by different users (with different computer skills) and for organisations with different levels of resources, as described below:

- The first method allows the user to view the flood boundary line on the pre-generated image of the flood prone area, which considers the flood affecting physical attributes such as river, roads and streets. Since this method uses a pre-generated image of the flood prone area, the user is not able to get the details of flood water levels of the properties of the area. This method did not require any external software for development of the SGDDA subsystem, or does not require any external software to use the method.
- The second method integrates the simulated flood inundated area with other geographical information data using the MapObjects software in DSSFCMR, and allows the user to investigate the spatial details of the flooded area and the potential flood damage extensively to the level of properties. This method requires the MapObjects software to reside in the user's computer, and also requires the user to have better computer skills to use this method than the first method.

These two methods were incorporated in the SGDDA subsystem and the design was based on the available GIS software tools and the potential user. However, the GIS software was not directly used as DSSFCMR's development environment, but the technology of GIS and GIS software tools (such as MapInfo which was mainly available for development) were used in

DSSFCMR development for spatial data conversion, pre-generation of images of maps, and interactive spatial analysis. All flood forecasting scenarios could be spatially displayed and analysed within DSSFCMR with both methods.

The second SGDDA method used shapefiles as the basic spatial data. After studying the format of the shapefiles, a computer program was developed in this study to create the shapefile of flood inundated area instantly in DSSFCMR, which then integrates with other spatial data to perform spatial analysis of the flooded area using MapObjects. The MapObjects software is available from ESRI for software development work and is a set of mapping software components that allow the developers to add/delete maps to their DSS applications. MapObjects is ideal for use in the industry standard Windows programming environments such as in DSSFCMR development environment. The developer of applications can connect MapObjects with components from other vendors, such as graphs and database objects to build DSSs using the standard Windows programming languages (e.g. Visual Basic). The applications using MapObjects can be developed for the specific requirements of the end-users in spatial data display and analysis.

The SGDDA subsystem provides two separate functions to help the decision maker to investigate the flood area and the relevant flood damage for each flood forecasting scenario that are stored in databases D5SFS.MDB and D6RFW.MDB. These functions are based on the first and second SGDDA methods, and are also shown in the two dotted boxes in Figure 4.15 respectively. The above two functions namely Interactive Image (corresponding to the first method) and Interactive Spatial Analysis (corresponding to the second method) in Figure 4.15 are key technology application and development of the SGDDA subsystem.

The Interactive Image function combined the flood prone area map (which was pre-generated) with the flood area line (online generated) to produce a flood area image. With this method, the flood area of the currently navigated flood forecasting scenario in database D5SFS.MDB or D6RFW.MDB is over-laid on the pre-generated map of flood prone area, considering the flood affecting physical attributes such as roads, rivers and streets. This method also gives Eastings and Northings of positions within the area. Creating the over-laid image of the flood area map due to current flood forecasting scenario, using its computed water levels at cross sections, is the core development of this method.

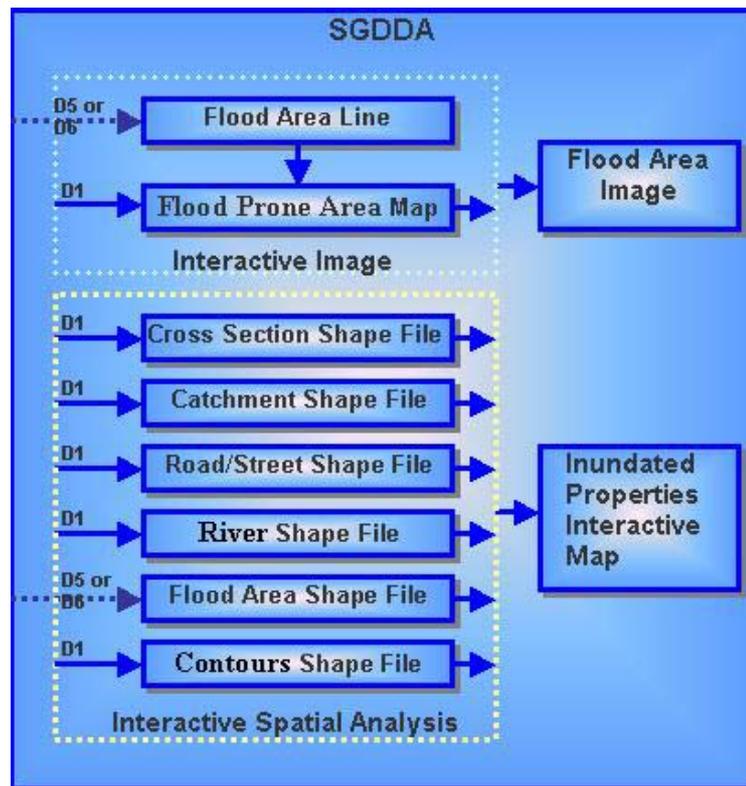


Figure 4.15 Data Flow in SGDDA

The Interactive Spatial Analysis function deals with cross-sections, catchment, roads/streets, contours, and flood area shapefiles, and conducts interactive spatial analysis to produce the Inundation Properties Interactive Map. This method integrates the flood inundated area details generated from the currently navigated flood forecasting scenario with other geographical information data (Figure 4.15) using the MapObjects software in DSSFCMR. The water levels at cross sections and geographical control points are used to generate the shapefile of the inundated area instantly, which then interacts with the properties/boundary data to generate the information on the inundated properties and other information such as property type (e.g. school), which assists the decision maker to make the decision at the current time. The control points are pre-defined geographical positions on both sides of the river, and are used when the cross section data alone cannot generate a smooth shapefile for the flood area. In Figure 4.15, D1, D5 and D6 are databases of Catchment Characteristics (D1CC.MDB) Simulated Flood Scenarios (D5SFS.MDB) and Real-Time Flood Warning (D6RFW.MDB) respectively; the solid arrow indicates the image or shapefile is pre-generated, while the dotted arrow indicates the item is created instantly during the flood forecasting stage due to a flood forecasting scenario.

#### **4.6 Decision Support Subsystem**

This subsystem was designed and developed to choose a smaller number of alternative flood forecasting decision scenarios to build acceptable decisions at a certain time of decision making. The DSSFCMR allows the user to simulate many flood scenarios at a certain decision making time during a flood event. The information related to each of these flood scenarios are stored in the database D5SFS.MDB. This information include the decision making time (date and time), the important model parameters, the observed rainfall and runoff up to the decision making time, forecast rainfall, forecast hydrograph and corresponding water levels. The Decision Support subsystem uses the above information in D5SFS.MDB to select a smaller number of flood forecasting scenarios to build acceptable decisions at this decision making time. These selected flood scenario decisions are then stored in the database D6RFW.MDB. As stated in Sections 2.2 and 3.5, the decision support in DSSFCMR was designed through the database searching technology to support the user to choose a smaller number of decisions.

As stated in Section 3.5, a primary key is an attribute or variable (i.e. one column in a database table) or a set of attributes or variables that uniquely identifies a record in a database table. Although a record (or simulated flood scenario) in a database (e.g. D5SFS.MDB) is designed to have many variables such as forecast rainfall, important parameters, and so on, locating a record in database D5SFS.MDB only depends on the primary key. What this means is searching a specific record only needs this primary key in a record, while the searched result includes all variables in the record such as key input parameters, forecast hydrograph and correspond water levels at each cross section. The conceptual design of Decision Support subsystem is based on this search technology, and is given in Figure 4.16. The detailed design of this subsystem is given in Chapter 5.

#### **4.7 Interface Subsystem**

The Interface subsystem was designed and developed to exchange information between the user and the computer, and also to integrate all other subsystems. This subsystem combines hardware and software to provide the user with tools that facilitate efficient interfacing with the computer. It was designed to be able to integrate the following four principal components:

- users;
- tasks;

- hardware (such as visual display devices, keyboards, other input and output devices) and application software;
- the environment (such as the operating system).

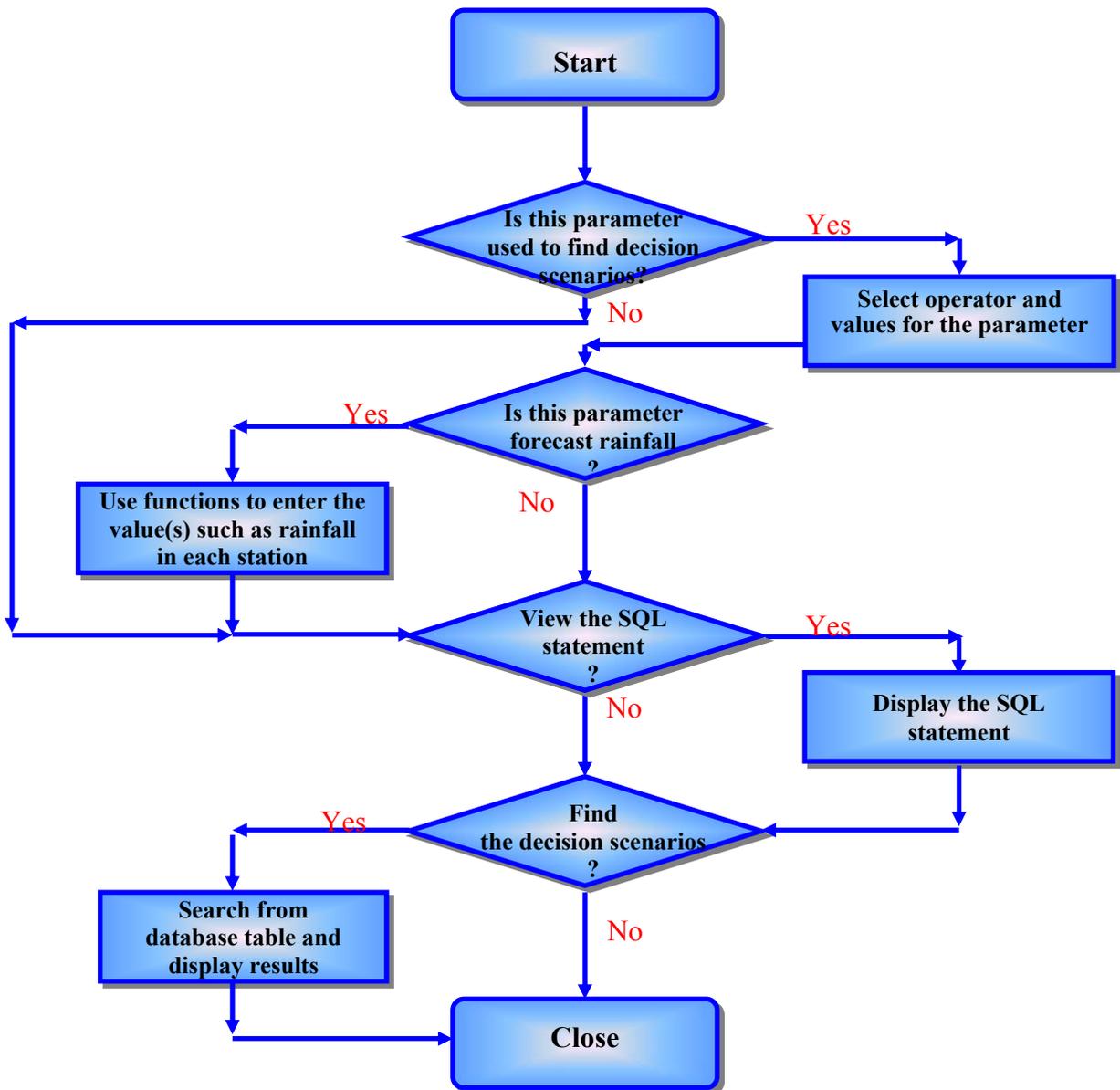


Figure 4.16 Conceptual Design Decision Support subsystem

The Visual Basic software was used as the principle application language to develop the Interface subsystem of DSSFCMR. Only the design of the Main Menu is presented in this section, while the designs of the interfaces directly related to other subsystems were previously described in each subsystem.

The DSSFCMR interface consists of three parts: start page, Main Menu and end page. The Main Menu is the core part of the interface and the most functions in DSSFCMR originate

from this menu. The Main Menu was designed to have six submenus: File, Map, Database, Run Model, Decision, and Help. The submenus may have further submenus that trigger (further) windows forms or functions. However, these forms are displayed over the Catchment Image, which allows the user to perform operations related to the gauging stations in the catchment. The submenu forms (or functions) are acted in sequence, which means a new form is opened only when the preceding form was closed. This process is continued from the start form to the end form of each submenu of the Main menu. This design allows the user to safely use the DSSFCMR. Figure 4.17 shows the designed structure of the Main Menu. The details of the Main Menu items are given in Table 4.6.

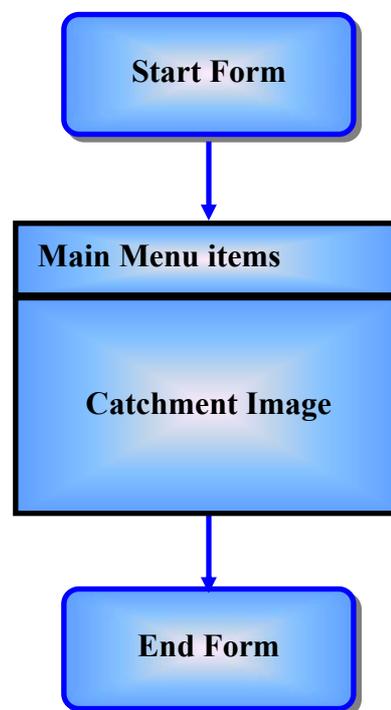


Figure 4.17 Main Menu of DSSFCMR

#### 4.8 Decision Making in Real-Time Flood Forecasting and Warning

Figure 4.18 shows the decision making process in real-time flood forecasting and warning. To illustrate how the DSSFCMR will assist in decision making for flood warning, consider a flood event that occurs between time  $t_s$  and  $t_e$ , where  $t_s < t_e$ . It is assumed that flood forecasting and warning is required at the current time  $t_l$  (i.e.  $t_s < t_l < t_e$ ), of the current flood event. It is also considered that it is required to calibrate the hydrological and hydraulic models before using them for flood forecasting.

Table 4.6 Details of Main Menu Items

Main Menu Items	Submenus of Main Menu Items	Submenus	Description
<b>File:</b>	<b>Undo:</b>  <b>Exit:</b>		<p>To make all submenus on main menu available, when some submenus are disabled with an active submenu.</p> <p>To close DSSFCMR.</p>
<b>Map:</b>	<b>Catchment Map:</b>  <b>Lower Township Map:</b>  <b>Flood Line in L-Town:</b>		<p>To display the catchment map (with the main river and tributaries).</p> <p>To display the flood prone area with attributes such as rivers, streets and roads.</p> <p>To display the flood line of the peak discharge of 1974 flood event on the lower township map (or the flood prone area). This flood was of particular interest to Melbourne Water Corporation.</p>
<b>Database:</b>	<b>Model Parameters:</b>    <b>Historical Flood Events:</b>  <b>Real-Time Flood Event:</b>  <b>Simulated Flood Scenarios:</b>   <b>Real-Time Flood Warning</b>	<b>URBS Model:</b>  <b>HEC-RAS Model:</b>      <b>Forecast or Calibration URBS only</b>  <b>Calibration HEC-RAS only</b>	<p>To manage URBS model parameters (e.g. enter/delete data) in model parameter database.</p> <p>To manage HEC-RAS model parameters (e.g. enter/delete data) in model parameter database.</p> <p>To manage data of historical flood events (e.g. enter, find, update, delete and display data in tabular and graphical forms).</p> <p>To manage data of the current flood event, which is being under investigation for flood forecasting and warning (the functions are similar those for historical flood events).</p> <p>To manage forecast floods using both URBS and HEC-RAS model results (with their relevant parameters) or those from URBS model calibration.</p> <p>To view the calibration results of the HEC-RAS model.</p> <p>To manage the flood warning decisions made at different time steps during current flood event or past flood events, which have been stored in this database.</p>
<b>Run-Models:</b>			

	<b>Calibration</b>	<b>URBS</b>	To run scenarios for calibration of the URBS hydrological model.
		<b>HEC-RAS</b>	To run scenarios for calibration of the HEC-RAS hydraulic model.
	<b>Forecasting</b>		To calculate the forecast flood hydrographs and flood water levels corresponding to the peak discharges of these flood hydrographs.
<b>Decision</b>			To choose a smaller number of alternative flood forecasting decision scenarios from many scenarios, to build acceptable decisions.
<b>Help</b>			To display help information.

First, the observed rainfall and runoff data for the current flood event up to time  $t_1$  are required to be stored in the database D4RFE.MDB or D3HFE.MDB. The model parameters of the URBS hydrological model (i.e.  $\alpha$ ,  $m$ , *Initial Loss*, *Continuing Loss* and *Baseflow*) and the subcatchment data of the specific catchment (Maribyrnong catchment in this case), which are usually hardwired, are stored in the database D2\_U\_C.MDB. When the user activates the Modelbase, the Windows interface in this part of the DSSFCMR allows the user to edit the model parameters and the run-time parameters required for calibration, and then to run the URBS hydrological model. The user may perform many calibration runs by changing the model parameters. All these calibration results with their associated model parameters can be stored in database D5SFS.MDB. They can be viewed at any time during calibration to select the best model parameter set for use in flood forecasting, comparing the calculated and observed hydrographs through the Windows interface associated with the Database subsystem (DBMS). Finally, the best parameter set is stored in database D2\_U\_C.MDB for forecasting of flood hydrographs. A similar procedure is used for the HEC-RAS model calibration.

It is not necessary to calibrate the hydrologic model and the hydraulic model each time when the user wants to use these models for flood forecasting. However, it is necessary to have a set of calibrated model parameters and the database D4RHE.MDB updated to the current time, before forecasting.

Three different forecast rainfalls namely, no-forecast rainfall, 1-hour forecast rainfall and 3-hour forecast rainfall, can be considered in DSSFCMR. These rainfall forecasts are from the current time  $t_1$ . Different rainfall depths can be considered, which produce many different forecast rainfall scenarios. It should be noted that the forecast rainfall needs to be estimated

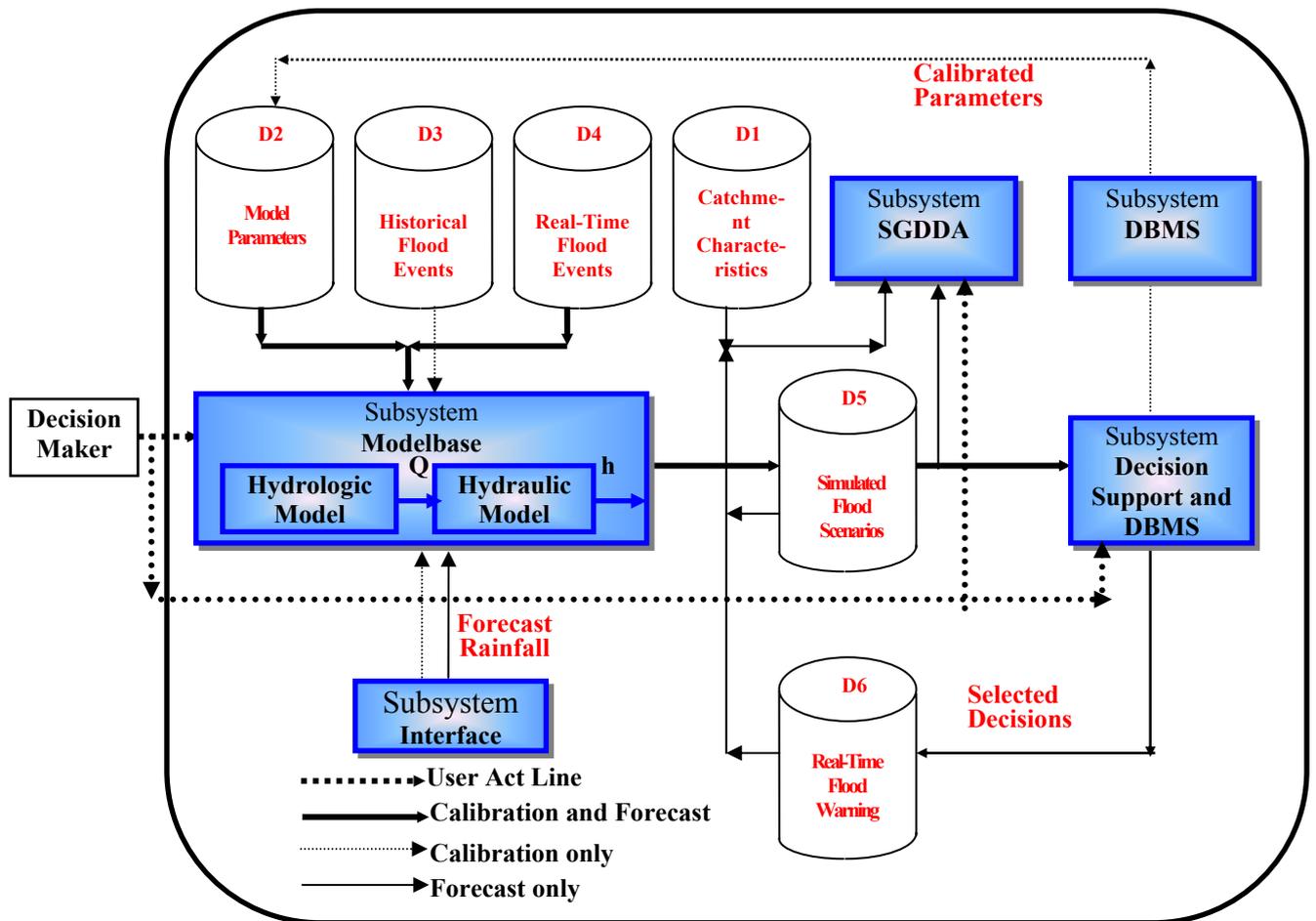


Figure 4.18 Process of Decision Making with Real-Time Flood Forecasting

outside DSSFCMR and entered as input into DSSFCMR through its Windows interface. Once the model parameters and forecast rainfall depths are entered for a scenario, the URBS model is run to produce the forecast hydrograph. One forecast scenario is considered at a time. Data entering and running of URBS for each forecast scenario are done through the Windows interface, which is similar to calibration, except that the forecast rainfall is entered for forecasting (which is not required for calibration). The peak discharge of the hydrograph at the catchment outlet and the time at which the peak discharge occurs from the current time, and the relevant model parameters are stored in database D5SFS.MDB. This peak discharge at the catchment outlet is also written to a data file, which is used as input to the HEC-RAS hydraulic model. This peak discharge is then used in HEC-RAS to produce the water levels at each cross section of the flood prone area.

Many forecast scenarios can be considered and these scenario details (including the results in terms of model parameters and corresponding water levels) are stored in database

D5SFS.MDB for the current flood, which is being considered for flood forecasting and warning. The information in D5SFS.MDB is then used by the Decision Support Subsystem to select a smaller number of alternative decision scenarios, (which include peak discharge, maximum flood levels at critical points and the time at which peak discharge occurs from the current time) to build acceptable decisions at time  $t_1$ . The selected decisions and the corresponding information including the observed rainfall and runoff, and forecast rainfall are stored in database D6RFE.MDB, which can be retrieved for later decision making.

The SGDDA subsystem can help the decision maker to investigate the flooded area and corresponding damage for each flood forecasting scenario that are stored in databases D5SFS.MDB and D6RFW.MDB. All flood forecasting scenarios can be spatially displayed and analysed with spatial and graphic data display and analysis methods developed within DSSFCMR, which allow the decision maker to make the effective decisions.

This procedure of calibration (optional) and forecasting (together with spatial analysis of results) is repeated for each time step until further flood forecasting is not required.

#### **4.9 Summary**

The conceptual design of DSSFCMR was detailed in this chapter. The Maribyrnong river catchment, and its physical attributes related to the URBS hydrological model and the HEC-RAS hydraulic model were presented first to help understand the design of relevant subsystems. The system structure of the DSSFCMR and the conceptual designs of all subsystems were then introduced with details.

The principles of the database design were discussed followed by the details of the design of the general database functions such as data entry, data delete, data update and data query. Some characteristics in DSS application such as the use of acquired knowledge and knowledge learning are included through model parameters in the Modelbase subsystem. The methodology of using model parameter values to realize the acquired knowledge and to build the new knowledge in DSSFCMR was illustrated. The details of the design of calibration of both the URBS hydrological model and the HEC-RAS hydraulic model (both in the Modelbase subsystem) were then presented.

The procedure of GIS data process related to the SGDDA subsystem development and application was discussed, showing the principles of SGDDA design and methodology used

for SGDDA development. Provision of decision support in DSSFCMR was detailed in the Decision Support subsystem. The design of the Interface subsystem and its contents were then described. Finally, a detailed data flow and action diagram was presented to show the use of DSSFCMR to support decision making in flood forecasting and warning.

In previous similar research work, the detailed conceptual system design of the Decision Support Systems (DSSs) was often not presented, however, in this chapter, the conceptual system designs for all subsystems and major functions are described in detail. The general concepts presented here can be used for DSS studies in water resources and other fields, and in particular for flood forecasting and warning DSSs of any catchment.

# CHAPTER 5

## DSSFCMR SYSTEM DEVELOPMENT

The system development of DSSFCMR is described in this chapter, focusing on the development and the testing of each subsystem. The development of the Interface subsystems deals with the interface of Main Menu and its functions. The developments of Database, Modelbase and Decision Support subsystems are focused on interface, functions, and error handling and safety systems. The development of the spatial and graphical data display and analysis (SGDDA) subsystem is focused on the integration technology, the GIS technology and spatial analysis, and the generation of shapefiles instantly to display the flood inundated area. The SGDDA subsystem is a significant development in this thesis.

Section 5.1 describes the development of the Main Menu (i.e. the core part of Interface subsystem). Section 5.2 presents the development of Database and SGDDA subsystems together, as they are closely related and the SGDDA subsystem uses the data stored in the Database subsystem. Sections 5.3 and 5.4 describe the development of the Modelbase and the Decision Support subsystems respectively. DSSFCMR system installation and requirements are presented in Section 5.5. Finally, Section 5.6 summarizes the chapter.

It should be noted that throughout this chapter, the menu items are shown in Bold characters, while the interface controls or parameter items are shown by Italic letters. The basics of the system development such as the use of combo boxes, text boxes etc. are not described in this chapter.

### 5.1 Main Menu of DSSFCMR

The Main Menu is a core part of the Interface subsystem of DSSFCMR. The function of the Interface subsystem is to facilitate the interaction of subsystems with each other and to assist decision support for potential flood warning in DSSFCMR. The DSSFCMR starts with an animated interface (Figure 5.1), and then shows the Main Menu (Figure 5.2). The user can exit DSSFCMR through the end form (Figure 5.3) activated through the **Exit** item of **File** menu in Figure 5.2. The Main Menu can facilitate exiting the system, map view, database management,

flood simulation using URBS and HEC-RAS software tools, developing flood forecasting and warning scenarios and decisions, spatial display and analysis of simulated flood scenarios, and user help.

The related submenus in the Main Menu are based on the conceptual design described in Chapter 4 and are displayed on Figure 5.2 for easy identification. The functions of the items of these submenus are described in detail in Section 4.7.



Figure 5.1 Welcome Screen of DSSFCMR

## 5.2 Database and SGDDA Subsystems

In this section, Database and SGDDA subsystems are described together, since SGDDA uses the data from the Database subsystem. The **Database** subsystem was developed to perform the database management and (in conjunction with SGDDA subsystem) to display flood images and/or to perform spatial analysis of flood water levels of simulated flood scenarios that are stored in the database. The functions were introduced through the following chain (Figure 5.2):

- Model Parameters.
- Historical Flood Events.

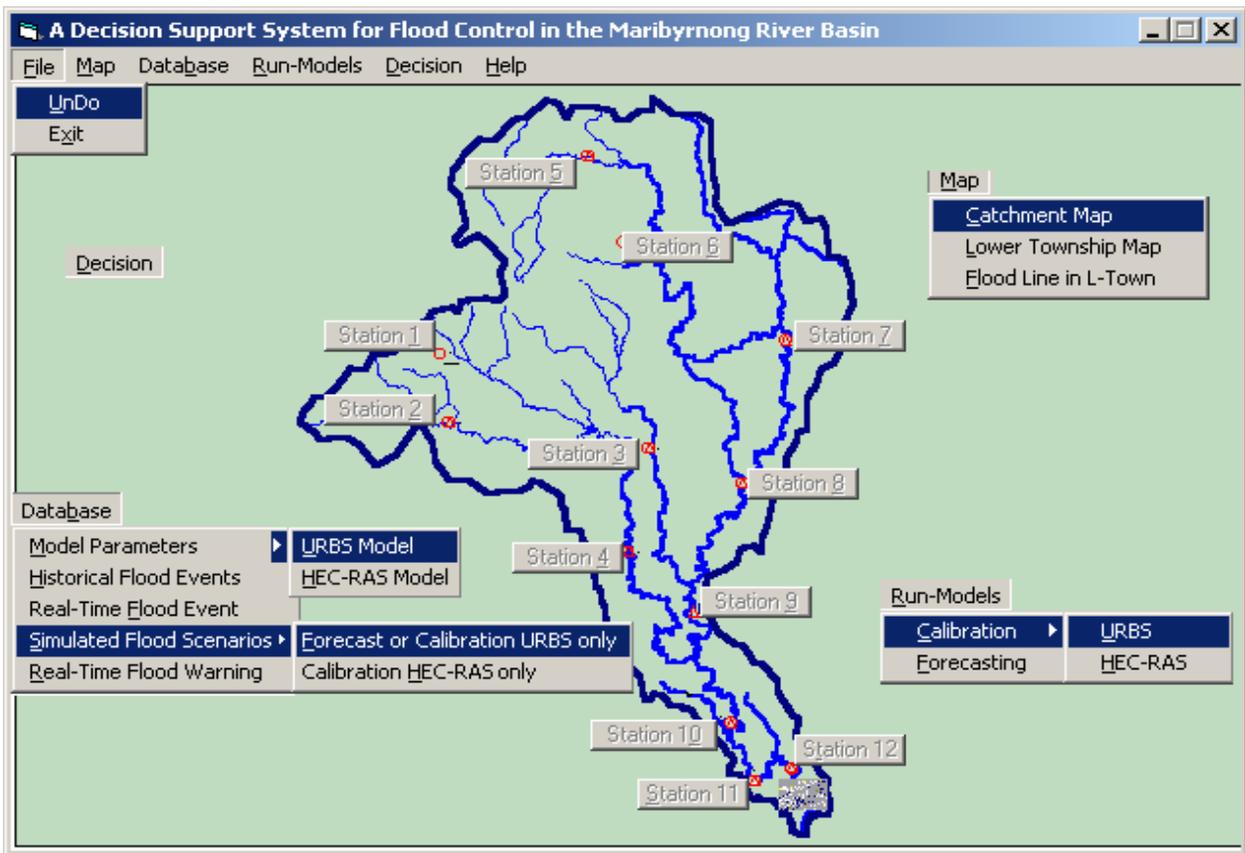


Figure 5.2 Interface of Main Menu in DSSFCMR



Figure 5.3 End Interface of DSSFCMR

- Real-Time Flood Event.
- Simulated Flood Scenarios.
- Real-Time Flood Warning.

Six MS ACCESS databases, namely *D1CC.MDB*, *D2\_U\_C.MDB*, *D3HFE.MDB*, *D4RFE.MDB*, *D5SFS.MDB* and *D6RFW.MDB*, were developed. These databases are stored in the subdirectory of *database* in the root directory (i.e. C:\DSSFCMR). The database *D1CC.MDB* was developed to describe the catchment physical characteristics. In this database, most of such catchment characteristics were defined using the GIS format, but the river cross section data of the flood prone area of the lower part of catchment / river are described both in GIS format and MS ACCESS database format. As stated in Section 4.1, the cross section data were supplied by Melbourne Water Corporation. These data without any modifications were used in this application. The conceptional designs of various databases were described in Section 4.3, while the development of these databases are described in Section 5.2.1 to 5.2.6.

### 5.2.1 Model Parameters

**Model Parameters** on Figure 5.2 was developed to deal with the model parameters stored in database *D2\_U\_C.MDB*. These model parameters are the URBS hydrological model parameters and the HEC-RAS hydraulic model parameters. Implementation of system development in model parameters is discussed using

- Physical database table development: what kinds of database tables are created and their purposes?
- Functions including the interface development: what kinds of functions are developed to manage the data in database of model parameters, and the relevant interface?
- Error handling and system safety: how to deal with errors and minimize the system crash?
- Testing and performance: how to test and assess the developed functions?

#### 5.2.1.1 Physical Database Table Development

The physical database tables describing the URBS model parameters of alpha, m, initial loss, continuing loss, base flow, pluviometer locations, rating curve locations, and gauging stations are

stored in the database tables of *urbs\_a*, *urbs\_m*, *urbs\_il*, *urbs\_cl*, *urbs\_b*, *urbs\_pl*, *urbs\_rl* and *urbs\_g* respectively in the database of *D2\_U\_C.MDB*. These parameters are related to the whole Maribyrnong catchment. However, several sets of URBS model parameters are stored in the above database tables. The relationship between storage volume and outflow discharge at Rosslynn reservoir is stored in a table called *rosslynn*. The details of the Maribyrnong catchment and its subcatchments were described in Section 4.1.

The HEC-RAS model parameters are also stored in the model parameter database of *D2\_U\_C.MDB*. These parameters are the contraction coefficient, the expansion coefficient, and the Manning roughness coefficients in three parts of the river cross sections (i.e. left bank, channel and right bank) of each river cross section in the flood prone area of the lower part of the catchment/river. These parameters can vary from one cross section to another. Several sets of these HEC-RAS model parameters are stored in these database tables. These parameter sets are stored in the tables *hec\_cont*, *hec\_exp*, *hec\_nl*, *hec\_nc* and *hec\_nr* respectively. In addition, the table *hec\_pars* has values of all above parameters at each cross section, which were calibrated during the last calibration run of DSSFCMR. They are considered to be the default parameters.

The database windows, (which are described in Section 5.2.1.2), are designed to modify the database tables of model parameters. However, the experienced user can also directly modify the database tables of model parameters, without going through model parameters database windows.

### **5.2.1.2 Functions and Interface Development**

#### **(a) Interface for URBS Model Parameters**

The Interface shown in Figure 5.4 is displayed when clicked on the item of **Model Parameters** in Figure 5.2, and then **URBS Model**. Three components exist in Figure 5.4. The first component contains command buttons. The second component allows the user to edit the model parameters of the URBS model. The third component is only for display, and allows the user to view the catchment data. These are referred to as *command buttons*, *editing parameters* and *display only parameters* in later discussion. All parameters in Figure 5.4 are described in detail in the URBS User Manual (Carroll, 1995).

## Command buttons

The *command button* frame shown in Figure 5.4 is also used for all databases of Model Parameters, Historical Flood Events, Real-Time Flood Event, Simulated Flood Scenarios and Real-Time Flood Warning (Figure 5.2). In some cases, certain command buttons are not relevant, which are made disabled. For example, in Figure 5.4, buttons of **N**ew, **Q**uery, **U**ppdate and **V**iew are disabled.

The screenshot shows the 'DBMS Main Menu---D2: URBS Model Parameters' window. The 'DataBase Management' toolbar includes buttons for New, Add, Delete, Query, Update, View, Undo, OK, Cancel, and Help. The 'New', 'Query', 'Update', and 'View' buttons are disabled. The main area contains several parameter groups with dropdown menus and checkboxes. The 'Display Only' section contains a table of subcatchment data.

Display Only			
Total Subcatchments	18	Area (km <sup>2</sup> )	114.4
Subcatchment No	1	U (Urbanisation)	0
L (Reach Length )(km)	11.7	Reach Length Factor	0.5
Confluence at the Outlet of Subcatchment	No	F (Forest)	0
DownCatchingment	2	Output Q	NO
Route L		VBF	
Route U		Res. s <sup>q</sup> File Name	
Route F		Route Factor	
Total Pluviometers	5	Location	Bulla
Total Rating Curves	0	Location	''
Total Gauging Stations	3	Location	bull
			Covered Subcatchment by Pluviometers
			11
			12
			17
			18

Figure 5.4 Screen of URBS Model Parameters in Database Menu

- The buttons of **A**dd and **D**elate in Figure 5.4 can be used to add and delete the value of the *editing parameters* group. For example, the user enters 22 into the text box of *Initial Loss* (Figure 5.5), and then clicks on the button of **A**dd. The value of 22 is then added into the list of *Initial Loss*. Similarly, if the user selects 22 or enters 22 into the text box of *Initial Loss*, and clicks on the button **D**elate, then the value 22 will be deleted from the list of *Initial Loss*.

- The button **U**ndo in Figure 5.4 makes both **A**dd/**D**elete buttons enable if one of them is active and the other is disabled.

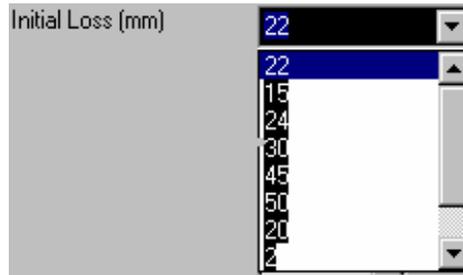


Figure 5.5 Example Screen of Adding or Deleting a Model Parameter Value

- The button **O**K in Figure 5.4 closes the current interface (Figure 5.4) and return to the Main Menu (Figure 5.2). This action also saves the (changed) data set of *editing parameters* in the database files.
- The button **C**ancel in Figure 5.4 also closes the current interface (Figure 5.4) and return to the Main Menu. This action does not save the (changed) information of *editing parameters* in database files.
- The button **S**ELECT in Figure 5.4 displays the name of the selected button for Database Management. For example, when the **A**dd button is active, the name of ADD is displayed on the **S**ELECT button.
- The button **H**elp in Figure 5.4 provides detailed help information.

### **Editing parameters**

Some items in the *editing parameters* group are self-explanatory. A brief definition of the other parameters is given below. However, the reader is referred to the URBS User Manual (Carroll, 1995) for detailed information on the parameters in Figure 5.4.

<i>Alpha</i>	=	storage lag parameter
<i>m</i>	=	catchment non-linearity parameter
<i>Compute IL</i>	=	a check-box to compute the initial loss

The parameters *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* can be edited, which means the user can add and delete values. The check-box *Compute IL* is an alternative method to

calculate the *Initial Loss* from the parameter of *7-day mean daily Q* (Flow). The *7-day mean daily Q* is the average daily flow over the 7 days prior to the storm. This method has been used for the Maribyrnong River in the past (Crapper, 1989). The built-in calculation procedure for this option is as follows. The user selects the check-box of *Compute IL*, then enters a value in the text box of *7-day Mean daily Q* (or selects a value from it) and finally moves the cursor to *Initial Loss* text box. This sequence of operations computes the initial loss and displays it in the text box of *Initial Loss*.

### **Display only parameters**

The *display only parameters* are dependent on the catchment and its subcatchments that are used in URBS. As outlined in Section 4.1.2, a total of 18 subcatchments has been used to model the Maribyrnong catchment in a previous study (Perera and Shipton 2005). These subcatchments and corresponding data were used in this research project. These data (related to subcatchments) do not change from flood event to event. They were already stored in the database table in the database *D2\_U\_C.MDB*. These data can only be viewed. Several *display only parameters* were described in Section 4.1.2 and the others are briefly described below.

Total Subcatchments	=	Total number of subcatchments in the catchment.
Subcatchment No	=	Identification number of subcatchment.
Reach Length Factor	=	A parameter, which modifies the reach length due to slope of the reach. Its value is from 0 (steepest) to 1 (normal).
Confluence at the Outlet of Subcatchment	=	Is the outlet of the current subcatchment a confluence with other subcatchments (Yes/No?).
UpCatchment	=	Identification number of the subcatchment upstream of the current subcatchment along the main stream.
DownCatchment	=	Identification number of the subcatchment downstream of the current subcatchment along the main stream.
Output Q	=	Is the hydrograph at the outlet of the current

subcatchment needed?

Most parameters in this group are related to the index parameter: *Subcatchment No.* If the user wishes to view the parameters for a particular subcatchment, then the user selects the subcatchment number from the list of *Subcatchment No.*, as shown in Figure 5.6. This will display the *display only parameters* relevant to the selected catchment.

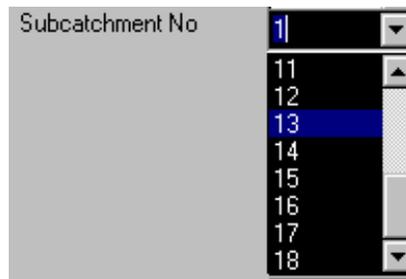


Figure 5.6 Example Screen of Selecting a Subcatchment

The explanation of displayed parameters below the dotted lines in Figure 5.4 are given below. These parameters do not have any relationship to the selected subcatchment. The displayed parameters of *Total Pluviometers*, *Total Rating Curves* and *Total Gauging Stations* cannot be changed in the Interface, since they are fixed for the Maribyrnong River. In this case, there are 5 pluviometers, 0 rating curves and 3 streamflow gauging stations. The combo boxes of *Location* display the pluviometer locations, rating curve locations and streamflow gauging station locations respectively. Since *Total Rating Curves* is 0, no rating curve locations are shown in Figure 5.4. The *Covered Subcatchment by Pluviometers* shows the subcatchments (shown with their identification numbers) covered by the selected pluviometer in the text box of location next to the pluviometers. For example, when Romsey is selected, the *Covered Subcatchment by Pluviometers* shows that the subcatchments 1, 2 and 3 are covered by the pluviometer at Romsey.

The developer or an experienced user can change data stored in *D2\_U\_C.MDB* to modify these displayed only parameters.

**(b) Interface for HEC-RAS Model Parameters Database**

- The Interface shown in Figure 5.7 is displayed when clicked on the item **Model Parameters** in Figure 5.2 and then on **HEC-RAS Model**. This interface was developed as

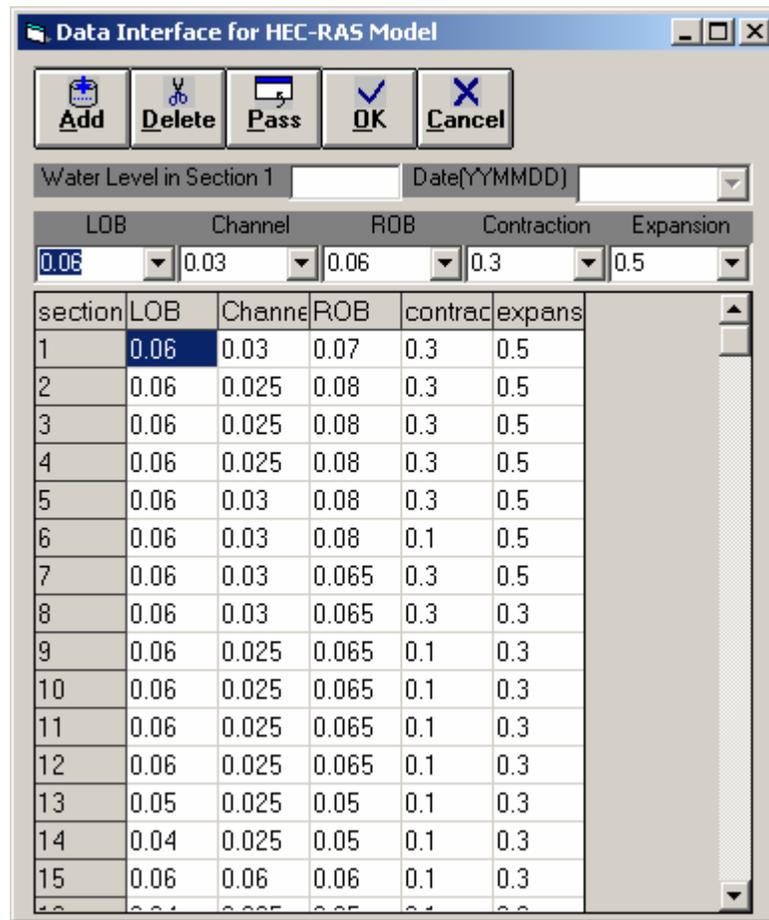


Figure 5.7 Screen of HEC-RAS Model Parameters in Database Menu

three functional areas. The command buttons are in the top part, the combo boxes for interactive selection of editable parameters are in the middle part, and the selected values of each editable parameter at each cross section are located in the bottom section of the interface. These are referred to as *command buttons*, *editing parameters (LOB, Channel, ROB, Contraction and Expansion)* and *selected data set* groups in later discussion. Figure 5.7 has HEC-RAS model parameters (Manning’s roughness coefficients of left bank, channel and right bank, and expansion and contraction coefficients) at each cross section of the flood prone area from the previous HEC-RAS run within DSSFMR, irrespective of calibration or forecast. The user can use this interface (Figure 5.7) to manage HEC-RAS model parameters stored in *D2\_U\_C.MDB* by inserting, deleting and updating data. However, it is recommended that only the experienced

users of the HEC-RAS hydraulic model should modify the data set related to cross sections in *selected data set* groups. This is because if these parameters are changed and **OK** is clicked, these parameters will be the default parameters for the next HEC-RAS run within DSSFCMR. Nevertheless, the user can modify these parameters during the calibration stage (using the calibrated results), which will automatically save these parameters in the database.

### **Command buttons**

- The buttons **A**dd and **D**elete in Figure 5.7 were developed to add or delete possible values of *editing parameters*. The working procedures of both buttons are similar to those in Figure 5.4.
- The button **P**ass in Figure 5.7 replaces the value of the selected parameter in a selected cross section with the current value in the combo box of the selected parameter. For example, click on the cell of *LOB* in section 1, then select 0.06 from the combo box of *LOB*, and finally click on the button of **P**ass. The *LOB* value in section 1 will then be changed to 0.06.
- The buttons **O**K stores the (changed) values of *editable parameters* and the parameter data set in each cross section into the corresponding database table in database *D2\_U\_C.MDB* and closes the interface.
- The button **C**ancel closes this interface without modifying the parameter values in the database.

### **Editing parameters**

This interface (Figure 5.7) is also used for the HEC-RAS model calibration. The details of the HEC-RAS model calibration are described in Section 5.3.1.2. During the database management phase, the text box of *Water Level in Secion1* and Combo Box of *Date[YYMMDD]* are not relevant and therefore they are disabled, but they will be active during the calibration phase. The definitions of the *editing parameters* are given below.

<i>LOB</i>	=	value of the Manning's roughness coefficient of left bank
<i>Channel</i>	=	value of the Manning's roughness coefficient of main channel
<i>ROB</i>	=	value of the Manning's roughness coefficient of right bank

<i>Contraction</i>	=	value of the contraction coefficient
<i>Expansion</i>	=	value of the expansion coefficient

### **Selected data set**

The selected data set is the selected values of each editable parameter at each cross section. These values are used as default values in geometric data file in the HEC-RAS model.

#### **5.2.1.3 Error Handling and Safety Systems**

Three cases were considered to deal with the error handling in Model Parameters of the Database subsystem to manage different types of errors or conflicts.

The first case was considered for expected errors. An example of an expected error is, when the user enters a value of 100, which does not exist in the list, and then try to delete it by clicking the **Delete** button. For these expected errors, an error warning Window similar to Figure 5.8 will be shown, which will not abort DSSFCMR. The user can close the error Window, and then correct the action. This type of error handling was developed for the following actions. Note that these are examples only.

- Deleting data that do not exist in the list.
- Duplicate data entry.
- Reading/deleting from an empty database through list boxes (e.g. no values in the list box).
- Edit values of *display only parameters*.
- Database table too big to be stored in combo box.
- Data such as total number of pluviometers are not consistent with pluviometers used (i.e. data are not given for all listed pluviometers).
- No parameters selected for action such as none in *editing parameters* is selected to delete its value.

The second case was considered for the unexpected errors, when an unexpected error is detected. In this case, further operations will be stopped and an error Window is displayed. For example, the database *D2\_U\_C.MDB* is accidentally deleted manually through normal Windows

operations. When DSSFCMR starts to deal with the model parameters database, the progress is stopped, and the system goes back to the previous menu, (which is the Main Menu for this example), and the error information Window is displayed (Figure 5.9). Similar to the first case of error handling, DSSFCMR will not be aborted. The error Window also gives information on how to rectify the problem.



Figure 5.8 An Expected Error Warning Window



Figure 5.9 An Unexpected Error Warning Window

The third case was considered for system safety and correct operation. Two approaches were developed for this case, as follows.

- The first approach was to set the other command buttons with conflicting functions as inactive (or unavailable) to the one currently being used, which is also displayed on the **Select** button.
- The second approach was used when adding value(s) into the list boxes or deleting value(s) from the list boxes. Two steps were used in this case. In the first step, the data are added to the list box or deleted from the list box, and in the second step, the use of **OK** button modifies the database and closes the window, while **Cancel** button closes the window without modifying the database. The advantage of such development is to keep the database safe.

#### 5.2.1.4 System Status

The system status of the current subsystem shows the user the operations he/she is performing currently, and what operations can be performed being in this subsystem. The system studies can be monitored in two ways:

- The first way is from the appearance of the buttons. For example, only the function buttons **ADD** and **Delete** in **Database Management** in Figure 5.4 are currently available for Model Parameters database, while the supporting buttons (**Select**, **Help** and **Undo**) in Figure 5.4 are also accessible for all 5 databases of *D2\_U\_C.MDB*, *D3HFE.MDB*, *D4RFE.MDB*, *D5SFS.MDB* and *D6RFW.MDB*.
- The second way is that the active function button (i.e. **ADD** or **Delete** in Figure 5.4) is displayed on the **Select** button in Figure 5.4, while the button with conflicting function is disabled. The **Undo** button in Figure 5.4 can reset all function buttons (i.e. buttons **ADD** and **Delete** in Figure 5.4) available for use.

#### 5.2.1.5 Testing

System testing is carried out to test the satisfactory performance of the designed functions, error handling and safety systems for their performance. Three types of testings considered are illustrated below:

- Object Testing: Some examples are given below:
  - Is the object enabled (eg. can the user edit the text in a text box)?
  - Is the object correct for its function (eg. Does the **Add** button perform the add function and not the delete function)?
  - Does the editable parameter value go to the correct place in the list box and database table? (eg. Is the added *m* value stored in the combo box *m* in the interface?)
  - Does the ticked check-box of *Compute IL* lead to the calculation of initial loss?
- Value Testing: Some examples are given below:
  - Does the parameter value correctly enter into the list box, and then into the database?
  - If the same parameter value is entered again, is the second value rejected from the list box, and the database?

- Does the parameter value correctly delete from the list box, and then from the database?
- Is the calculated initial loss correct?
- Response Testing: Some examples are given below:
  - Is a warning message given when deleting the data?
  - Is a proper error message given and the computational process stopped without aborting the system when an expected error occurs, or an unexpected error is captured?

Other than those examples given above, there were many testings that were conducted during the development of Model Parameters database. Similar testings were done for the development of other databases and other subsystems. Since they are similar, they are not described again under the other database and subsystem developments.

## 5.2.2 Historical Flood Events

The Historical Flood Events submenu shown in Figure 5.2 was developed to deal with stored historical flood records of water level, flow, precipitation and evaporation at gauging stations and the flood inundation area of the flood prone area of the lower catchment/river. The system implementation and relevant functions related to Historical Flood Events are discussed below.

### 5.2.2.1 Physical Database Table Development

As discussed in Section 4.1, the Maribyrnong catchment has 10 gauging stations measuring both streamflow and rainfall, and 2 other rainfall gauging stations. All these gauging stations were used in the initial development of DSSFCMR. However, only rainfall data at 5 stations and flow data at 3 stations in the flood event of 14 October 1983 were available for the case study. Nevertheless, as explained in Section 4.1.1, only rainfall data at gauging stations and flow data at Keilor were used for the case study application described in Chapter 6. Section 4.1.1 also described the scheme that was devised to use the DSSFCMR with any number of gauging stations in the catchment, without modifying the DSSFCMR computer programming.

Data on historical flood events (i.e. flow, water level/stage, rainfall and evaporation) are stored in one database file (i.e. *D3HFE.MDB*). These historical data are stored based on the gauging station. Each station has its own database table, which means there are 12 tables for 12 stations.

This information is used for the calibration of the URBS hydrological model. An additional database table was developed to store peak discharges of the historical floods and the corresponding water level data at each river cross section of the flood prone area of the lower section of the catchment/river, and this table is used for calibration of the HEC-RAS model only.

This database is able to store the above information on many historical flood events.

### 5.2.2.2 Functions and Interface Development

When clicked on the menu item of **H**istorical Flood Events in Figure 5.2, the interface shown in Figure 5.10 is displayed. As outlined in Section 5.2.2.1, it is possible to store many historical flood events, which are stored in one database file. The user can access these flood events using **Q**uery and **V**iew buttons. The control buttons on the screen (Figure 5.10) perform the following functions.

#### (a) Button **N**ew

The button **N**ew is developed to enter one or more records into the database table of a gauging station either through a DOS-based data file or a table from the Windows environment. First, the user must click on one of the gauging station buttons (e.g. **S**tation **1**) to select which station the user wants to add the new data in. The default station is **S**tation **1**. The interface (Figure 5.11) is displayed to select the input data type.

- The choice of **Y**es in Figure 5.11 displays the interface shown in Figure 5.12, which allows the user to confirm the deletion of all records that exist in the selected database table (i.e. table for Station 1).
  - **Y**es on Figure 5.12 lets the user to delete all records in the current database table. Figure 5.13 is then displayed. The user then moves cursor to the place to add (or update in case of correcting an error of the new record) the records to the table.
  - **N**o on Figure 5.12 allows the user to retain all records that exist in the current database table, which displays the interface of Figure 5.14. The user then moves the cursor to the end of the records in the table in Figure 5.14, which shows the blank record that can be

used to enter the new record. If it is necessary to correct the previous entries (or update) of other records, it can also be done at this stage.

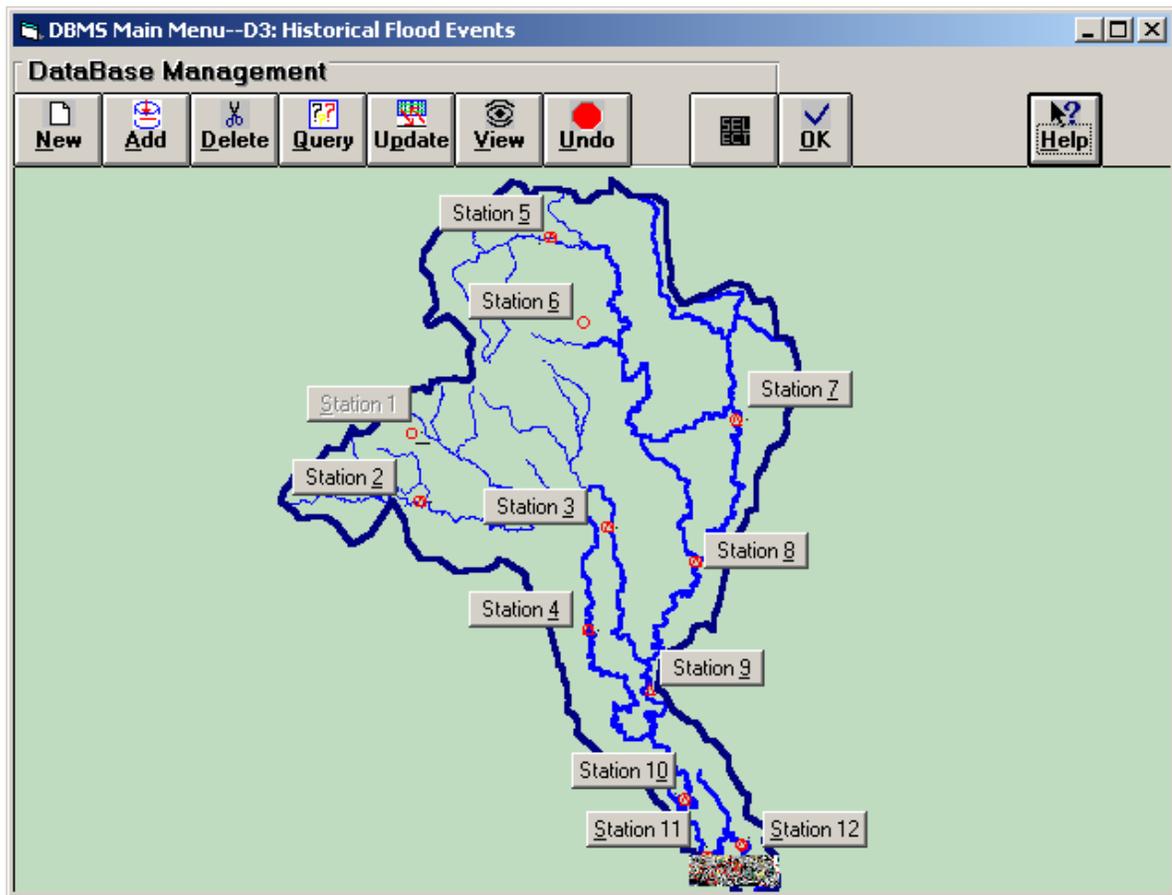


Figure 5.10 Historical Flood Events Window



Figure 5.11 Input Confirmation Screen for Historical Flood Events Data Adding



Figure 5.12 Screen to Confirm Deleting All Records in Database Table

	SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow	Pre
*										

Figure 5.13 Table for Directly Entering Data After Deleting All Records

	SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow
	2	0	0	20	14	10	1983	0	0
	3	0	0	21	14	10	1983	0	0
	4	0	0	22	14	10	1983	7.8	7.8
	5	0	0	23	14	10	1983	1.2	1.2
	6	0	0	0	15	10	1983	1	1
	7	0	0	1	15	10	1983	0.8	0.8
	8	0	0	2	15	10	1983	0.2	0.2
	9	0	0	3	15	10	1983	0.6	0.6
	10	0	0	4	15	10	1983	0	0
	11	0	0	5	15	10	1983	1.4	1.4
	12	0	0	6	15	10	1983	1.8	1.8
	13	0	0	7	15	10	1983	4.6	4.6
	14	0	0	8	15	10	1983	4.4	4.4
	15	0	0	9	15	10	1983	2.6	2.6

Figure 5.14 Table for Directly Entering Data after Keeping All Records in Database Table

- The choice of **N**o button in Figure 5.11 brings the user to the interface shown in Figure 5.15 for entering data from a data file. However, the text box for entering the full path and data name file is blank. The user can enter the name file in this text box with its full path. Alternatively, a double click on this blank text box or the use of the **B**rowse button will display a standard Windows screen (Figure 5.16) for browsing the data file. The required data file format is presented in the upper text box of Figure 5.15.

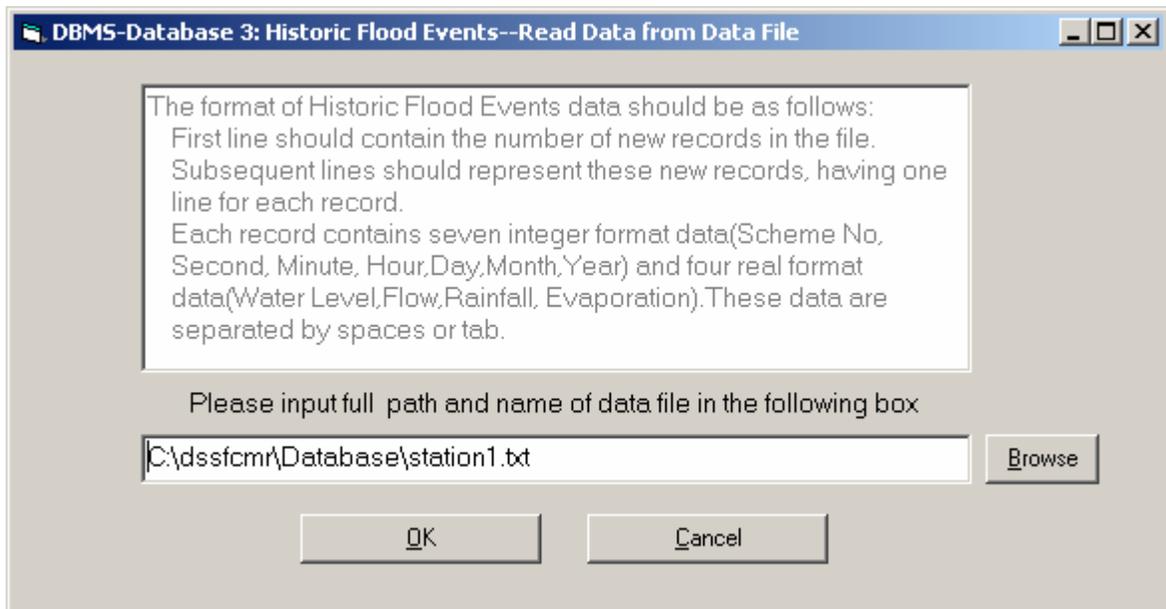


Figure 5.15 Screen for Entering the Data from Data File

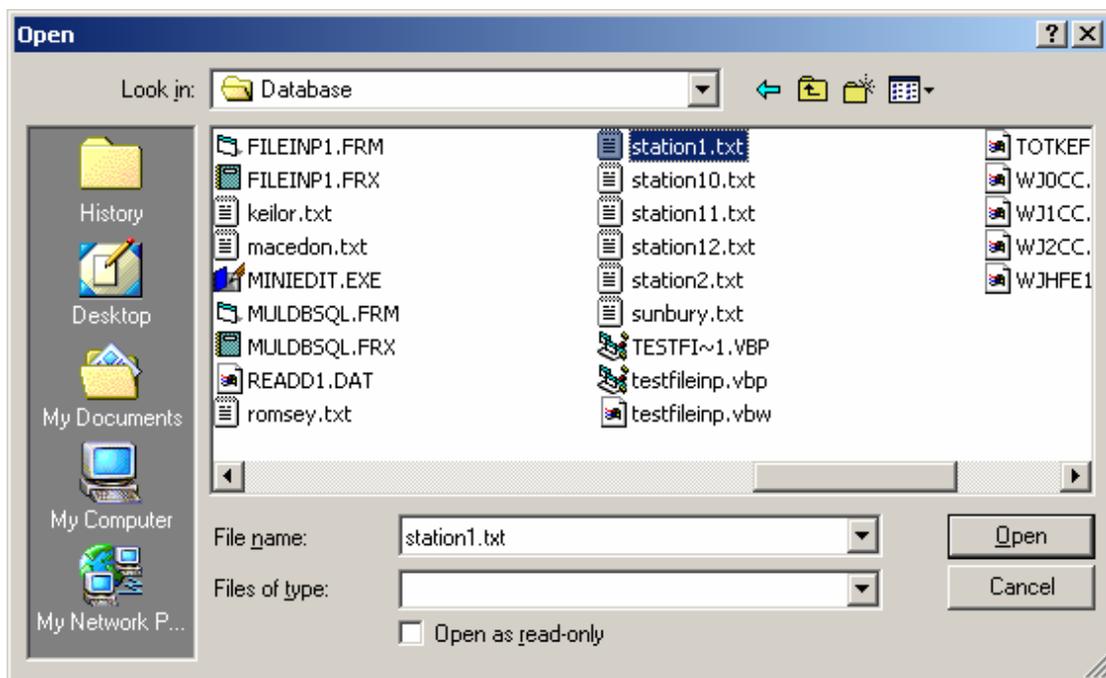


Figure 5.16 Screen for Browsing Data File

- The **OK** button in Figure 5.15 transfers all data in the data file to the current database table of **Historical Flood Events** appending the data to the last existing record, and the screen (Figure 5.15) closes then.

- The **C**ancel button in Figure 5.15 closes the screen without adding data to the database table.
- The choice of **C**ancel button in Figure 5.11 will stop data entering operation using the **N**ew button.

(b) Button **A**dd

The button **A**dd in Figure 5.10 is designed to add one record into the database table of a gauging station at one time. The added record will be appended to the end of the database file. Clicking on this button (after selecting the station) displays a Window (Figure 5.17) to add a record. Figure 5.17 shows that this database table has already 101 records and the user is about to enter data for the record 102 (i.e. new record number). Initially, all text boxes in Figure 5.17 are blank except the record number. The remaining text boxes allow the user to enter the data related to the new record. The **O**K button on Figure 5.17 closes the widow after saving data in the database and returns to Historical Flood Events Window (Figure 5.10). The **C**ancel button on Figure 5.17 closes the screen without saving the record and returns to Figure 5.10.

Figure 5.17 Adding a Record in Historical Flood Events

(c) Button **D**eflete

- The button **D**eflete on Figure 5.10 can be used to delete a record from the database table of a gauging station. When the user clicks on this button (after selecting the station), two Windows screens (Figure 5.18a and 5.18b) are displayed together.

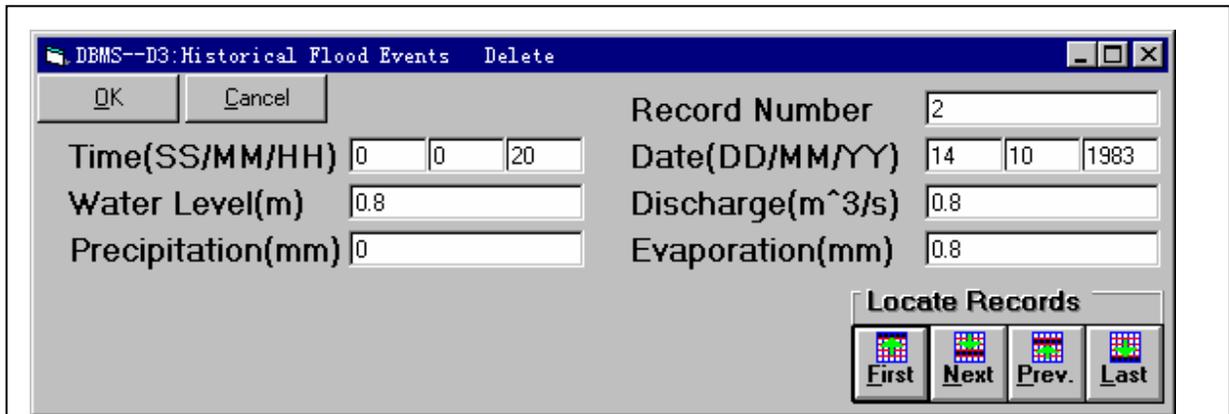


Figure 5.18a Interface of Deleting a Record in Historical Flood Events

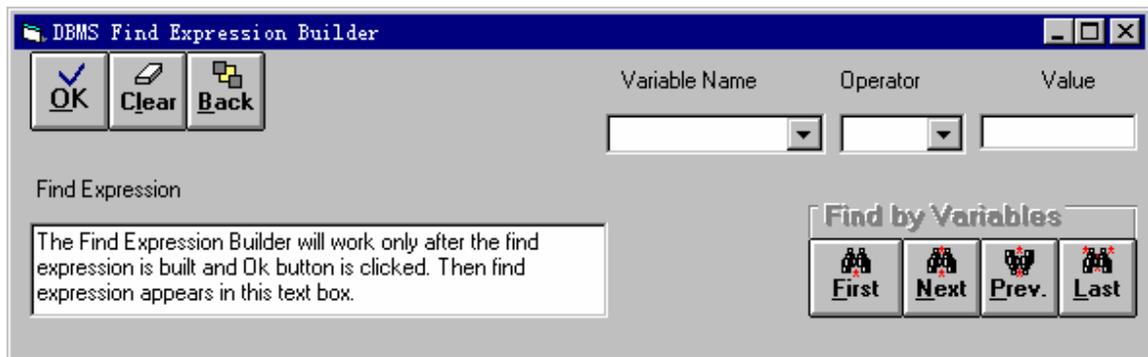


Figure 5.18b Interface of Find Expression Builder in DBMS

There are six buttons on Figure 5.18a. Their functions are described below:

- The buttons **F**irst, **N**ext, **P**rev and **L**ast display the first record, next record after the current record, the preceding record to the current record and the last record of the current database table of the gauging station respectively.
- The button **O**K deletes the current record (in Figure 5.18a, it is record number 2) from the database table of this gauging station. The user can use the buttons **F**irst, **N**ext, **P**rev and **L**ast to locate the record that needs to be deleted (which is called the current record). A confirmation screen as shown on Figure 5.19 is then displayed. The button **Y**es in Figure 5.19 allows the user delete the record, while the button **N**o on Figure 5.19 retains the record in the database table of the gauging station. Both operations in Figure 5.19 close the current

Windows (both Figure 5.18a and Figure 5.18b) and return to Historical Flood Events Window (Figure 5.10).

- The button **C**ancel in Figure 5.18a does not delete the current record but closes the current Windows (both Figure 5.18a and Figure 5.18b) and returns to Historical Flood Events Window (Figure 5.10).



Figure 5.19 Delete Confirmation Screen

The **Find Expression Builder** (Figure 5.18b) provides an alternative method to find the record that the user wishes to delete. It is usually applied when the user deals with a large database file. The functions of buttons and text boxes are described below:

- The text box of *Variable Name* is to enter the field name in the database table. The user can directly enter the field name into the text box, or select a field name from the list of field names. The field names in the list include all fields in the database table, such as *SchemeNo*, *Year*, *Flow*, *WaterLevel*.
- The text box of *Operator* is to enter the operator for building the Find Expression. The user can directly enter the operator into the text box, or select an operator from the list of operators. The list includes common operators, such as  $>$ ,  $<$ ,  $>=$ , etc.
- The text box of *Value* is to enter the value of the corresponding variable.
- The button **O**K builds the *Find Expression* statement and displays it in the text box of *Find Expression*, and enables the buttons **F**irst, **N**ext, **P**rev and **L**ast. The button **C**lear deletes the text in all text boxes. The button **B**ack closes this Window (Figure 5.18b).
- The buttons **F**irst, **N**ext, **P**rev and **L**ast display the first matched record, the next matched record after the current record, the preceding matched record to the current record, or the last matched record of the database table, and displays on Figure 5.18a, which can be deleted.

(d) Button **Q**uery

The button **Query** in Figure 5.10 helps the user to find the records that match certain criteria at a gauging station. If the user clicks on this button (after selecting the station), the DBMS Query Builder screen (Figure 5.20) is displayed with all text boxes initially blank. The procedure of building a statement for querying is explained below through an example dealing with 'Flow  $\geq$  260' at the gauging station (in this case Station 2). This example is shown in Figure 5.21. The check boxes and radio buttons, which are not used in this example (but appear on Figures 5.20 and 5.21), are also explained.

The screenshot shows the 'DBMS Query Builder' window. It has three main input fields at the top: 'Variable Name', 'Operator', and 'Value', all of which are currently blank. Below these are several options:
 

- Sorting Order:** A grid of six checkboxes, all of which are checked: '1st Order: Year', '2nd Order: Month', '3rd Order: Day', '4th Order: Hour', '5th Order: Minute', and '6th Order: Second'.
- Sort in:** Two radio buttons, 'Asc' (selected) and 'Desc'.
- Single/Multiple Criteria:** Three radio buttons, 'Single' (selected), 'Multiple: And', and 'Multiple: Or'.
- Query Sentence:** A large empty text area.

 At the bottom are three buttons: 'OK', 'Cancel', and 'Clear'.

Figure 5.20 Query Builder Screen in DBMS

This screenshot shows the same 'DBMS Query Builder' window but with an example query entered. The 'Variable Name' field contains 'Flow', the 'Operator' field contains '>=' (greater than or equal to), and the 'Value' field contains '260'. The 'Sorting Order' checkboxes remain checked. The 'Sort in' radio button 'Asc' is selected. The 'Single/Multiple Criteria' radio button 'Single' is selected. The 'Query Sentence' text area now contains the following SQL statement:
 

```
Select * From station2 Where Flow >= 260 Order By Year, Month, Day, Hour, Minute, Second Asc
```

 The 'OK', 'Cancel', and 'Clear' buttons are still present at the bottom.

Figure 5.21 Query Builder Screen Dealing With an Example

- Select **Flow** from the list of *Variable Name*.
- Select **>=** from the list of *Operator*.
- Enter **260** in the text box of *Value*.
- Select all check boxes in *Sorting Order*. The check boxes of *1<sup>st</sup>Order:Year*, *2<sup>nd</sup>Order:Month*, *3<sup>rd</sup>Order:Day*, *4<sup>th</sup>Order:Hour*, *5<sup>th</sup>Order:Minute* and *6<sup>th</sup>Order:Second* are used to order the queried results in that order. These check boxes are optional. Sorting is done only for selected check boxes. If all check boxes are selected, the records are sorted by the year first, then by the month, and so on until by the second.
- Select the option button *Asc* to sort records with respect to its value in the ascending order. The option buttons of *Asc* and *Desc* sort the queried results by ascending or descending order respectively, after sorting is done based on the *Sorting Order*.
- Select *Single* in *Single/Multiple Criteria* to build a query based on a single criterion (or a single statement). Click on the **OK** button to show the Query Sentence as shown in the text box in Figure 5.21, as “**Select \* From station2 Where Flow >=260 Order By Year, Month, Day, Hour, Minute, Second Asc**”, which will also display the queried results. Note that, Station 2 has been selected for query example. It is found that all records displayed in Figure 5.22 are with flows that is greater than 260, as requested in the query.

	SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow	Pre
▶	33	0	0	3	16	10	1983	1.8	263.2	
	34	0	0	4	16	10	1983	1	271.3	
	35	0	0	5	16	10	1983	0.8	275.3	
	36	0	0	6	16	10	1983	1.6	275.3	
	44	0	0	14	16	10	1983	0.2	275.3	
	45	0	0	15	16	10	1983	0.6	287.8	
	46	0	0	16	16	10	1983	0.8	279.5	
	47	0	0	17	16	10	1983	0	263.2	

Figure 5.22 Query Result Show Screen for Query Statement in Figure 5.21

- If the user selects the *Multiple:And* in *Single/Multiple Criteria* in Figure 5.20, with other information as above, then the query sentence in the text box of *Query Sentence* is

displayed as “ **Select \* From station2 Where Flow >= 260 and**”. The text boxes of *Variable Name*, *Operator* and *Value* then become empty, which allow the user to enter values to complete this query statement. For example, at this time, if the user selects **Hour** from *Variable*, selects **>=** from *Operator*, enters **14** in *value*, selects **Single** in *Single/Multiple* to instruct the system that the current criteria is the last criterion in building the query statement, and then clicks on the button **OK**, then the query sentence in the text box of *Query Sentence* is displayed as “**Select \* From station2 Where Flow >=260 and Hour>=14 Order by Year, Month, Day, Hour, Minute, Second Asc**”, followed by the queried results (Figure 5.23).

	SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow	Pre
▶	44	0	0	14	16	10	1983	0.2	275.3	0.2
	45	0	0	15	16	10	1983	0.6	287.8	
	46	0	0	16	16	10	1983	0.8	279.5	
	47	0	0	17	16	10	1983	0	263.2	

Figure 5.23 Query Result Show Screen for Query Statement using *Multiple:And*

- The *Multiple:Or* in *Single/Multiple Criteria* in Figure 5.20 is similar to *Multiple:And*. In this case, the query is done based on the “ Or “ boolean concept. It is possible to have more than 2 query conditions combined.
- The default order is shown in Figure 5.20, with ticked check boxes and selected option buttons. Records are sorted first with respect to time (Year/Month/Day/Hour/Minute/Second as relevant) and then with respect to the value in Asc/Desc.
- The button **C**lear in Figure 5.20 clears all text boxes in Figure 5.20 and allows the user to build a new query statement.
- The button **C**ancel in Figure 5.20 closes the screen and returns to Figure 5.10.

(e) Button **Update**

The button **Update** in Figure 5.10 is used to modify a record of a database table corresponding to a gauging station. If the user clicks on this button (after selection the station), two screens are displayed together, namely **DBMS---D3: Historical Flood Events Update** (Figure 5.24a) and **DBMS Find Expression Builder** (Figure 5.24b). As can be seen, these two screens are exactly same as those displayed with the button **Delete** (Figures 5.18a,b), except the headings in Figure 5.18a and in Figure 5.24a. Therefore, the data entry and the operations are also the same with those buttons. The difference is that the **OK** button in Figures 5.18a deletes the record, while it updates the record in Figures 5.24a.

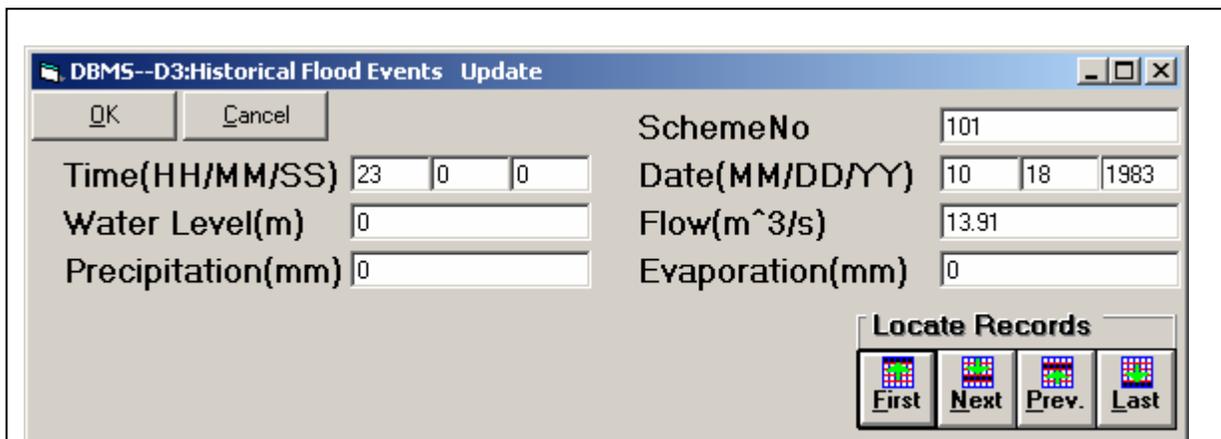


Figure 5.24a Interface of Update of Historical Flood Events in DBMS

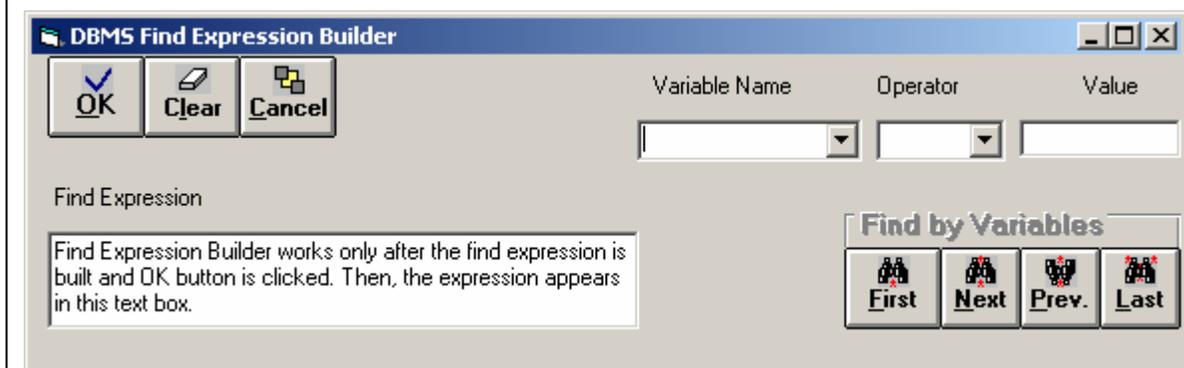


Figure 5.24b Interface of Find Expression Builder in DBMS

(f) Button **View**

The button **View** in Figure 5.10 is used to view records in the database of a gauging station by tabular and graphical forms. When the user clicks on this button (after selecting the station), the hydrograph at the selected station is displayed on the upper part of the Windows Interface with the table describing the hydrograph displayed on the lower part (Figure 5.25). Note that again this hydrograph details are shown for **Station 2**. The user can change the time base of hydrograph by entering appropriate values in *From Date*, *From Time*, *To Date* and *To Time*. The table includes all stored variables for historical flood events (i.e. flow, water level/stage, rainfall and evaporation).

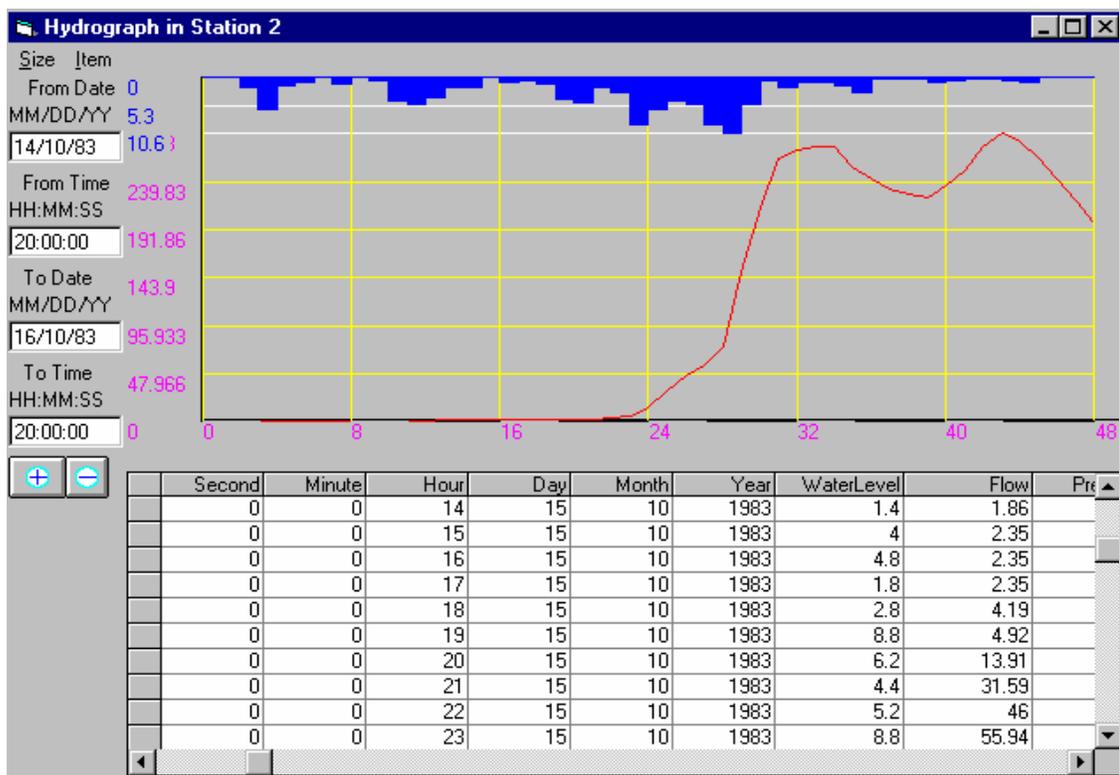


Figure 5.25 Interface of View of Historical Flood Events in DBMS

The blue colour number in the left scale of the hydrograph show the rainfall (mm) scale, while the red numbers show the scale for flow data ( $m^3/s$ ). The menu 'Size' in Figure 5.25 was originally intended for zoom in and zoom out (and same as + and - buttons), but are not functional currently. They can be considered for further development.

The menu *Item* in Figure 5.25 includes five sub-items to display various hydrological attributes related to historical flood events (Figure 5.26). In Figure 5.26, *Rain and Flow* has been selected to display the rainfall together with the hydrograph, as shown in Figure 5.25.

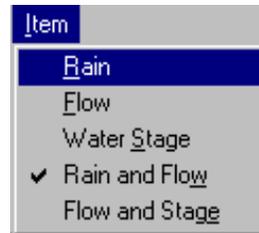


Figure 5.26 Sub Menu of Menu *Item* on Figure 5.25

### (g) Other Buttons

The functions of buttons **U**ndo, **S**elect, **O**K and **H**elp in Figure 5.10 are same as those in Section 5.2.1.2.

### 5.2.2.3 Error Handling

Three cases that were described in Section 5.2.1.3 were also considered for handling different types of errors and conflicts in Historical Flood Events database of the Database subsystem. Some examples are given below for the first case where the error handling was done for expected errors.

- No station selected.
- Empty database table.
- No enough data for graph (e.g. one data point only).
- Format of entered data not matched with the database.
- Wrong data file format, when entering data through a data file.

### 5.2.3 Real-Time Flood Event

The **Real-Time Flood Event** submenu was developed to deal with the records of water level, flow, precipitation and evaporation at gauging stations stored in the database (i.e. D4RFE.MDB)

for the current flood event, which is occurring (and under flood forecasting and warning). The database tables, the variables stored in the database table and the relevant system functions are exactly same as those for **Historical Flood Events** (Section 5.2.2), except that **Real-Time Flood Event** is only used for the current flood event while **Historical Flood Events** is for many historical flood events. Once the forecasting for the real-time flood event is over, it can become a historical flood event and can be moved to the database of historical flood events. It is suggested that once the forecasting for the real-time flood event is over, the database *D4RFE.MDB* should become empty for use in flood forecasting and warning of the next flood event. The conceptual database design and contents in the database for **Real-Time Flood Events** were detailed in Section 4.3.

When clicked on the item of **Real-Time Flood Events** on Figure 5.2, the interface shown in Figure 5.27 is displayed. As can be seen, the functions on Figure 5.27 are the same as those on Figure 5.10 and therefore the reader is referred to Section 5.2.2 for details.

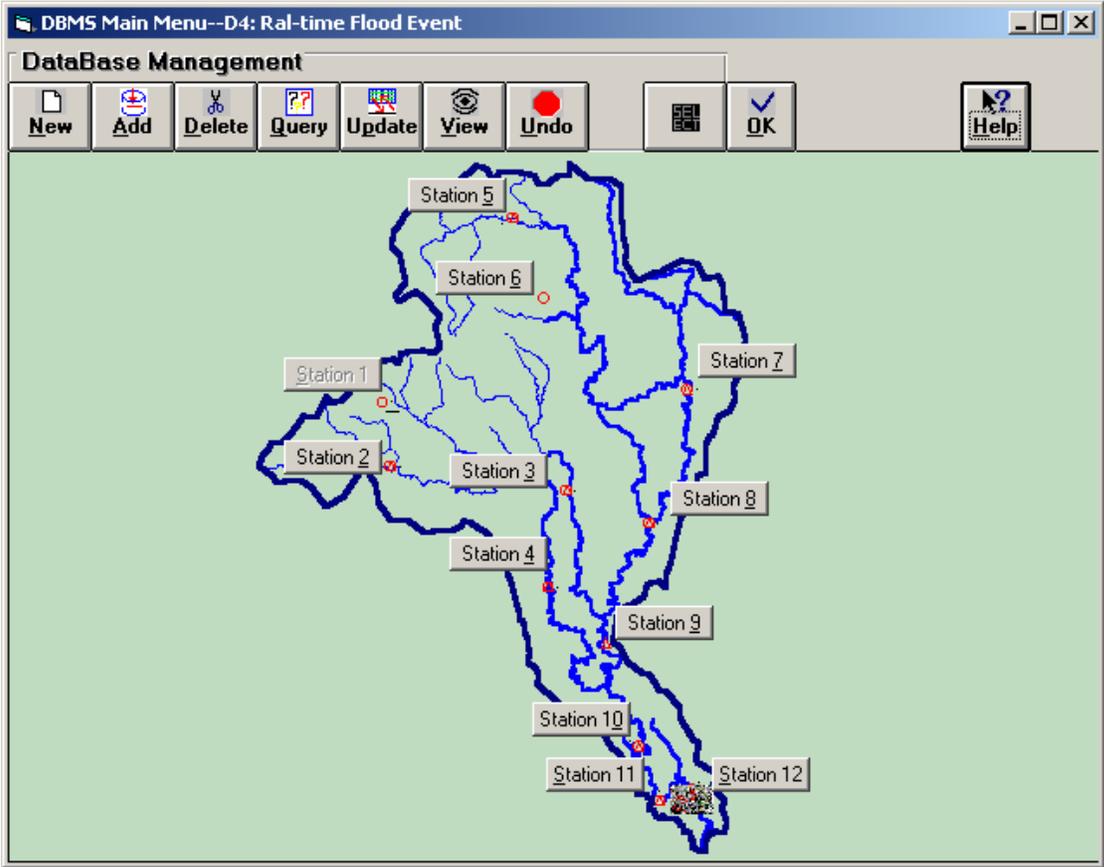


Figure 5.27 Real-Time Flood Event Window

## 5.2.4 **Simulated Flood Scenarios**

The **Simulated Flood Scenarios** database contains several forecast flood scenarios, which give information on forecast flow and flood levels. In addition, it can store calibrated flood scenarios, since they have the same format as the forecast flood scenarios. This database was developed to deal with three types of data stored in the database D5SFS.MDB, as follows.

- Results of calibration of the URBS hydrological model.
- Results of calibration of the HEC-RAS hydraulic model.
- Results of flood forecasting from both URBS and HEC-RAS models.

As was shown in Figure 5.2, the **Simulated Flood Scenarios** submenu has two submenus, namely **Forecast or Calibration URBS only** and **Calibration HEC-RAS only**. The **Forecast or Calibration URBS only** submenu deals with forecast flows and flood levels of the flood prone area of the cross catchment/river for various forecasting scenarios, as well as calibration results from the URBS model. The calibration results of the URBS model can be considered as a subset of forecast flood scenarios and therefore included together to avoid multiple tables in the database. It also has the advantage that same graphic analysis functions can be used for both calibrated and forecast hydrographs. The submenu **Calibration HEC-RAS only** has data to compare the calibration results of the HEC-RAS model. This is explained in detail in Section 5.3.1.2 under calibration of HEC-RAS hydraulic model, and therefore is not repeated in this section.

### 5.2.4.1 **Physical Database Table Development**

The physical database D5SFS.MDB was developed to store the results of calibration of both the URBS hydrological model and the HEC-RAS hydraulic model, and the results of simulated flood scenarios such as peak discharge and corresponding flood water levels of the flood prone area of the lower catchment/river. There are two types of tables in D5SFS.MDB. They are described below:

- The first type of tables was developed to store relevant URBS model parameters and the results in terms of flow and flood water levels of the flood prone area of the lower catchment/river corresponding to simulated flood scenarios. In addition, it includes the calibrated flood hydrographs of the URBS model and the calibration results of the HEC-RAS model. Several tables were developed for this purpose. For example, the table *HProcess* was developed to store the calibration results of the HEC-RAS model; the table *SFSI* was developed for storing parameters of each simulated flood scenario and corresponding results such as its peak discharge and time of peak discharge, and calculated flood water levels at each cross section of the flood prone area of the lower catchment/river (related to peak discharge during the forecasting stage); the table *DoneTime* is developed to record the date and time when the last flood forecasting/warning decision was made.
- The second type of tables was developed to store the detailed results such as the complete calculated hydrographs from the URBS model (the first type of tables only stores the peak discharge and time to peak) and the values of the calibrated HEC-RAS model parameters such as the roughness coefficients in left bank, main channel and right bank, and contraction and expansion coefficients at each cross section of the flood prone area of the lower catchment/river. A total of 50 HEC-RAS process tables and 50 URBS process tables was pre-created to save the system run time. For each flood scenario (either calibration or forecast), an URBS table and a HEC-RAS table will be used. When the 50 tables are used up in writing the results for flood scenarios, the programming will automatically overwrite the first table. To maximize the benefits of DSSFCMR, the user can delete the calibration results after calibration is done or delete scenario results, which are not useful. This design of 50 data tables is mainly limited by MS ACCESS database size, however, it meets the general development and the user's requirements.

#### 5.2.4.2 Functions and Interface Development - Forecast or Calibration URBS only

The item Forecast or Calibration URBS only of Simulated Flood Scenarios in Figure 5.2 is developed to deal with the data of the simulated floods (both discharge and water levels of flood prone area of the lower catchment/river) and the calibration results of the URBS model. The interface shown in Figure 5.28 will be displayed, when clicked on Forecast or Calibration URBS only of Simulated Flood Scenarios.

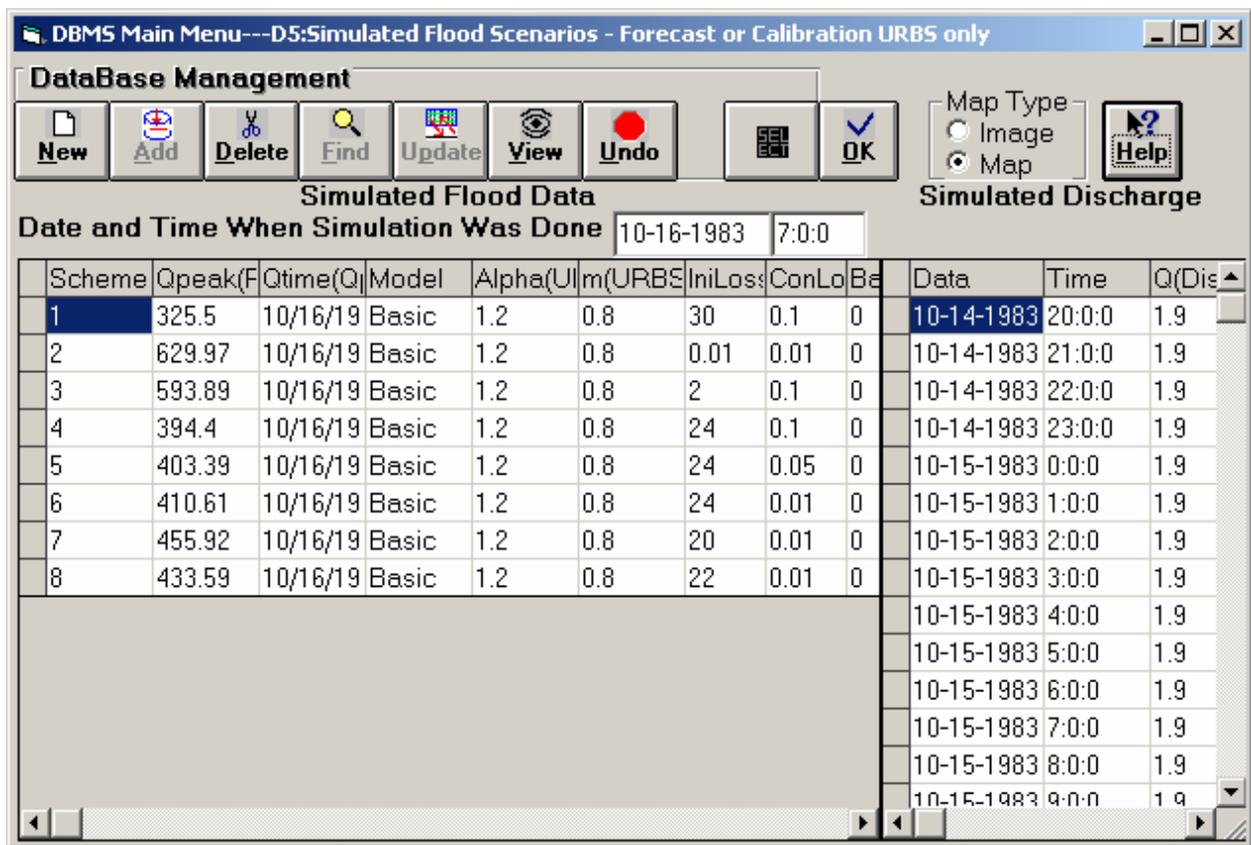


Figure 5.28 Interface of Forecast or Calibration URBS only

The left table on Figure 5.28 shows the URBS model parameters and some results such as the peak discharge for various stored simulated flood scenarios (or shows as *SchemeNo* in the figure). The right table on Figure 5.28 is the forecast hydrograph related to a particular record (or scheme) in the left table. When the user clicks on the field of *SchemeNo* at a certain record, the calculated hydrograph related to this record is displayed in the right table.

The buttons **New**, **Delete**, **View**, **Undo**, **Select**, **OK** and **Help** on Figure 5.28 are active, while the buttons **Add**, **Find** and **Uppdate** are inactive. The data adding and updating in D5SFS.MDB for simulated flood scenarios are automatically done by the DSSFCMR during the **Run-Models** stage, while the record finding function is not required for D5SFS.MDB because the purpose of this database is only to store and analyse the simulated flood scenarios. The functions of buttons **Undo**, **Select**, **OK** and **Help** on Figure 5.28 are same as those in Section 5.2.1.2. The functions of other active buttons are described below.

The button **New** on Figure 5.28 was developed to transfer the current displayed records on the left table to the database D6RFW.MDB for Real-Time Flood Warning. These records are considered as the decisions at this time step. The use of the **New** button also deletes all records in the database D5SFS.MDB. A confirmation Window from DSSFCMR is displayed (Figure 5.29) before transferring these records into the database D6RFW.MDB and subsequent deleting. The button **No** on Figure 5.29 will cancel deleting. Before deleting, the confirmation screen is also displayed (Figure 5.30). However, the user may not use the **New** button frequently, since he/she needs only selected scenarios to be transferred from database D5SFS.MDB to database D6RFW.MDB. The scenario selection can be done during Decision Support stage.

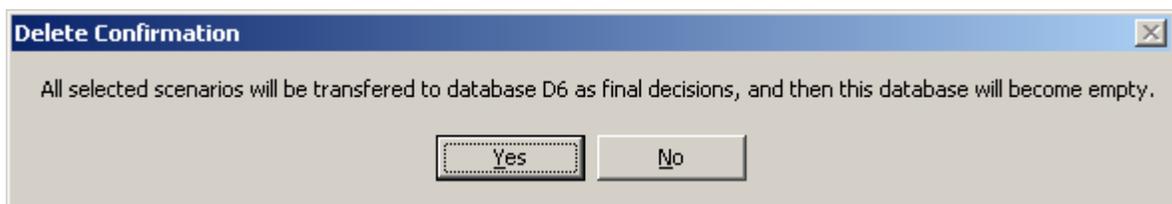


Figure 5.29 Interface of Confirmation for Button **New** Action in Figure 5.28

The button **Delete** on Figure 5.28 is used to delete all records in the database file. Before deleting, the confirmation screen is also displayed (Figure 5.30).

The button **View** on Figure 5.28 displays the calculated and observed hydrographs at Keilor (Figure 5.31) corresponding to all scenarios listed in Figure 5.28, but one scenario at a time. Note that, as explained in Section 4.1, flow at Keilor can be considered as the flow entering the flood prone area of the lower catchment/river. As can be seen from Figure 5.31, the scenario number (or Scheme No) 1 is considered in this case, and it is a calibration event. However, any other scenario can be considered from the list box of *Scheme No*. It shows the two hydrographs up to the point (i.e.35 hours vertical line in Figure 5.31), where the forecast would be done, which is given by *Simulated Date and Time*. The fields on the left side of the screen show the URBS model parameters used for the selected scenario. Note that even if the record contains forecast information, the button **View** on Figure 5.28 shows only observed and computed hydrographs up to the forecasting time.

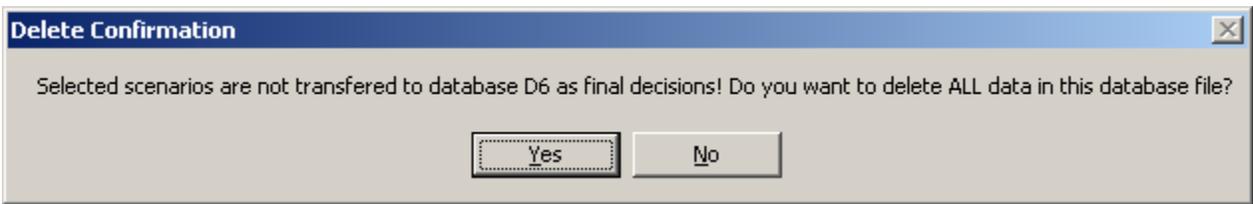


Figure 5.30 Interface of Confirmation for Button Delete Action in Figure 5.28

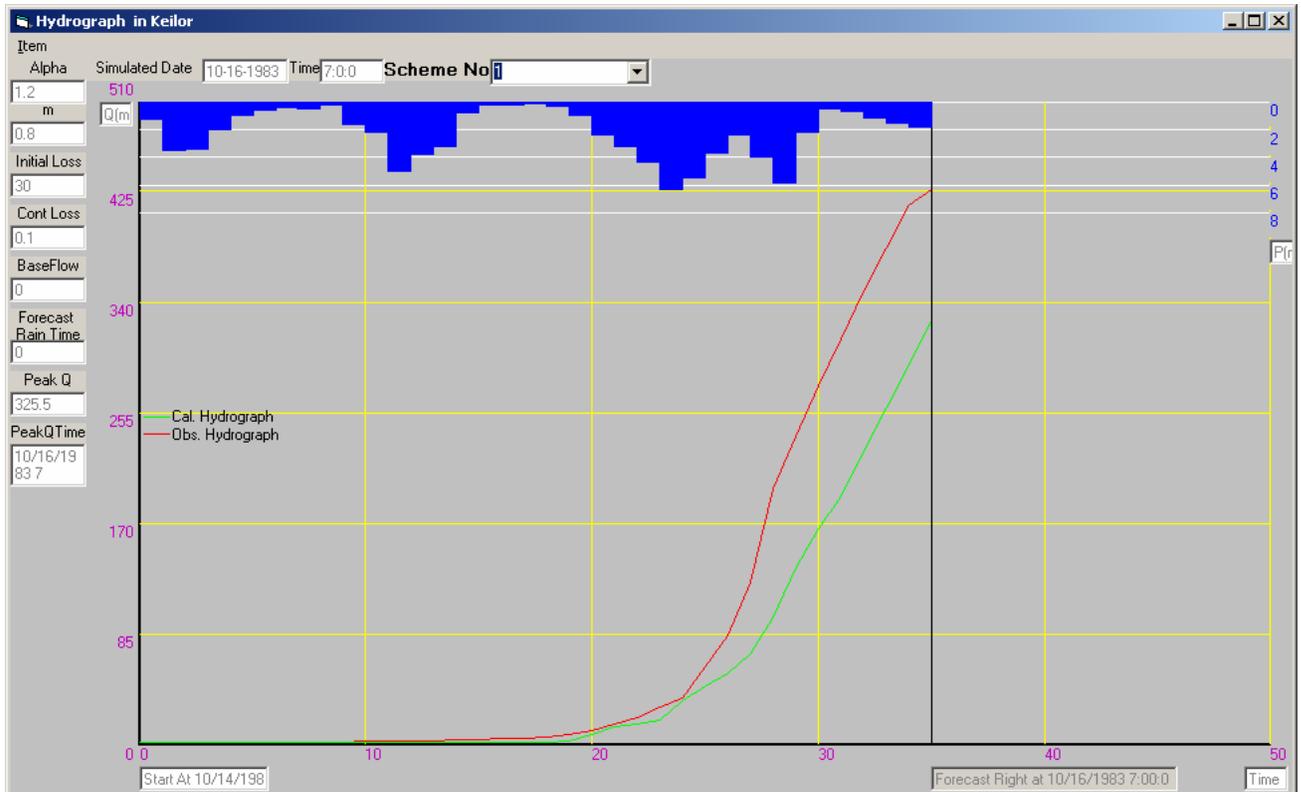


Figure 5.31 Interface of Observed and Calculated Hydrographs

The menu *Item* on Figure 5.31 includes four sub-items to display various hydrograph and rainfall details (Figure 5.32). In Figure 5.32, the item of **C**alibration Model has been selected to display the rainfall together with the calculated and observed hydrographs (Figure 5.31).

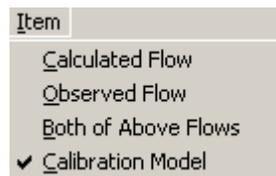


Figure 5.32 Sub Menu of Menu *Item* on Figure 5.31

The option buttons of **Image** and **Map** (corresponding to the first method and second method in SGDDA respectively detailed in Section 4.5.2) on Figure 5.28 were developed to display the flood area image and the interactive map interface for flood area spatial analysis for the selected record (or scenario/scheme) respectively. The **Image** option only displays the lower township map, which is prone to flooding (i.e. Figure 5.33) with the flood water level line superimposed corresponding to the selected record. The user does not need much knowledge and extra software to use the functions of **Image**. The **Map** option is more complicated and powerful, and it displays an interactive map interface, which allows the user to investigate spatial details of the flooded area and the potential flood damage extensively to the level of house properties (Figure 5.34). This method requires the MapObjects software to reside in the user's computer, and also requires the user to have better computer skills to use this method than the **Image** option.

When the option button of **Image** is chosen and clicking on the cell defined by the specific table column of *QProcess(ForecastFlowFile)* of one record (i.e. scenario/scheme) in Figure 5.28, the flood prone area map is displayed. Click on this image to overlay the flood water line (i.e. red line on Figure 5.33) due to the selected record to produce the flood inundation map. Click on a position on the flood inundation map, which will display another small Window (which is also included in Figure 5.33) that shows the Northing and Easting of the clicked position.

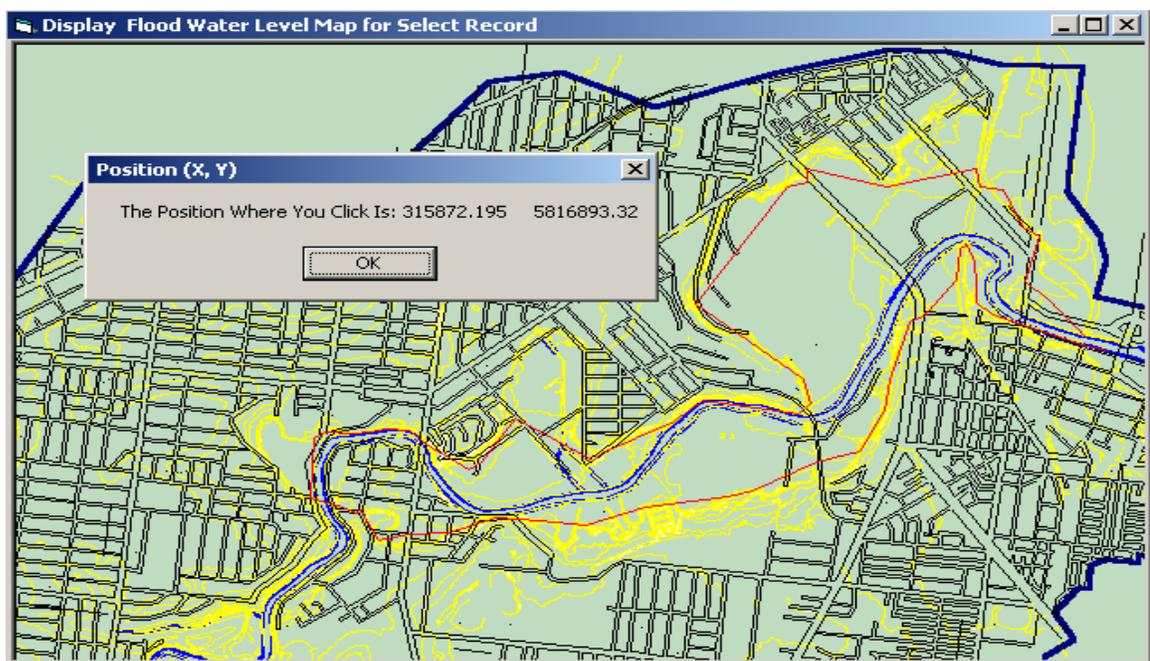


Figure 5.33 Interface of Image Display of a Selected Simulated Flood Record

When the option button of **Map** is chosen and clicking on the cell defined by the specific table column of *QProcess(ForecastFlowFile)* in one record in the left table in Figure 5.28, the shapefile of flooded area of the selected scenario is created instantly based on the water levels at cross sections. This shapefile of the flooded area together with other spatial data such as cross sections, river, streets, roads and house properties will be displayed in the interactive interface, as shown in Figure 5.34. This window can perform many functions such as Map Printing, Zoom In, Zoom Out, Pan, Label, Global, Current Position (Easting and Northing), etc. For example, if the user selects “water level” from the combo box of *Labelling layer*, then clicks on a cross section on the map, the water level (e.g. 2.69 near the centre on Figure 5.34) at this cross section will be displayed.

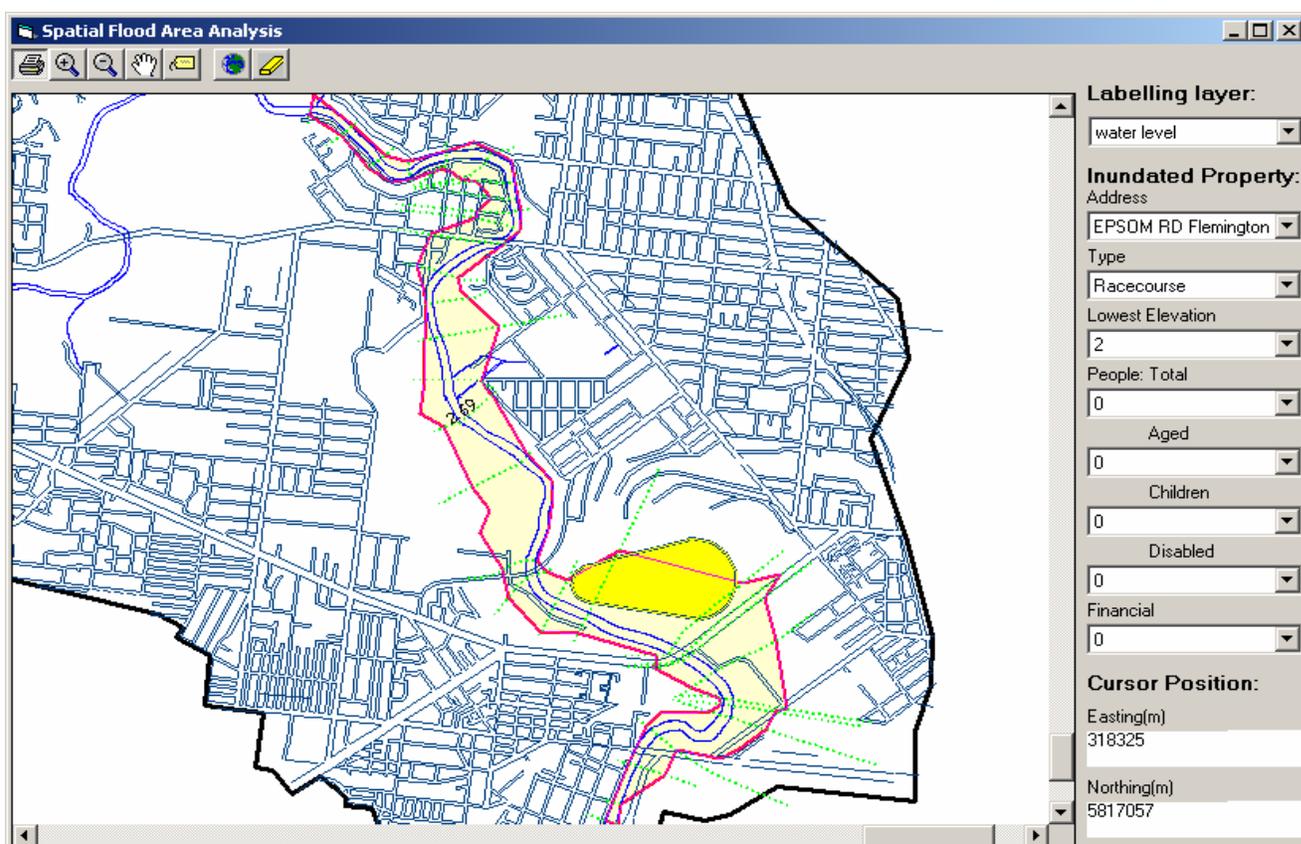


Figure 5.34 Interface of Interactive Flood Water Level Analysis

When Figure 5.34 is displayed, initially the contents of combo boxes under Inundated Property are empty. These combo boxes are used to store data on inundated house properties within a user selected area. When the user selects a rectangular area on the interactive map using the mouse, all

properties within the flood inundation area (flooded either in part or full) within the rectangular box will be detected, the colour of flood area boundary will be changed from red to pink, and the colour of the property boundary will be changed from solid line to a dotted line. These features will help the user to locate the inundated properties within the rectangular box. The information on properties related to flood warning and damage for the currently selected scenario within this rectangular box will also be stored in the combo boxes of Figure 5.34. The information includes property (house) address, type (i.e. school, hospital), number of persons (total/aged/children/disabled within the flood inundation area), and financial data. This information will help the decision maker make decisions effectively for flood warning related to the currently occurring flood. In this example in Figure 5.34, only the Racecourse is detected having been flooded in part.

The built functions in Figure 5.34 are described below:

- The icon  is developed to print the current map in the map box by clicking this button.
- The icon  (Zoom In) is developed to zoom in the map to see more details in a selected small area. The user clicks on this button first, and then clicks on the map or draws a rectangle area on the map using the mouse, which zooms in the map.
- The icon  (Zoom Out) is developed to zoom out the map, which shows a bigger area with less details. The user clicks on this button first, and then clicks on the map, which zooms out the map.
- The icon  (Pan) is developed to see certain parts of the flood inundation map at any time by dragging the map in any direction. The user clicks on this button first, and then drags the map in a particular direction.
- The icon  (Label) is developed to show text labels of spatial data (i.e. the cross section number and the calculated flood water level at each cross section). Clicking on several points on the map at cross sections will produce cross section number or water levels at those points. Either the water level or cross section number can be displayed as text labels, by selecting through the combo box of *Labelling layer*.
- The icon  (Global) is developed to zoom out to the full extent of the map. Click on this button when the user wants to see the whole map.

- The icon  (Clear) is developed to clear all text information generated from the Label action.
- The combo box of *Labelling layer* is developed to select either the water level or the cross section number to display. This operation will be used with the icon  Label, as explained above.
- *Inundated Property* combo boxes are self-explained.
- The text boxes of *Easting(m)* and *Northing(m)* dynamically display the Easting and Northing co-ordinates of the cursor position.

### 5.2.4.3 Error Handling

Three cases, as discussed in Section 5.2.1.3 were considered to manage different types of errors or conflicts in data handing in Simulated Flood Scenarios database.

The error handling for the first case was developed to handle the following expected error examples (but not limited to these only).

- Deleting an empty table.
- Requested data table does not exist (e.g. when plotting of hydrographs is required for a scenario in Figure 5.31, the data table corresponding to this scenario is empty).
- No flood data for the requested flood event.
- Attempted use of Spatial Flood Area Analysis Interface when it is already opened.

### 5.2.5 Real-Time Flood Warning

The Real-Time Flood Warning submenu in Figure 5.2 was developed to deal with the selected simulated flood scenarios at different times during one or more flood events stored in the database D6RFW.MDB, which can be used for real-time flood waning. This includes the flood event that is currently occurring and being investigated for flood forecasting and warning. This means the database D6RFW.MDB contains simulated flood scenarios corresponding to the flood event that is currently occurring and previous flood events, where decisions have been made in relation to flood forecasting and warning. The simulated flood scenarios corresponding to the

current flood event can be used for flood warning of this event. The simulated flood scenarios of the previous flood events can be used to investigate effectiveness of the decisions of flood warning made at that time.

The physical database tables in D6RFW.MDB for Real-Time Flood Warning are similar to those in database D5SFS.MDB for Simulated Flood Scenarios. The difference between them is that only a smaller number of suitable scenarios selected from the database D5SFS.MDB, (which are appropriate for decision making in relation to real-time flood warning for the current flood), are stored in D6RFW.MDB, while all scenario results are stored in D5SFS.MDB. In addition, the date and time when decision making was done (i.e. date/time the forecasting and warning was done) are also added to each record in D6RFW.MDB.

When the user clicks on the item of **Real-Time Flood Warning** in Figure 5.2, the interface shown in Figure 5.35 will be displayed. The DSSFCMR in this part will facilitate functions on Real-Time Flood Warning. The table contents are similar to those in Figure 5.28 (Section 5.2.4.2). As can be seen, the date and time when decision making was made are added to each record in Figure 5.35, compared to Figure 5.28. In Figure 5.35, the flood forecasting decision was made at 7:00 am on 16/10/1983 for the two scenarios.

The buttons **Delete**, **Find**, **View**, **Undo**, **Select**, **OK** and **Help** in Figure 5.35 are active, while the buttons **New**, **Add**, and **Update** in Figure 5.35 are inactive. The adding and transferring of new data into D6RFW.MDB for real-time flood warning were automatically completed by the DSSFCMR through Decision Support subsystem (Section 5.4), while the updating decision is not allowed during real-time flood warning stage. The functions of buttons **Undo**, **Select**, **OK** and **Help** on Figure 5.35 are same as those in Section 5.2.1.2. The functions of other active buttons are described below.

The button **Delete** on Figure 5.35 deletes all records in the database file. Before deleting, a confirmation screen from DSSFCMR is displayed for the user to confirm the deletion.

The button **Find** on Figure 5.35 helps the user to query decisions stored in the database D6RFW.MDB for Real-Time Flood Warning. When the user clicks on this button, the screen of **Find Some Final Decisions** is displayed (Figure 5.36). The user can construct the query by

selecting an operator from the combo box and a value from the right combo box or two values from the two right combo boxes as necessary. The controls and buttons on Figure 5.36 are described below.

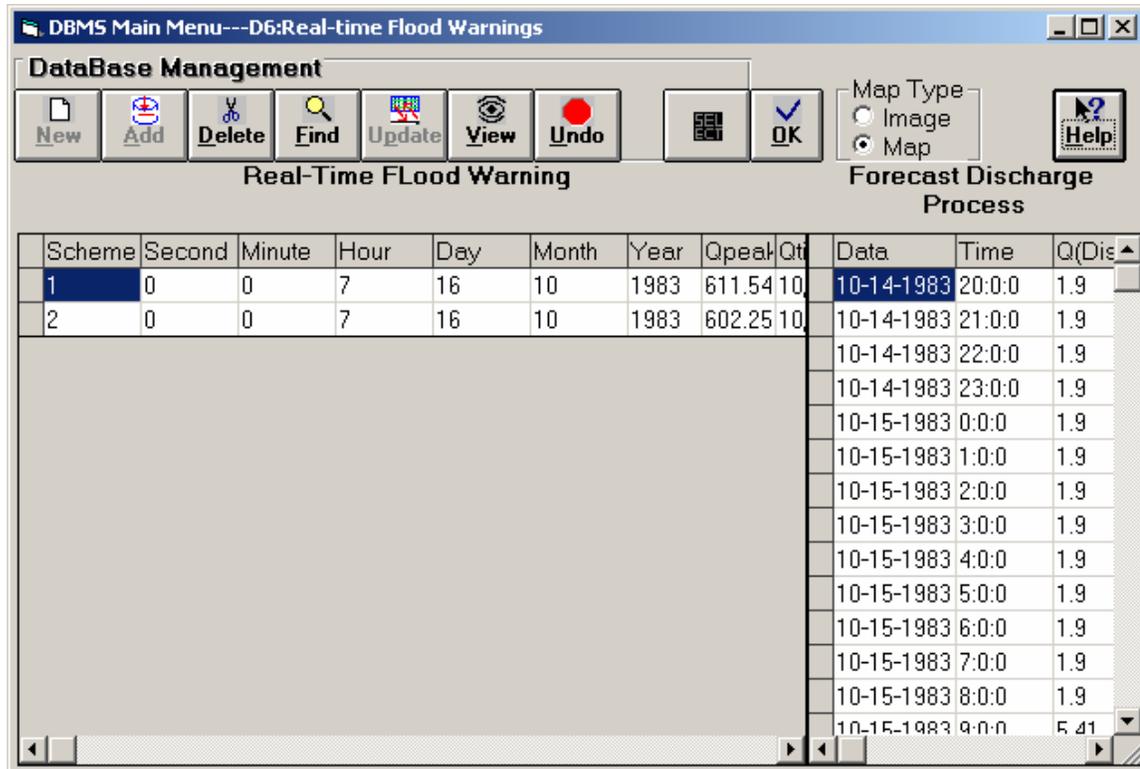


Figure 5.35 Interface of Real-Time Flood Warning

- The variables in Figure 5.36 are described below:
  - *Time(HH:MM:SS)* and *Date(YYYY:MM:DD)* are the time when the decisions are made in relation flood forecasting and warning ( i.e. 35 hours vertical line in Figure 5.31). In Figure 5.36, the user selects the operator of '=' from the list in the left combo box for the parameter of *Time(HH:MM:SS)*, and enter **7**, **0**, and **0** in three right boxes. The user also selects the operator of '=' from the list in the left combo box for the parameter of *Date(YYYY:MM:DD)*, and enter **1983**, **10**, and **16** in three right boxes. In this case, the user is searching for the flood warning decisions, which were made at 7 hours on October 16, 1983.
  - URBS model parameters *Alpha* and *m* are explained in Section 5.2.1.2 (a), while *Initial Loss*, *Continuing Loss* and *Baseflow* are self-explained.

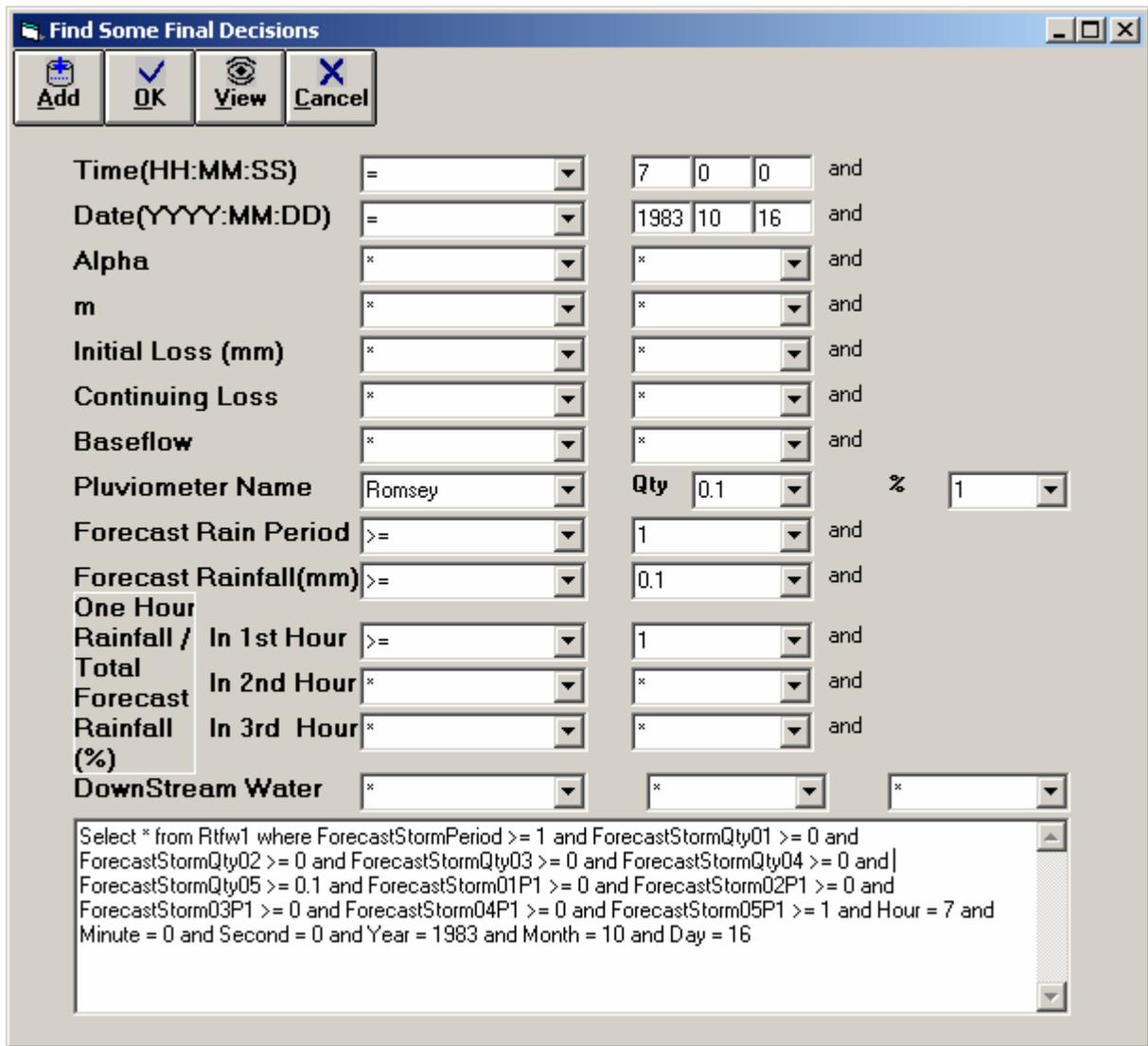


Figure 5.36 Interface for Searching Stored Decisions in Database D6RFW

- *Pluviometer Name* contains all pluviometers (i.e. 5 pluviometers in the case study) used for this application. The use of pluviometers Name is explained below.
- *Qty* and *%* are parameters used to enter the values for *Forecast Rain Period*, and *Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour, in 2nd Hour and In 3rd Hour*. The use of *Qty* and *%* is explained below.
- *Forecast Rain Period* is the total forecast rain time. This is same for all pluviometers. In Figure 5.36, the user selects the operator of ‘>=’ from the list in the left combo box for the parameter of *Forecast Rain Period* and select ‘1’ from the list in the right combo box. This means the user is searching for the flood warning decisions, which have rain

forecast periods as either 1 or 3. Note that only forecast periods of 0, 1 and 3 hours are allowed currently in DSSFCMR.

- *Forecast Rainfall(mm)* are the total forecast rainfall(s) in each pluviometer for *Forecast Rain Period*. The user can use *Pluviometer Name*, *Qty* and button **ADD** to enter the value(s) for this parameter at the pluviometers. For example, the user selects the operator of '>=' from the list in the left combo box of *Forecast Rainfall(mm)*, enters \* in *Pluviometer Name*, enters 0.0 in *Qty*, clicks on the right combo box of *Forecast Rainfall(mm)*, and finally clicks on the **ADD** button. All elements (i.e. corresponding each pluviometer in *Pluviometer Name*) in the combo box of *Forecast Rainfall(mm)* become 0.0. The user may want to enter different values for certain pluviometers. In Figure 5.36, Romsey (fifth element) from *Pluviometer Name* has been selected, with **0.1** in *Qty*. Clicking on the right combo box of *Forecast Rainfall(mm)* and finally clicking on the **ADD** button, the value of the fifth element in *Forecast Rainfall(mm)* had been changed to 0.1, while other elements were still 0.0. In this case, the user is searching for the records where the Romsey pluviometer has more than 0.1 mm rainfall during the forecast period, while the other pluviometers have more than 0 mm forecast rainfall.
- *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour* is the percentage of the total forecast rainfall in the first hour (after the end of the observed rainfall data) used for forecasting at pluviometers. This parameter is applicable only when the *Total Forecast Rain Time* is equal to either 1 or 3.

The user can use *Pluviometer Name*, % and button **ADD** to enter the value(s) for this parameter at the pluviometers. For example, the user selects the operator of '>=' from the list in the left combo box of *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*, enter \* in *Pluviometer Name*, enters 0.0 in combo box %, clicks on the right combo box of *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*, and finally clicks on the **ADD** button. All elements (i.e. corresponding each pluviometer in *Pluviometer Name*) in the combo box of *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour* become 0.0. The user may then want to change these values at certain pluviometers. In Figure 5.36, Romsey (fifth element) from *Pluviometer Name* has been selected with **1** in %. Clicking on the right combo box of *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*, and finally clicking on the **ADD** button, the value of the fifth element in *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour* become 1, while other elements were still 0.0.

- *Hour Rainfall / Total Forecast Rainfall (%) in 2nd Hour* is the percentage of the total forecast rainfall in the second hour (after the end of the observed rainfall data) used for forecasting at pluviometers. This parameter is applicable only when the *Total Forecast Rain Time* is equal to 3. The procedure for entering values for the parameter is same as that for *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*.
- *Hour Rainfall / Total Forecast Rainfall (%) in 3rd Hour* are the percentage of the total forecast rainfall in the third hour (after the end of the observed rainfall data) used for forecasting at pluviometers. This parameter is applicable only when the *Total Forecast Rain Time* is equal to 3. The procedure for entering values for the parameter is same as that for *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*.
- More details about *Forecast Rain Period*, *Forecast Rainfall(mm)*, *Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*, *in 2nd Hour* and *in 3rd Hour* will be given in Section 5.3.1.3.
- *DownStream Water* is the water level of the river cross section at the downstream end of the flood prone area of the lower catchment/river.
- The symbol \* in any combo box except *Pluviometer Name*, *Qty*, and % indicates that these variables are not considered in the SQL query statement and hence in searching.
- The button **ADD** in Figure 5.36 together with combo boxes *Qty* and % will add a value into the list of variables. This button is used in *Forecast Rain Period*, *Forecast Rainfall(mm)*, and *Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour*, *in 2nd Hour* and *in 3rd Hour*).
- The button **View** in Figure 5.36 will display the constructed query statement in the text box at the bottom of the screen. In Figure 5.36, based on the entered values for *Time(HH:MM:SS)*, *Date(YYYY:MM:DD)*, *Forecast Rain Period* and *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour* as above, the use of the button **View** displays the query sentence as “**Select \* from Rtfw1 where ForecastStormPeriod >= 1 and ForecastStormQty01 >= 0 and ForecastStormQty02 >= 0 and ForecastStormQty03 >= 0 and ForecastStormQty04 >= 0 and ForecastStormQty05 >= 0.1 and ForecastStorm01P1 >= 0 and ForecastStorm02P1 >= 0 and ForecastStorm03P1 >= 0 and ForecastStorm04P1 >= 0 and ForecastStorm05P1 >= 1 and Hour = 7 and Minute = 0 and Second = 0 and Year = 1983 and Month = 10 and Day = 16**”. The query statement searches for the decisions, which have:
  - Forecast rain periods as either 1 or 3 hours for flood warning.

- The forecast rainfall depths in all pluviometers are not less than 0 mm except in Romsey where forecast rainfall is not less than 0.1 mm.
- The percentage of the total forecast rainfall in the first hour (after the end of the observed rainfall data) in all pluviometers are not less than 0% except in Romsey where the percentage is not less than 1%.
- The flood warning was made at 7 hours on October 16, 1983. ‘*Rtfw1*’ describes for the database table, which is used to store the decisions (or flood forecasting scenarios) for ‘real-time flood warning’. The ‘ForecastStormQtyXX’ stands for the total forecast rainfall depth in Station XX, while the ‘ForecastStormXXP1’ indicates the percentage of the total forecast rainfall in the first hour in Station XX.
- The button **OK** in Figure 5.36 displays the selected flood forecasting decision scenarios in database D6RFW.MDB for Real-Time Flood Warning in the table in Figure 5.35 for the above query statement. Two decision scenarios, which match the condition in the SQL query statement, are extracted from the total of two scenarios in D6RFW.MDB. Although this is not a very good example, it illustrates the query functionality in selecting decision scenario based in certain criteria.
- The button **Cancel** in Figure 5.36 closes the current window without searching and goes back to Figure 5.35.

The button **View** on Figure 5.35 displays the calculated and observed hydrographs at Keilor (Figure 5.37) for any selected record, which is stored in the database D6RFW (and displayed in the left table on Figure 5.35). The observed hydrograph (shown in red) is drawn before *Forecast Done Date and Time*, while the calculated hydrograph (shown in green) due to forecast rainfall (shown in green) is drawn after *Forecast Done Date and Time*. The text box of *Peak Q* gives the maximum discharge in the calculated hydrograph after *Forecast Date and Time*. All other information in Figure 5.37 is similar to Figure 5.31.

The menu *Item* in Figure 5.37 includes four sub-items to display various hydrograph and rainfall information (Figure 5.38). In Figure 5.38, the user has selected the item of *Forecast Model* to display both observed and forecast catchment average rainfalls, as well as both observed and calculated hydrographs at Keilor (Figure 5.37).

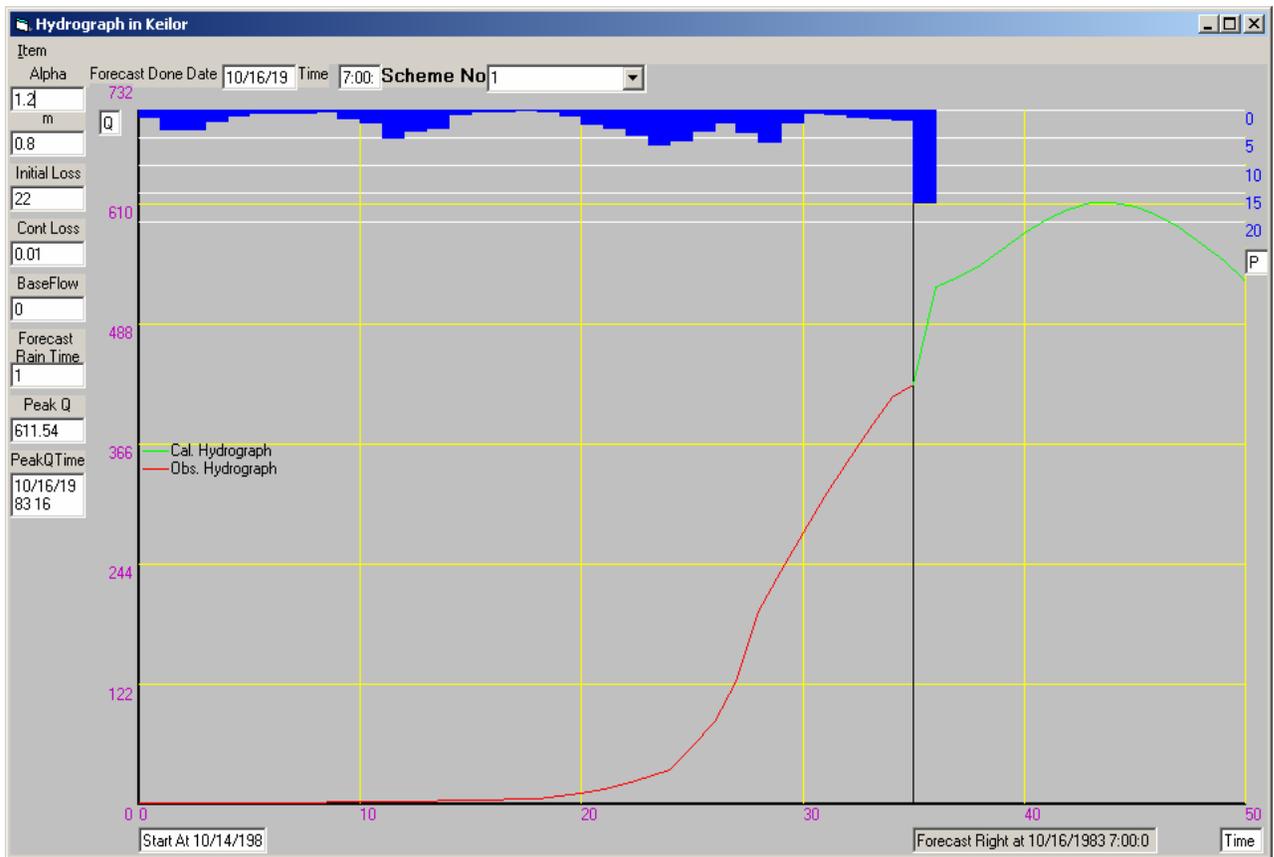


Figure 5.37 Interface of the Hydrograph in Keilor in the Phase of Forecasting

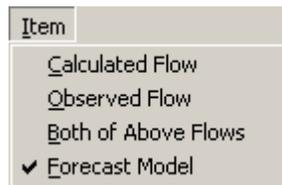


Figure 5.38 Sub Items of Menu *Item* on Figure 5.37

The functions of the radio buttons **Image** and **Map** on Figure 5.35 are exactly same as those on Figure 5.28. However, these buttons in Figure 5.35 are used to deal with all selected flood forecasting decision scenarios, while those on Figure 5.28 are used for all simulated flood scenarios.

Three cases, as discussed in Section 5.2.1.3 were also considered to manage different types of errors or conflicts in data handing in Real-Time Flood Warning database. The functions are exactly same as those for Simulated Flood Scenarios (Section 5.2.4.3).

### 5.2.6 Summary

The developed database subsystem can perform various tasks in database management for flood forecasting and warning such as data entry, updating, searching, deletion, view and so on. In some cases, several alternative methods were developed in DSSFCMR to support a task for use by people with different computer skills (e.g. three methods were developed in DSSFCMR to enter the observed data on Historical Flood Events in Section 5.2.2.2). The developed interface of tabular and graphical view functions can effectively help the user to check the entered data and analyse the data. Many common graphical formats in hydrological analysis such as hydrographs, hyetographs, and flood water elevations and discharge rating curve (Figure 5.26) were developed. These functions facilitate the analysis and management of relevant data effectively and conveniently, and exchange data quickly.

Two separate methods in SGDDA subsystem were developed in DSSFCMR to perform spatial and graphic data display and analysis of flooded areas resulting from the forecasts. They were developed for different users (with different computer skills) and/or for use by different organisations with different levels of resources. The first method overlaid the simulated flood area on a pre-generated image of the flood prone area, which also considered the flood affecting physical attributes such as the river, roads and streets. This was done through the Window interface of DSSFCMR. The second SGDDA method was developed to integrate the simulated flood inundated area with other geographical information data using MapObjects software in DSSFCMR to produce the flood inundation area. In addition to the flood levels, the user can obtain the flood damage data such as number of house properties subject to flooding, number and composition of people subject to flooding, etc. All flood forecasting scenarios can be spatially displayed and analysed with both methods, which allow the decision maker to make the effective decisions.

### 5.3 Run-Models

The item **Run-Models** of the Main Menu (Figure 5.2) was developed to calibrate the hydrologic and hydraulic models separately, to calculate the flood hydrographs and flood levels corresponding to the peak discharges (of these flood hydrographs), and to transfer the model

parameters and results (such as hydrographs and corresponding water levels) to appropriate database tables.

### 5.3.1 Functions and Interface

Two designed functions of **Run-Models** are embedded in the submenu of Figure 5.39. They are: **Calibration** and **Forecasting**. There are also two subitems under the **Calibration** function: **URBS** for calibration of the URBS hydrological model and **HEC-RAS** for calibration of the HEC-RAS hydraulic model.



Figure 5.39 Submenu of **Run-Models**

#### 5.3.1.1 Calibration of URBS Hydrological Model

The calibration of the URBS hydrological model is facilitated in DSSFCMR by developing several interactive Interfaces in a linear (or cascade) mode, as follows:

- Construct and save the Catchment Definition File.
- Construct and save the Rainfall Definition File.
- Run URBS and save the simulated hydrograph and relevant parameters in appropriate database tables.

##### (a) Catchment Definition File

When clicked on the item **URBS** in **Calibration** submenu, the interactive Interface for the Catchment Definition File is displayed (Figure 5.40). The controls and buttons on Figure 5.40 are same as those on Figure 5.4 except the buttons **Add** and **Delete**, and the combo boxes *River Basin* and *Model*. The buttons **Add** and **Delete** are disabled in Figure 5.40 since during the calibration, the user does not change the data in Model Parameters database D2\_U\_C.MDB.

These data are changed in the database only during the database management stage (Section 5.2.1.2(a)) for efficient and effective database management. The *River Basin* and *Model* are hardwired as Maribyrnong River Basin and Basic respectively, since DSSFCMR is specifically developed for the Maribyrnong River basin with URBS Basic model (the reasons for using the Basic model are given in Section 3.2). The reader is referred to Section 5.2.1.2 (a) for details of the other parameters.

**Data Input Screen for Catchment Definition File**

River Basin:

Model:

Alpha:  m

Initial Loss (mm):   Compute IL 7-day Mean Daily Q (m<sup>3</sup>/s):

Continuing Loss (mm/h):  Baseflow (m<sup>3</sup>/s):

**Display Only**

Total Subcatchments:

Subcatchment No:  Area (km<sup>2</sup>):  Reach Factor:

L (Reach Length)(km):  U (Urbanisation):  F (Forest):

Confluence at the Outlet of Subcatchment:  UpCatchment:

DownCatchment:  Output Q:  VBF:  Res. s~q File Name:

Route L:  Route U:  Route F:  Route Factor:

---

Total Pluviometers:  Location:  Covered Subcatchment by Pluviometer:

Total Rating Curves:  Location:

Total Gauging Stations:  Location:

Figure 5.40 Data Input Screen of Catchment Definition File in URBS Model Calibration

The editing parameters of *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* are displayed in Figure 5.40 as default parameters. These are the values used in the previous URBS model run within DSSFCMR (either calibration or forecasting model). These values can be changed during the calibration, but cannot be saved in the database. Two methods were developed to change the default values of these editable parameters during calibration. They are:

- When the value is not in the list of the relevant parameter, enter this value into the text box of the relevant combo box.
- Click on the dropdown of the combo box of the relevant parameter, and then select a value from the list of possible values (derived from historic flood events or experts' knowledge).

An alternative way of getting the value for *Initial Loss* is using expert knowledge (obtained from Melbourne Water Corporation) by ticking the check box *Compute IL*. The details of this method are given in Section 5.2.1.2 (a).

Once the editable data are entered or changed, click on the button **OK** to save the Catchment Definition data and close the screen. This also displays the Data Input Screen for Rainfall Definition File (Figure 5.41). Note that the editing parameters entered or changed from the default values in Figure 5.40 are saved in the Catchment Definition Data file, but they are not saved in the database. They need to be saved using database management operations (Section 5.2.1.2(a)).

The button **Cancel** in Figure 5.40 closes the screen without saving the edited data in the Catchment Definition File. The process of calibration is then stopped, and the Main Menu (Figure 5.2) is displayed.

#### **(b) Rainfall Definition File**

Most of the parameters displayed in Figure 5.41 are 'editable' parameters, except the 'display only' parameters of *Sub Catchment No*, *Simulate Date(DD/MM/YY)* and *Simulate Time(HH:MM:SS)*. This interface is also used for forecasting of hydrographs and therefore some parameters, which are specifically designed for forecasting, are not relevant for calibration and are disabled in Figure 5.41. The disabled parameters are *Total Forecast Rain Time (h)*, *Total Forecast Rainfall (mm)*, *One Hour Rainfall / Total Forecast Rainfall (%): In First Hour, In Second Hour* and *In Third Hour*, and *DownStream Water Level*. Note that the button **Delete** in Figure 5.41 is also disabled. All parameters in Figure 5.41 that will be used in calibration are described below:

Figure 5.41 Data Input Screen of Rainfall Definition File - Calibration

- The *River Basin* is hardwired as Maribyrnong River Basin.
- The *Type of Model Run* is hardwired as CALIBRATION.
- *URBS\_DATE* (format: Month/Day/Year). This is the reference date for the URBS model calibration. Although it is not necessary, it is recommended that the user enters (or selects from the list of combo box) the start date of the flood event in the field. Once this is set, this value remains on the screen for the subsequent calibration and forecasting of hydrographs.
- *URBS\_Time* (format: Hour:Minute:Second). This is the reference time for the URBS model calibration. Although it is not necessary, it is recommended that the user enters (or selects from the list of combo box) the hour of the start time of the flood event in the field. The Minute and Second is set as zero by DSSFCMR. Once the *URBS\_Time* is set, this value remains on the screen for the subsequent calibration and forecasting of hydrographs.

- *Time Interval (h)*. This is the time interval used for modelling of rainfall and runoff. The recommended value is 1 hour and is given as the default. It is an editable parameter.
- *Run Duration (h)*. Computations are carried out for this duration in computing flood hydrograph from *URBS\_Date* and *URBS\_Time* values. This value is an editable parameter and must be larger than or equal to that of *Total Rainfall Duration*.
- *Total Rainfall Duration (h)*. This is an editable parameter and is the duration of the storm event used for calibration.
- *Observed Rainfall Start Time (h)*. This is the duration in hours from *URBS\_Time* to the start time of the observed rainfall data used for the calibration event. If *URBS\_Time* is set as suggested earlier, this value is equal to zero. This is an editable parameter.
- *Observed Rainfall Interval*. This is the time interval used in observed rainfall data. The default value in DSSFCMR is 1 hour. This is an editable parameter.
- *Sub Catchment No.* The value of this parameter can be displayed only, and cannot be edited. However, the subcatchment number can be selected (or highlighted) to show the values of the other parameters, which are dependent on the subcatchment number. Click on the dropdown on the right of the box to view the list of subcatchment numbers and select (or highlight) a subcatchment. The value of *Rain on Sub Catchments* depends on selected SubCatchment No. and the value is the rainfall for this subcatchment over the period of storm considered in the calibration.
- *Rain on Sub Catchments*. Three methods were developed to enter data (for the user's convenience) as follows:
  - The first method uses observed rainfall data in pluviometers stored in D4RFE.MDB for relevant subcatchments and does not require any input from the user other than clicking on the **OK** button on Figure 5.41, which displays the warning screen shown in Figure 5.42. Click on the **OK** button on Figure 5.42 to close the warning screen. The DSSFCMR then reads the observed rainfall data stored under pluviometers for this calibration event for the *Total Rainfall Duration*, and extracts the values of *Rain on Sub Catchments* from the relevant pluviometers. These values are then listed in the combo box of *Rain on Sub Catchments* (Figure 5.43). At the same time, the text of 'Rainfall Ready' is displayed in the text box of *Rain on Sub Catchments*. The user can click on the **OK** button on Figure 5.41 again to continue the process.



Figure 5.42 Warning Screen for Using Observed Rainfall for Each Sub Catchment

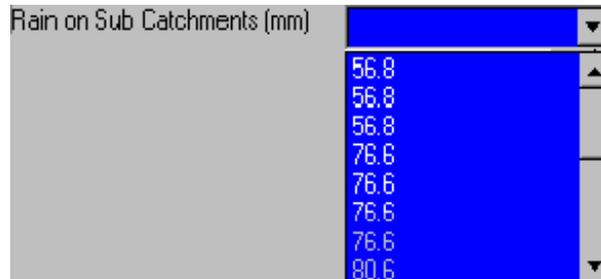


Figure 5.43 Screen of Rainfall in Each Sub Catchment Read from Database D4RFE.MDB

- The second method allows the user to enter the same value into all sub catchments. In this case, the user is required first to select (or highlight) the symbol \* in *Sub Catchment No* (\* is the default), then enter the required value in *Qty* box and next move the cursor to *Rain on Sub Catchments* and click on it. Finally, the user is required to click on the **ADD** button. Clicking on the dropdown of *Rain on Sub Catchments* allows the user to view the list of rainfalls on each sub catchment. For example, enter **100** in the *Qty* box, move the cursor to *Rain on Sub Catchments* and click on it, and then click on the **ADD** button. The values of *Rain on Sub Catchments* are shown in Figure 5.44.
- The third method allows the user to enter different values into different subcatchments by editing the values using either of the above two methods. Click on the dropdown of *Sub Catchment No* to select a subcatchment that requires a different rainfall value, then enter the required value in *Qty* box, next move the cursor to *Rain on Sub Catchments* and click on it, and finally click on the **ADD** button. Clicking on the dropdown of *Rain on Sub Catchments* shows the changed value. Figure 5.45 shows the results of using this method after changing rainfall for the subcatchment 2 from 100 mm to 50 mm.

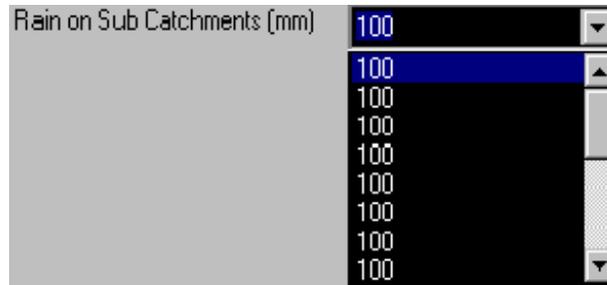


Figure 5.44 Screen Showing Same Rainfall in Each Sub Catchment



Figure 5.45 Screen Showing Different Rainfalls in Different Sub Catchments

Note that the values obtained from the first method can be overwritten by the second and third methods, but not the other way around. Similarly, the values obtained from the second method can be overwritten by the third method (and not the other way around).

- *Hydrograph Start Time*. This is the duration in hours from *URBS\_Time* to start time of the observed flow data used for the calibration event. If *URBS\_Time* is set as suggested earlier, then this value is zero. This is an editable parameter.
- *Hydrograph Time Interval*. This is the time interval for observed discharge data. The default value in DSSFCMR is 1 hour. This is an editable parameter.
- *Simulate Date(Day/Month/Year)*. This depends on *URBS\_DATE*, *URBS\_Time*, *Total Rainfall Duration* and *Observed Rainfall Start Time*. If values of these parameters are changed, the value in *Simulate Date* box will automatically be changed. This is not an editable parameter and specifies the end date of simulation.
- *Simulated Time (Hour:Minute:Second)*. This depends on *URBS\_DATE*, *URBS\_Time*, *Total Rainfall Duration* and *Observed Rainfall Start Time*. If values of these parameters are

changed, the value in *Simulate Time* box will automatically be changed too. This is not an editable parameter and specifies the end time of simulation.

The button **OK** on Figure 5.41 closes this screen, save the Rainfall Definition file, runs the URBS model, reads the results from DOS based file created by URBS, saves the results and parameters in relevant database files and displays the Main Menu (Figure 5.2). The button **Cancel** on Figure 5.41 closes this screen, and displays the Main Menu. In this case, the Rainfall Definition file is not saved and the process of calibration is stopped.

In general, the developed functions embedded the DOS based URBS model as the hydrological model in DSSFCMR. Although the URBS model is suitable for forecasting floods, it does not have the facility for any adaptive parameter modifications. From the developed Windows Interface, the user can easily edit the URBS model parameters interactively using stored parameter values or expert knowledge supported by the developed functions in DSSFCMR. The calibration can be repeated using any set of parameters edited by the user. The major processes of calibration, such as constructing the input files for the URBS model based on the values of parameters, running the URBS model, and writing the model parameters used for calibration and corresponding output into appropriate database tables, are all automatically done.

The developed functions in Database allow the user to view and analyse the output (such as comparison of the calculated hydrograph from the URBS model with the observed hydrograph) in both graphical and tabular formats. The user can effectively, interactively and conveniently calibrate the URBS model through these DSSFCMR interfaces.

### **5.3.1.2 Calibration of HEC-RAS Hydraulic Model**

When clicked on the item **HEC-RAS** of **Calibration** submenu of **Run-Models** (Figure 5.39), Figure 5.46 is displayed, which allows the user to enter data to calibrate the HEC-RAS hydraulic model. The contraction coefficient, the expansion coefficient and the roughness coefficients (in left bank, main channel and right bank) at each cross section are editable for calibration. The downstream water level (i.e. water level at the cross section 1) can also be changed (or edited) during calibration. The contraction coefficient, the expansion coefficient and the roughness coefficients at each cross section are extracted from the database D2\_U\_C.MDB and listed in

Figure 5.46 with respect to each cross section. The cross section 1 is the most downstream cross section and a backwater curve type water surface profile was considered for the flood prone area, which is appropriate for this particular river reach in the Maribyrnong River. This is also the case for most rivers, where flooding problems occur, and these river reaches have mild slopes and experience sub-critical flows. The *Date (YYMMDD)* combo box has dates corresponding to several observed flood events, which give flood discharge and corresponding flood levels at various cross sections. Any flood from this selection can be considered for calibration. The historical flood data such as the water levels at cross sections and corresponding flood peak discharges are already stored in the database D3HEF.MDB for these flood events. Figure 5.46 is similar to Figure 5.7 and therefore the reader is referred to Section 5.2.1.2 (b) for details of interface and controls of Figure 5.46. The differences between Figure 5.7 and 5.46 are the water level in Section 1 and Date(YYMMDD), which are required only for calibration.

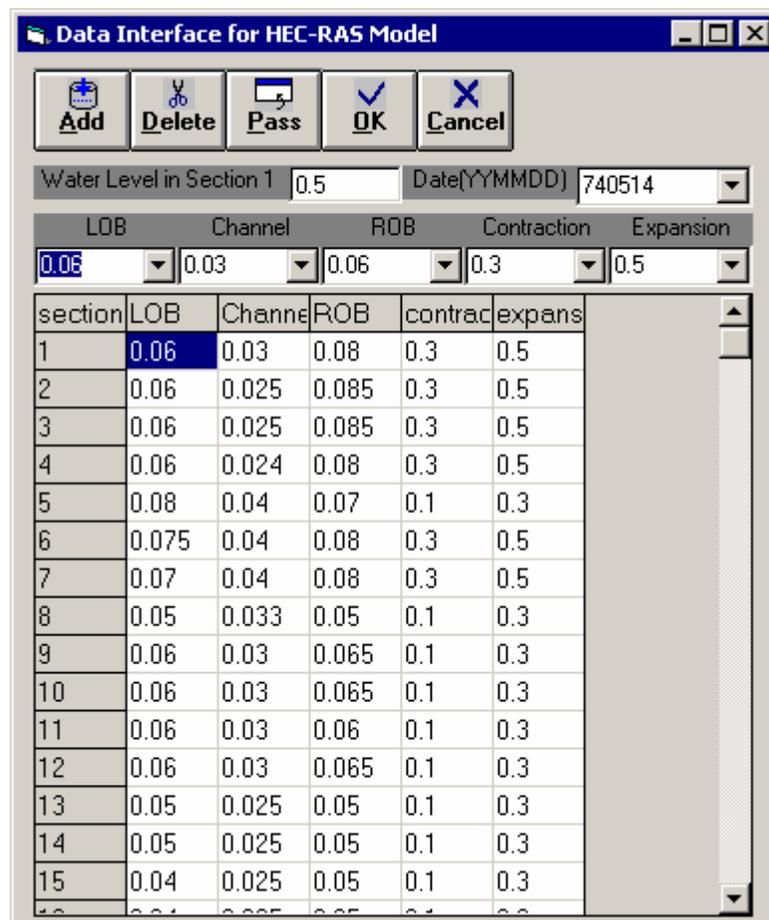


Figure 5.46 Interface for Calibrating HEC-RAS model

Initially, the default values for editable parameters are displayed. The possible values for editable parameters except the water level at the cross section 1 are already stored in combo box for selection. The **ADD** and **Delete** buttons are developed to add or delete these possible values. The button **Pass** replaces the value of the selected parameter in a cross section with the value in the combo box of the same parameter.

The **OK** button in Figure 5.46 are developed to write the above parameters to the HEC-RAS geometric data file, then run the HEC-RAS model, write the results (water levels at each cross section) to database D5SFS.MDB and finally close the interface. All these processes are automatically done. During this process, Figure 5.47 (HEC-RAS main window with loaded default project file), Figure 5.48 (steady flow analysis window), Figure 5.49 (steady flow calculation window), Figure 5.50 (profile output table) and Figure 5.51 (saving output file Window) are automatically displayed and then disappeared. The results are then stored in database D5SFS. MDB.

The button **Cancel** closes this interface of Figure 5.46 without carrying out above functions of the **OK** button.

The calibration processes can be repeated for any data set of editable parameters selected by the user, and all these calibration results can be saved. They can be viewed through the **Calibration HEC-RAS only** of **Simulated Flood Scenarios** under **Database**, which is described below.

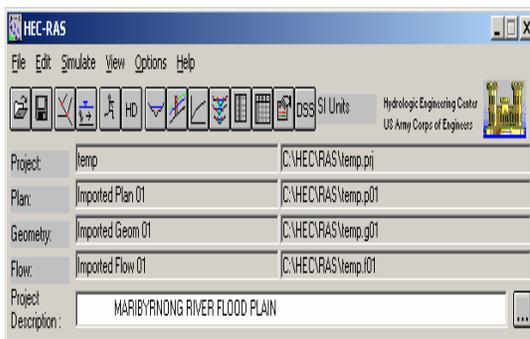


Figure 5.47 Main Menu of HEC-RAS

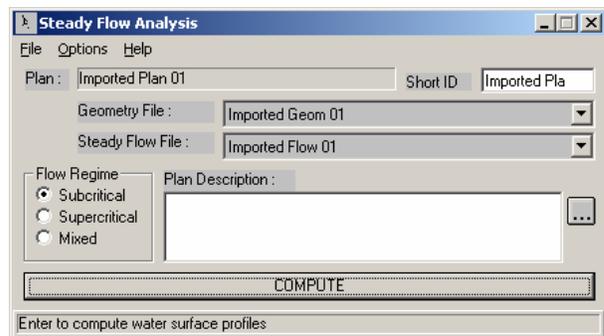


Figure 5.48 Steady Flow Analysis

	EG	WSEL	CRITICAL
WSEC 1	2.63	1.64	-3.90
WSEC 1.5	2.92	2.35	
WSEC 2	2.99	2.37	-4.37
BRIDGE			
WSEC 2.5	3.39	2.37	-2.62
WSEC 2.5	3.39	2.37	-2.58
WSEC 3	3.42	2.84	-4.42
WSEC 4	3.62	3.08	
WSEC 5	4.32	3.92	
WSEC 6	4.69	4.01	-3.81
BRIDGE			
WSEC 6.5	4.86	4.01	-3.13
WSEC 6.5	4.86	4.01	-3.14
WSEC 7	4.88	4.23	-3.82
WSEC 8	5.12	4.00	
WSEC 9	5.12	4.81	
BRIDGE			
WSEC 9.5	5.16	4.81	-5.06
WSEC 9.5	5.16	4.81	-5.07
WSEC 10	5.16	4.85	-5.37
WSEC 11	5.34	4.88	
WSEC 12	5.38	4.93	-3.73
BRIDGE			

Figure 5.49 Process for Calculation

Reach	River Sta	Q Total (m3/s)	Min Ch El (m)	W.S. Elev (m)	Ch W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Val Chrl (m/s)	Flow Area (m2)	Top Width (m)	Froutde #	Ch
Reach-1	46	446.00	-4.07	3.66		3.78	0.000233	1.60	361.97	110.56	0.21	
Reach-1	45	446.00	-2.53	3.56		3.71	0.000349	1.79	300.61	86.33	0.26	
Reach-1	44	446.00	-4.12	3.50		3.63	0.000446	1.67	321.44	86.38	0.22	
Reach-1	43	446.00	-2.57	3.41		3.51	0.000240	1.42	354.94	106.22	0.21	
Reach-1	42	446.00	-3.04	3.35		3.47	0.000284	1.55	354.75	171.44	0.23	
Reach-1	41	446.00	-3.04	3.31	0.21	3.45	0.000315	1.62	274.70	168.79	0.24	
Reach-1	40.5	Bridge										
Reach-1	40	446.00	-3.04	3.30	0.21	3.44	0.000317	1.63	274.07	167.97	0.24	
Reach-1	39	446.00	-3.27	3.29		3.39	0.000213	1.37	345.96	97.77	0.20	
Reach-1	38	446.00	-2.98	3.24		3.34	0.000168	1.43	338.55	133.32	0.21	
Reach-1	37	446.00	-3.52	3.18		3.32	0.000245	1.67	276.99	83.36	0.25	
Reach-1	36	446.00	-2.99	3.10		3.23	0.000208	1.61	300.85	130.05	0.23	
Reach-1	35	446.00	-3.83	3.10		3.18	0.000110	1.27	397.21	118.03	0.17	
Reach-1	34	446.00	-3.84	3.06		3.15	0.000128	1.34	381.49	210.14	0.19	

Figure 5.50 Profile Output Table

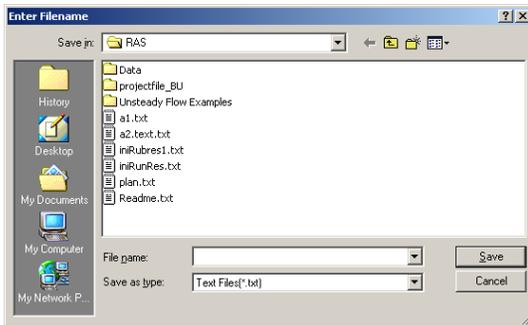


Figure 5.51 Save Output into Text File

As stated earlier in Section 5.2.4, the **Calibration HEC-RAS only** of **Simulated Flood Scenarios** under **Database** (Figure 5.2) was developed to view and analyse the calibration results of the HEC-RAS model. After all required calibration runs are completed with HEC-RAS, clicking on **Calibration HEC-RAS only** of **Simulated Flood Scenarios** under **Database** displays the interface shown in Figure 5.52. The left table on Figure 5.52 gives the calculated results. The right table on Figure 5.52 shows the HEC-RAS model parameters used for the calibration event selected (or highlighted) in the left table. Each calibration scheme (or event) in the left table in Figure 5.52 has three rows of data related to water levels. The first row gives the calculated water levels obtained during calibration, which had been stored in the database D5SFS.MDB, the second row is the observed water levels read from D3HFE.MDB, and the third row is the differences between calculated and observed water levels. As can be seen, it is not necessary to have an observed water level at each cross section. When the user clicks on the field of *SchemeNo* of the calculated water level row (i.e. the cells with a number in *SchemeNo*), the parameters that related this record are displayed in the right table.

Scheme	Sec01H	Sec02H	Sec03H	Sec04H	Sec05H	Sec06	Sec07	Sec08
1	0.5	0.75	0.75	0.92	1.01	1.44	1.51	1.5
							1.22	
							0.28	
2	0.5	0.71	0.71	0.88	0.95	1.16	1.14	1.2
							1.22	
							-0.09	

sections	LOB	Chan
1	0.06	0.03
2	0.06	0.025
3	0.06	0.025
4	0.06	0.024
5	0.08	0.04
6	0.075	0.04
7	0.07	0.04
8	0.05	0.033
9	0.06	0.03
10	0.06	0.03
11	0.06	0.03
12	0.06	0.03
13	0.05	0.025
14	0.05	0.025

Figure 5.52 Results of Calibration HEC-RAS Model

The buttons **Del**ete, **Undo**, **Select**, **OK** and **Help** on Figure 5.52 are active, while the buttons **New**, **Add**, **Find**, **Uppdate** and **View** are inactive. The adding data in D5SFS.MDB for simulated water level scenarios are automatically done by DSSFCMR using the button **OK** on Figure 5.46, while the record finding, updating and viewing functions are not necessary for HEC-RAS calibration. The functions of buttons **Undo**, **Select**, **OK** and **Help** on Figure 5.52 are same as those on Figure 5.4 in Section 5.2.1.2 (a) and the reader is referred to the Section 5.2.1.2 (a) for details. The button **Del**ete on Figure 5.52 can be used to delete all results of calibration.

The developed interface had made the calibration easier by allowing the user to edit boundary conditions and model parameters for HEC-RAS running, and then to view the calibration results and to compare calculated water levels with observations. It has automated the process of rewriting the flow and geometric data files after changes to boundary conditions and model parameters, running the HEC-RAS model, reading the results file and storing the required results in the database.

### 5.3.1.3 Forecasting

The function of forecasting was achieved through several interfaces in the cascade mode, and is triggered by **Forecasting** under **Run-Models** of the Main Menu of DSSFCMR (Figure 5.2).

The *Data Input Screen of Catchment Definition File* of the URBS model is displayed first as Figure 5.53. The functions of controls on this interface are similar to these on Figure 5.40 and therefore the reader is referred to Section 5.3.1.1 (a) for details. The parameter values of *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* displayed in Figure 5.53 are the values used in calibration or forecasting, when this screen was used prior to this forecasting session. However, the user can change these values, if necessary, before forecasting.

Figure 5.53 Data Input Screen of Catchment Definition File in URBS Model - Forecasting

The button **OK** in Figure 5.53 saves the Catchment Definition file and closes the screen. This also displays the *Data Input Screen for Rainfall Definition File* (Figure 5.54). The controls and their functions on this interface are similar to those on Figure 5.41. Note that there are 2

additional control boxes, namely, *Observed Rainfall Duration* and *Pluviometer Name* in Figure 5.54 compared to Figure 5.41. These additional combo box information is only required during the forecasting stage (and not during the calibration). The *Pluviometer Name* is self-explanatory. The *Observed Rainfall Duration (h)* refers to the duration up to forecasting time, which is not relevant in calibration. Some fields (related to forecasting) that were not active (i.e. *Total Forecast Rain Time; Total Forecast Rainfall; One Hour Rainfall / Total Forecast Rainfall (%) in First Hour, in Second Hour, and in Third Hour and %*) during the calibration stage are active during the forecasting stage. The specific functions developed for forecasting on Figure 5.54 (which are different to the calibration) are described below:

Figure 5.54 Data Input Screen of Rainfall Definition File in VRBS Model – Forecasting

- *Run Duration (h)*. This value must be larger than that of *Total Rainfall Duration*.

- *Total Rainfall Duration (h)*. This value must be equal to the sum of *Total Forecast Rain Time* and *Observed Rainfall Duration*.
- *Total Forecast Rain Time (h)*. This is the total time for input of forecast rainfall data. Three values, namely 0, 1 and 3 can be selected from the list. Values above 3 hours were not considered in the system development, since it is difficult to forecast rainfall accurately beyond 3 hours. The flood forecasting uses observed rainfall data up to the *Simulate Date* and *Simulate Time* and forecast rainfall during *Total Forecast Rain Time (h)*. When *Total Forecast Rain Time* is 0, the flood forecasting only uses observed rainfall data up to *Simulate Date* and *Simulate Time*.
- *Total Forecast Rainfall (mm)*. This is the total forecast rainfall in each pluviometer in the text box of *Pluviometer Name*. There are two methods to enter these values, as described below:
  - The first method allows the user to enter the same value into all pluviometers. In this case, the user first selects (or highlights) the symbol \* in *Pluviometer Name* (\* is the default value), then enters the required value in *Qty* box, next moves the cursor to *Total Forecast Rainfall* and clicks on it, and finally clicks on the **Add** button. Clicking on the dropdown of *Total Forecast Rainfall* allows the user to view the list of rainfalls on each pluviometer.
  - The second method allows the user to enter different values in different pluviometers by editing the entered value by the (above) first method. Click on the dropdown of *Pluviometer Name* to select a pluviometer (which requires a different rainfall value), then enter the required value in *Qty*, move cursor to *Total Forecast Rainfall* and click on it, and finally click on the **Add** button. Clicking on the dropdown of *Total Forecast Rainfall* shows the changed value. This process can be repeated for any pluviometer.
- *One Hour Rainfall / Total Forecast Rainfall in First Hour*. This is the percentage of the total forecast rainfall in the first hour (after the end of the observed rainfall data) used for forecasting. This parameter is applicable only when the *Total Forecast Rain Time* is equal to either 1 or 3. Three methods were developed to deal with this parameter and they are:
  - If the value of *Total Forecast Rain Time (h)* is equal to one, the user does not need to enter this value. The system will automatically set the value as 100%. If the value of *Total Forecast Rain Time (h)* is equal to 3, use the second and third methods.
  - The second method is used when the percentages in all pluviometer stations are the same. First, select a value from this text box of % (or enter a value into the text box),

then enter the symbol \* in text box of *Pluviometer Name*, move the cursor to the text box of *In First Hour* and click on it, and finally click on the button **ADD**. This percentage is displayed for all pluviometer stations in *In First Hour*. This method is recommended when the percentages in all stations are the same.

- If the percentages are not the same at all pluviometer stations, the third method is used. First, use the (above) second method to display the same value for all pluviometer stations in *In First Hour*. Then, select the new value from the text box of % (or enter a new value into this text box), select the pluviometer (e.g. Romsey) from *Pluviometer Name* that requires change in value, move cursor to *In First Hour* and click on it, and finally click on the **Add** button. The dropdown of *In First Hour* shows the change in value. This process can be repeated for any pluviometer, which requires change in its value.
- *One Hour Rainfall / Total Forecast Rainfall (%) in Second Hour*. This parameter is applicable only when the *Total Forecast Rain Time* is equal to three. The input procedure is same as that of *In First Hour*. Note that the percentages at each pluviometer for first / second / third hours should add to 100% and this needs to be checked by the user.
- *One Hour Rainfall / Total Forecast Rainfall (%) in Third Hour*. This parameter is applicable only when the *Total Forecast Rain Time* is equal to three. The input procedure is same as that of *In First Hour*. Note that the percentages at each pluviometer for first / second / third hours should add to 100% and this needs to be checked by the user.
- *Rain on Sub Catchments (mm)*. The value of *Rain on Sub Catchments (mm)* depends on the *Sub Catchment No* variable and this value represents the observed rainfall for this storm up to the forecast time. There are three ways to enter data for this parameter and they are exactly same as those in Section 5.3.1.1(b).

The button **OK** in Figure 5.54 closes this screen, writes the Rainfall Definition File, runs the URBS model, reads the results from the DOS based output file, saves the model parameters and results in relevant database files and finally displays the Main Menu (Figure 5.2).

The button **Cancel** in Figure 5.54 closes this screen, and displays the Main Menu. In this case, the Rainfall Definition File is not written and the process of forecasting is stopped.

### 5.3.2 Error Handling

Three cases as described in Section 5.2.1.3 were also considered (and implemented) for handling different types of errors and conflicts in the Modelbase subsystem.

The error handling for the first case was developed to handle the following expected errors examples. Note that these are examples only and error handling was not limited to these examples.

- Attempting to edit values of display only parameters.
- Performing an action when no parameter is selected for the action. An example is clicking on the button **Add** to add the rainfall into combo box of *Rain on Sub Catchments (mm)* without clicking *Rain on Sub Catchments (mm)* first to select this variable.
- Entering data into a combo box with no values (e.g. if a parameter value is entered to *LOB* combo box in Figure 5.46, which does not contain any values, the new value is not accepted.)
- Deleting data that do not exist in the list.
- Data such as total number of pluviometers are not consistent with pluviometers used (i.e. data are not given for all listed pluviometers)
- Detecting incorrect values for parameters such as no value for forecasting period, or forecast period specified, but without forecast rainfall depth.
- Database table is too big to be stored in combo box.
- Reading / deleting from an empty database through list boxes. (i.e. no values is the list box)
- Duplicate data entry.

### 5.3.3 Final Remarks

The Modelbase subsystem allows easy calibration of both URBS and HEC-RAS models and the use of these models to generate forecast flood hydrographs and flood water levels.

The developed functions allow efficient use of database management functions to interact with the URBS and HEC-RAS models during calibration. It should be noted that the two models use different approaches in their calibration.

- The URBS hydrological model has model parameters, which are dependent on the storm event (i.e. *initial loss*, *continuing loss* and *base flow*) and other model parameters, which are not storm dependent (i.e. *alpha* and *m*). Therefore, it is recommended that the URBS model should be calibrated for the current flood event, which is under flood forecasting and warning. Prior to the decision making, the calibration of the URBS model can be done relatively easily compared to that of the HEC-RAS model.
- The HEC-RAS model, on the other hand, has parameters, which are not storm dependent. They are the Manning's roughness coefficients of left bank, channel and right bank and the expansion and contraction coefficients of each cross section. Because of the number of model parameters involved in the calibration of the HEC-RAS model, it is not recommended to calibrate the model for the current storm event just before decision making, but should be calibrated before decision making.

The developed functions also allow forecasting of flood hydrographs using the URBS model under the scenarios of no forecast rainfall, 1-hour forecast rainfall and 3-hour forecast rainfall. The peak discharges from forecast hydrographs are used to calculate flood levels in the flood prone area. The forecasting results such as model parameters, flood hydrographs and flood water levels are stored in database files for further analysis including generating the flood prone area image map, and interactive spatial display and analysis of the flooded area. The process of complicated data transfer during the investigation (e.g. the peak discharge to the water levels, then water levels to the shapefile of flooded area) is automatically done by the developed system functions. The procedure of forecasting and then decision making for flood warning can be repeated easily and conveniently with these developed functions at each time step during a flood event.

#### **5.4 Decision Support**

As stated earlier in Section 4.8, the user can simulate several flood scenarios due to forecast rainfalls for analysis at a certain time  $t_1$  during a flood event. The results of these analyses are stored in the database D5SFS.MDB. The Decision Support subsystem was developed for the user to select a smaller number of appropriate scenarios from the database D5SFS.MDB to make acceptable flood forecasting and warning decisions at time  $t_1$ . These selected decision scenarios and the corresponding information including the simulated date and time (i.e.  $t_1$ ) and the scenario

results such as observed rainfall and runoff, forecast rainfall, other important parameters relevant to these decision scenarios, forecast hydrograph and corresponding water stages are copied from the database D5SFS.MDB into the database D6RFW.MDB. The developed functions in DSSFCMR allow the user then to investigate the detailed decision making variables related to flood warning such as the flood inundated areas and people relocation (Section 5.2.4). The item of **Decision** in the Main Menu in Figure 5.2 was developed for this purpose.

When the user clicks on the item of **Decision** in the Main Menu of DSSFCMR, the interface in Figure 5.55 is displayed for the user to find relevant and appropriate decision scenarios through constructing a query statement. As can be seen, only the key parameters are displayed on this Interface, however, the result of the query statement will include all variables in a record (or scenario) such as key input parameters, forecast hydrograph and corresponding flood water levels at each cross section. The controls and buttons on Figure 5.55 are described below. Most functions and controls on Figure 5.55 are same as those on Figure 5.36 (Section 5.2.5). The functions and controls that require more details are explained below.

- The button **ADD** on Figure 5.55 together with combo boxes *Qty* and *%* will add a value into the list of parameters of *Total Forecast Rainfall* and *One Hour Rainfall / Total Forecast Rainfall (%) in 1st Hour, in 2nd Hour and In 3rd Hour* (refer to Section 5.3.1.3 for data entry details).
- The button **View** in Figure 5.55 will display the constructed query statement in the text box at the bottom of the screen. For example, the user selects the operator of = from the list in the left text box for the parameter of *Forecast Rain Period*, selects **3** from the list in the right box for the same parameter, selects the operator of *Between* from the list in the left text box for the parameter of *Downstream Water*, and enters 0.8 in the middle box and 1.5 in the right box for the same parameter, to build the query statement. When the user clicks on the button **View**, then the sentence of “**Select \* from SFS1 where ForecastStormPeriod = 3 and Sec01H Between 0.8 and 1.5**” is displayed as shown in Figure 5.55 (*SFS1* refers to the database table which stores the simulated flood scenarios). The query statement selects for the simulated flood scenarios, which have forecast rainfall period as 3 hours and downstream water level between 0.8 and 1.5.

	Operator	Value1		Value2
Alpha	*	*	and	*
m	*	*	and	*
Initial Loss (mm)	*	*	and	*
Continuing Loss	*	*	and	*
Baseflow	*	*	and	*
Pluviometer Name	*	Qty 100		% 100
Forecast Rain Period	=	3	and	
Forecast Rainfall (mm) One Hour	*	*	and	*
Rainfall / Total Forecast Rainfall (%)				
In 1st Hour	*	*	and	*
In 2nd Hour	*	*	and	*
In 3rd Hour	*	*	and	*
DownStream Water	Between	0.8	and	1.5

Select \* from SFS1 where ForecastStormPeriod = 3 and Sec01H Between 0.8 and 1.5

Figure 5.55 Interface to Find Scenarios in D5SFS.MDB to Build Acceptable Decision Scenarios

- The button **OK** on Figure 5.55 closes the current window and displays the decision scenarios selected based on the query statement (Figure 5.56). These decision scenarios are intended for flood warning decision at time  $t_1$  (i.e. 7 hours on October 16, 1983 in Figure 5.56). The user can click on the button **New** to transfer these selected scenarios (as the decisions at this time) to the database D6RFW.MDB. The functions and controls on Figure 5.56 are exactly same as those in Figure 5.28. The reader can refer to Section 5.2.4.2 for details.
- The button **Cancel** in Figure 5.55 closes the current window without producing any decision scenarios.

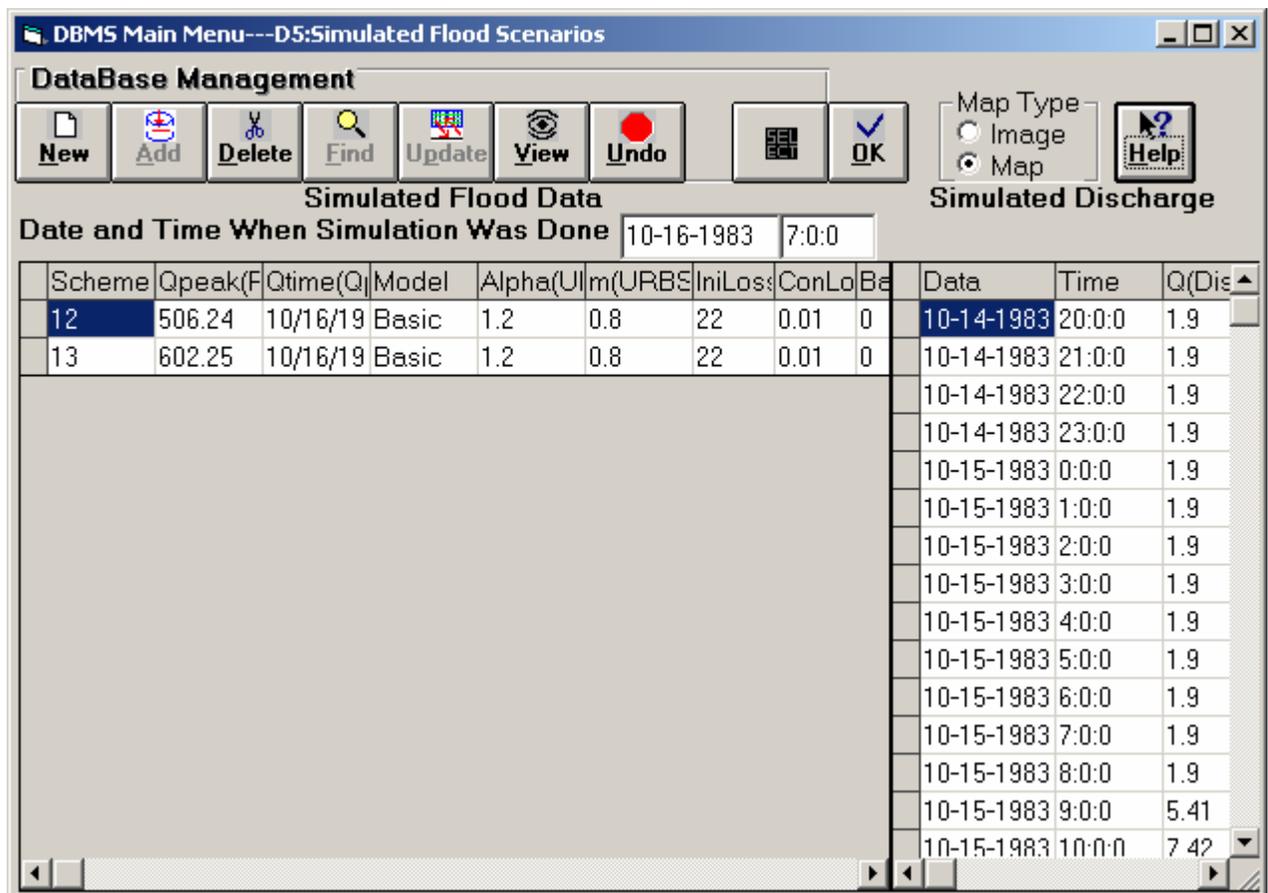


Figure 5.56 Decision Scenarios Corresponding to Query in Figure 5.55

## 5.5 Installation and System Requirements

In order to run DSSFCMR, the user must create a directory (with the name of *dssfcmr*) in the root directory of user's hard disk *c*. There should be then three subdirectories namely *Database*, *SGDDA* and *Modelbase* in the directory of *dssfcmr* and the file *dssfcmr.exe* file in the *dssfcmr* directory, as shown in Figure 5.57.

The system was originally developed to run on Windows 98, then updated to Windows 2000. A minimum of 64 MB of RAM and a minimum of Pentium 16MHZ CPU are recommended to run DSSFCMR. An installation program was developed to include most necessary files, but have not included some files due to copyright. Therefore, the following software tools need to be installed separately.

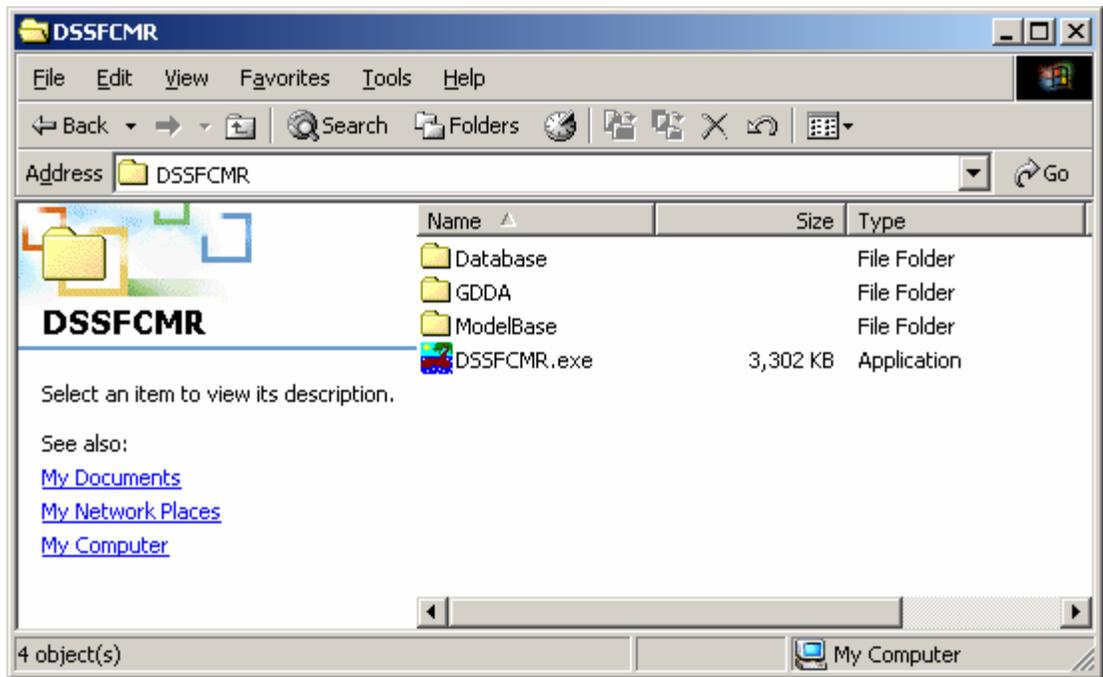


Figure 5.57 Contents of DSSFCMR Directory

- The HEC-RAS software tool should be installed in the root directory in drive *c*. It is a free download software, which can be downloaded from the website <http://www.cee.edu>. A HEC-RAS project file called *temp.prj* will be installed during installation of DSSFCMR package in the directory *c:\HEC\RAS*, and this project file will be updated when HEC-RAS is run within DSSFCMR.
- The *URBS.exe* file should be stored in the *Modelbase* subdirectory.
- The MapObjects software should also be installed in the computer. It is a commercial software tool and its details can be found in ESRI website (i.e. <http://www.esri.com>).

## 5.6 Summary

The system development of DSSFCMR discussed in this chapter was generally based on the functions and interface development, database development, system status, error handling and safety systems, testing and evaluation, and many others. This system development is more detailed, systematic and wider than those that had been developed for early definition of Decision Support Systems (DSSs), which mainly consisted of three subsystems (i.e. Interface, Database and Modelbase). As a result, an unique system (from technical point view) was developed in this

research project to help decision making in flood warning, dealing with all stages from data entry to searching final decisions. To achieve these goals, some unique technologies were used in the development of DSSFCMR. They are summarized as follows:

The developed Database subsystem can perform various tasks for general requirement in database management for flood warning. The developed functions help the user to analyse and manage relevant data effectively and conveniently, and exchange data quickly.

The DOS based URBS hydrological model was embedded in Windows based DSSFCMR. The user can edit the URBS model parameters from the developed Windows Interface to construct catchment and rainfall files. The data in DOS based output file of URBS and model parameters used in generating the output are then automatically transferred to DSSFCMR databases. The user is able to view and analyse the output of the URBS model both graphically and tabularly through the developed functions. Functions are developed for both calibration and forecasting using the URBS model. A deep understanding of the URBS model, database and advanced integrated programming skills were necessary to develop these functions.

The next challenge was the inclusion of the Window based HEC-RAS model in DSSFCMR (which was embedded). The user is allowed to edit boundary conditions and model parameters from the developed Windows Interface. DSSFCMR then rewrites the geometric and flow data files of the HEC-RAS project model. DSSFCMR then automatically runs the HEC-RAS model, and outputs the results and stores them in the relevant databases. Each calibration or forecast flood event results can be viewed in tabular format. DSSFCMR can display the flood inundation area by image format or undertake spatial analysis of the flood inundated area by interactive map, based on the flood water levels at each cross section obtained from the HEC-RAS model during forecasting stage. The shapefile (of ESRI) was used for the functionality of spatial analysis of flood inundation area. The full knowledge of the HEC-RAS software, GIS and advanced integrated programming skills were essential to develop this part of DSSFCMR.

The shapefile format developed by ESRI is a common GIS format and is used in this research project. The generation of shapefile instantly (or on line) for the flood inundated area corresponding to each simulated flood is a significant development in this thesis. Based on the calculated water level at each cross section, the shapefile for the flood inundated area is instantly

created, which is then used for spatial analysis of the flood inundated area through the developed interactive map interface. Two separate methods were developed in DSSFCMR to perform spatial data display and analysis of the flood inundated area for use by different users (with different computer skills) and/or for organizations with different levels of resources. The advanced integration technology applied to link various models (and their outputs) with the flood prone area images to generate the required maps and to develop an interactive spatial display and analysis tool is a core part of the development work in SGDDA module of DSSFCMR. The process of complicated data transfer during the investigation (e.g. the peak discharge to the water levels, then water levels to the shapefile of flood area) is automatically done by the developed system functions.

Unlike many previous DSSs, the developed decision support function in DSSFCMR allows the user to select a small number of alternative (but appropriate and relevant) decision flood forecasting and warning scenarios to build acceptable decisions at certain decision making times. The selected decision scenarios, which include information such as the time forecast was done, important model parameters, the observed rainfall and runoff up to forecast time, forecast rainfall, forecast hydrograph and corresponding water levels are transferred to the database D6RFW.MDB. This function helps the user make the decision easily and effectively, since the user is dealing with only a few acceptable decision scenarios.

# CHAPTER 6

## USE OF DSSFCMR FOR FLOOD WARNING IN MARIBYRNONG RIVER

### 6.1 Problem Definition and Decision Making Process

This chapter demonstrates how DSSFCMR can be used to help the decision making in flood warning in the Maribyrnong River basin. The description of the Maribyrnong River Basin is given in Section 4.1. As noted in Section 4.1, the area along the lower section of the river is residential with popular business centres, and this area has been inundated by floods in the past (e.g. 1974 and 1983). The application described in this chapter deals with the flood event in October 1983, but with topographical conditions as of 1997. It was assumed in this application that a hypothetical flood event identical to the flood event in October 1983 is occurring, and decision making is required for this event. This flood event was caused by heavy rainfall on the catchment. This event had started at 2000 hours on 14 October 1983. The DSSFCMR was used to demonstrate the decision making support for this event, which also included database management (such as entry of observed hydrological data), calibration of both hydrological and hydraulic models, forecasting of hydrographs and calculation of flood water levels due to peak discharges of the forecast hydrographs, map display and spatial analysis of flood inundation area, analysis of different hydrological scenarios for flood damage, and decision making support. As explained in Section 4.1, the forecast hydrographs at Keilor were considered for flood forecasting and warning of the flood prone residential area of the lower section of the river.

Figure 6.1 shows the decision making process of DSSFCMR for flood forecasting and warning at a certain time (i.e.  $t_1$ ) for the event that started at 20.00 hours on 14 October 1983. At time  $t_1$ , many possible forecast rainfall scenarios (4 shown in Figure 6.1) were considered for the next three hours (after time  $t_1$ ). For each rainfall scenario, the forecast hydrographs at Keilor was simulated by the URBS hydrological model; the peak discharge of the forecast hydrograph and the user-entered river water level at downstream end of the flood prone were then automatically written into the flow file of HEC-RAS project file; the HEC-RAS hydraulic model was then automatically triggered; and the water levels at each cross section corresponding to the peak discharge of forecast hydrograph were calculated. The calculated water levels at each cross section were then written into a file and these water levels together

with the peak discharge at the outlet of the catchment, and model parameters were stored in database D5SFS.MDB (D5). The information in D5SFS.MDB was then used by the Decision Support subsystem to choose a small number of simulated flood scenarios to build acceptable flood warning decisions at time  $t_1$ , and store their relevant information into the database D6RFW.MDB (D6). The above process can be repeated at any time after time  $t_1$  (for example at time  $t_2$  in Figure 6.1) when the decision maker feels a new flood warning decision is necessary. Note that the database management actions and calibration of both hydrological and hydraulic models are not included in the decision making process in Figure 6.1. Nevertheless, they are part of the complete decision making process and are included in this chapter.

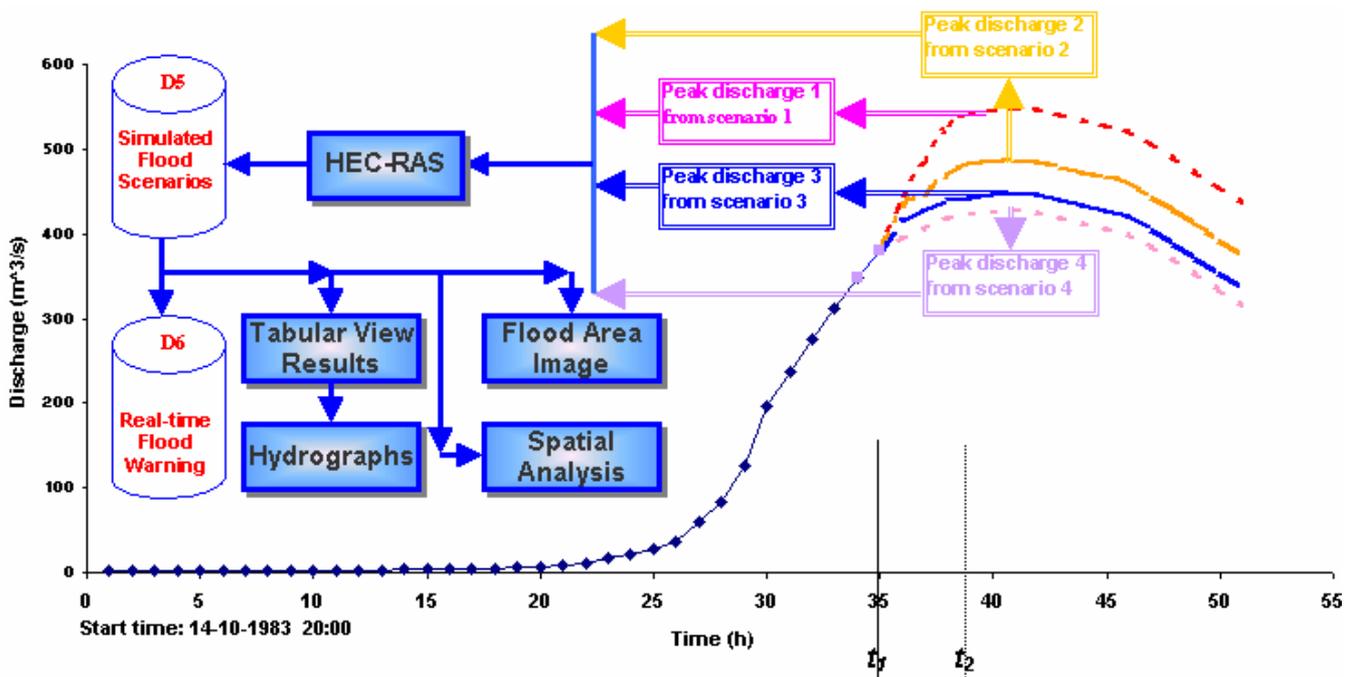


Figure 6.1 Decision Making Process for Flood Forecasting and Warning

The related works involved in decision making for the above example are illustrated in Table 6.1. First, the user needs to enter the observed data including rainfall and runoff up to  $t_1$  (i.e. at 0700 hours on 16 October 1983), which is described in Section 6.2. In some cases, the user may wish to calibrate (or re-calibrate) the hydrological, and/or the hydraulic model; the details of these calibrations are described in Sections 6.3 and Section 6.4 respectively. The user can then perform flood hydrograph forecasting using the URBS model and calculation of flood water levels using the HEC-RAS model for these forecasting scenarios. This work is illustrated in Section 6.5. Several flood forecasting scenarios are considered. The spatial analysis of the flood area results from the above scenarios is demonstrated in Section 6.6.

Finally, the decision support for flood warning is shown in Section 6.7. It should also be noted that this chapter not only demonstrate the applicability of DSSFCMR for October 1983 flood event, but also attempts to describe the functionality of all subsystems and functions through this event.

Table 6.1 Required Work for Flood Forecasting and Warning Decision Making

<b>Time</b>	<b>Required Work</b>	<b>Relevant Section in this Chapter</b>
up to $t_1$	Enter observed rainfall and runoff data before (up to) $t_1$ into the database	6.2
	Calibration of hydrological model	6.3
	Calibration of hydraulic model	6.4
	Forecast rainfall scenarios for forecast period	6.5
$t_1$	Forecast hydrographs	6.5
	Review the flood forecasting scenarios	6.6
	Decision support	6.7
$t_2$	Repeat the above procedure if required	

## 6.2 Data Process and Database Management

To demonstrate the designed and developed functions related to data process and database management in DSSFCMR, all four different methods of data entry (discussed in Section 5.2.2.2) were used at the gauging stations. As noted in Section 4.1.1, although 12 gauging stations were considered in the initial development of DSSFCMR rainfall, data were available only for 5 stations at Macedon, Romsey, Clarkefield, Darraweit Guim and Bulla, while flow data were available for Sunbury, Bulla and Keilor. In total, there are 7 gauging stations considered for this case study. The method proposed and used to apply DSSFCMR (which was originally developed to consider all 12 gauging stations) with 7 gauging stations was outlined in Sections 4.1.1 and 5.2.2.1.

The method of data entry from the text data file (Section 5.2.2.2 a) was used for stations Macedon and Romsey; the method of tabular data entry directly from interface (Section 5.2.2.2 a) was used for station Clarkefield and the method of single record entry from the interface (Section 5.2.2.2 b) was used for station Darraweit Guim. Finally, the method of entering data into database table directly was issued for station Bulla. As outlined in Section 5.2.1.2, this method of data entry or updating should be done only by experienced database

users who have reasonable database operation and management experience. All these 4 methods were used (and explained in this chapter) for demonstration purposes only. The user can use any of the four methods to enter data for any station as appropriate. Note that the flow only data entering at Sunbury, Bulla and Keilor are not explained in this Section, but the user can use any of the above 4 methods for this flow data entry.

After data entry, the developed functions in the Database subsystem of DSSFCMR were used to illustrate the database management of entered data such as finding the incorrect data using data display in tabular and graphic formats, fixing incorrect data using the update function, deleting incorrect data and so on. Note that these erroneous data were deliberately entered for illustration purposes. It should also be noted that some data such as evaporation at some stations were not available for this application and some other data such as flow data at Sunbury and bulla are used for display only. The flow data at Keilor were used to compare the calculated flood hydrograph with these observed flow data.

Click on the submenu **Historical Flood Events** of **Database** in the **Main Menu** (Figure 5.2), which displays the interface for historical flood events (Figure 6.2). This interface is same as that of Figure 5.10. In this case study, the historical flood event is same as the real-time flood event, since 14 October 1983 flood event is considered for flood forecasting and warning. Therefore, the database D3HEF.MDB and D4RFE.MDB are prepared as described in Section 6.2.1. Similarly, database management operations are the same for these two databases and explained in Section 6.2.2. Unfortunately, these two databases, which have the same information, need to be prepared separately for a current flood event whose data require to be in both databases. It is suggested that the functionality should be developed to copy the data relevant to a flood event from one database to the other, as future work.

### **6.2.1 Data Entry in DSSFCMR**

As stated earlier, four different methods of data entry were used to demonstrate the designed and developed functions related to data process and database management, as described below. Note that the methods 1described in Sections 6.2.1.1, 6.2.1.2 and 6.2.1.4 can either append or replace data in the database tables. However, the method described in Section 6.2.1.3 can only append data in the database table.

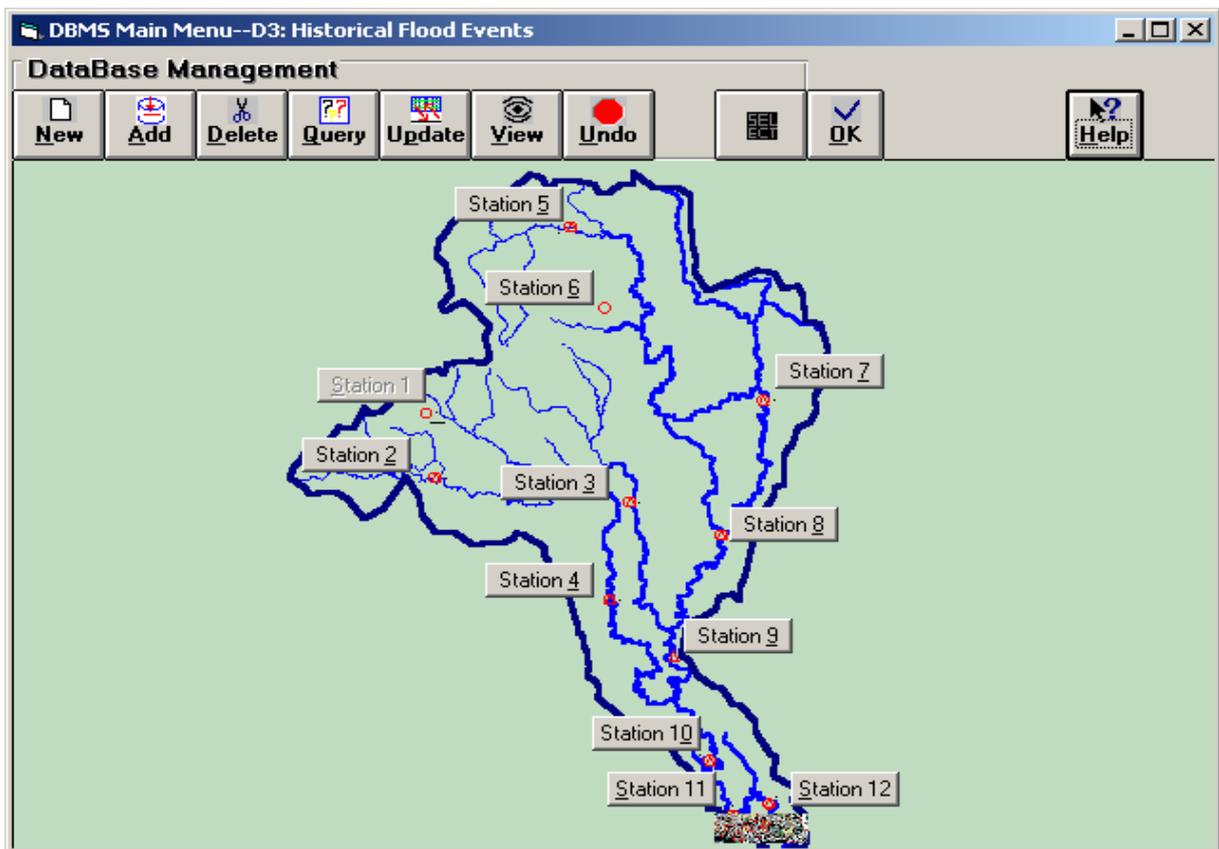


Figure 6.2 Historical Flood Events Window

### 6.2.1.1 Observed Data Entry Using Text File (at Romsey and Macedon)

- Step 1 Select the Station  
 Click on button **Station 1** (i.e. Romsey) from the map on the interface of Figure 6.2. With this operation, Romsey is selected as the active station.
- Step 2 Start Data Entry  
 Click on the button **New** on the interface of Figure 6.2 to start data entry using the text file method. The Input Confirmation Screen (Figure 5.11) is displayed.
- Step 3 Select Method  
 Click on the button **No** in Figure 5.11, which displays the interface for confirming deletion of all existing records (Figure 5.12). Note that clicking **Yes** in Figure 5.11 allows the user to append data to existing records. Click on the button **Yes** in Figure 5.12 to delete all existing records in database table *station1* in database D3HFE.MDB and/or D4RFE.MDB. The interface for entering data from data file is displayed then as in Figure 6.3 (which is same as Figure 5.15).

Step 4 Find Source File

There are two methods to enter source data file in Figure 6.3. The first method is to enter the source file path and name into the text box directly (e.g. *c:\dssfcmr\Database\station1.txt*). The second method is by double clicking on the text box in Figure 6.3, which displays the standard Open Window (Figure 6.4). Select the source file and then click on the **OPEN** button in Figure 6.4. The file path and name (e.g. *c:\dssfcmr\Database\station1.txt*) is appeared in the text box, as in Figure 6.3.

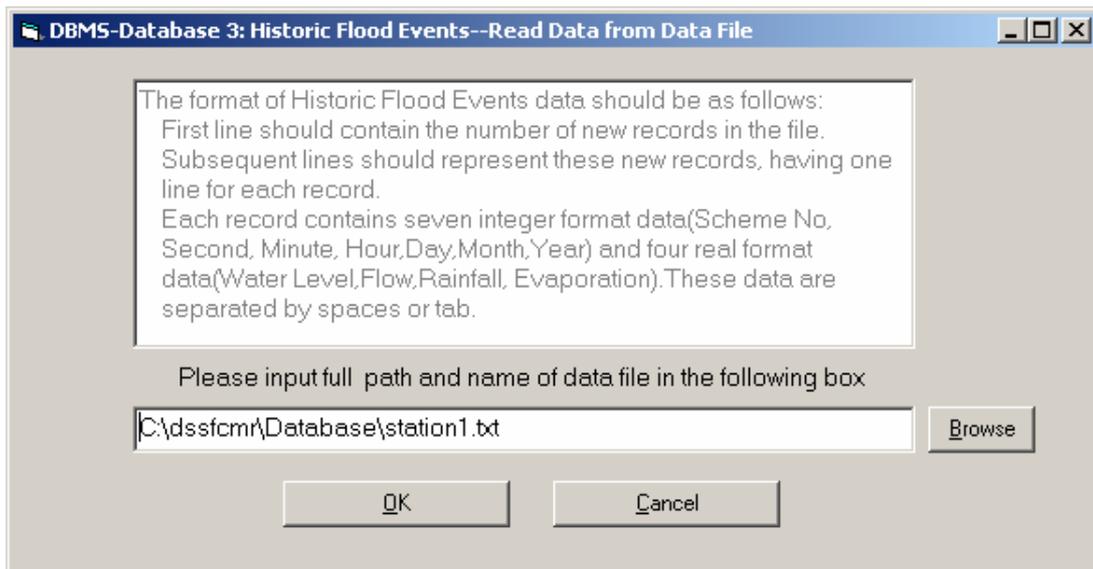


Figure 6.3 Screen for Entering the Data from Data File

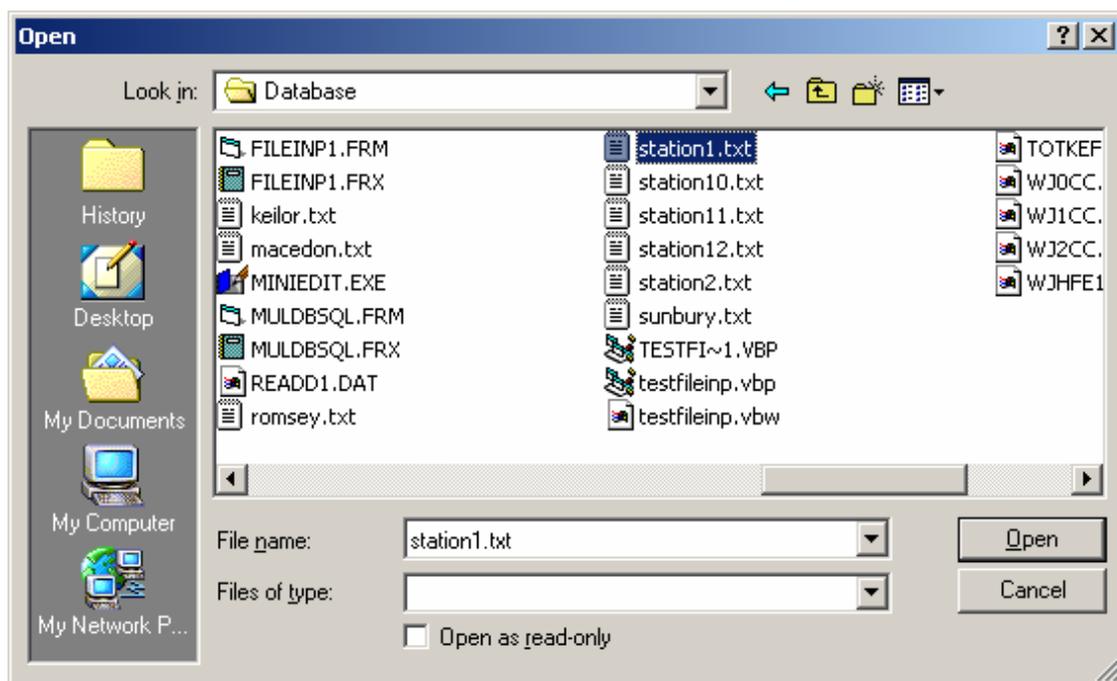


Figure 6.4 Screen for Opening Data File

Step 5 Transfer Data

Click on the **OK** button in Figure 6.3 to transfer the data in the text file to the database table *station1* in D3HFE.MDB (and /or D4RFE.MDB).

Step 6 Repeat for Macedon

Repeat Steps 1 to 5 to select **Station 12** and to transfer data in *station12.txt* to the database table *station12* for Macedon.

### 6.2.1.2 Observed Data Entry Using Table (at Clarkefield)

Step 1 Select the Station

Click on the button **Station 11** on the interface of Figure 6.2 to select Clarkefield as the active station.

Step 2 Start Data Entry

Click on the button **New** on the interface of Figure 6.2 to start the method of tabular data entry directly from the interface. The Input Confirmation Screen (Figure 5.11) is displayed.

Step 3 Select Method

Click on the button **Yes** on Figure 5.11, which displays the interface to confirm deleting all existing records (Figure 5.12). Click on the button **No** on Figure 5.12 to keep all existing data and append new data. The interface of a table (Figure 6.5) is then displayed. In Figure 6.5, the data in the database table exist up to 2300 hours on 15 October 1983.

SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow
18	0	0	12	15	10	1983	0.2	0.2
19	0	0	13	15	10	1983	0	0
20	0	0	14	15	10	1983	0.4	0.4
21	0	0	15	15	10	1983	1.4	1.4
22	0	0	16	15	10	1983	3.8	3.8
23	0	0	17	15	10	1983	5.6	5.6
24	0	0	18	15	10	1983	5.8	5.8
25	0	0	19	15	10	1983	5	5
26	0	0	20	15	10	1983	4.6	4.6
27	0	0	21	15	10	1983	4.8	4.8
28	0	0	22	15	10	1983	3	3
29	0	0	23	15	10	1983	3.6	3.6
*								

Figure 6.5 Interface for Tabular Data Entry Method for Clarkefield (Before Data Entry)

Step 4 Enter Data

Move the cursor to the end of the table in Figure 6.5, which shows a blank record. Enter 30, 0, 0, 0, 16, 10, 1983, 7.8, 7.8, 3.6 and 7.8 in each column in the blank record (row) from left to right, as the data for 0000 hours on 16 October 1983. Move the cursor down, and a new blank record is displayed again. Repeat the data entry procedure until all data are entered up to  $t_1$  (0700 hours on 16 October 1983) in database table *station11* in D3HFE.MDB (and/or D4RFE.MDB). Figure 6.6 shows all entered data.

Step 5 Finish

Close the interface by clicking on the top right cross button.

	SchemeNo	Second	Minute	Hour	Day	Month	Year	WaterLevel	Flow
	26	0	0	20	15	10	1983	4.6	4.6
	27	0	0	21	15	10	1983	4.8	4.8
	28	0	0	22	15	10	1983	3	3
	29	0	0	23	15	10	1983	3.6	3.6
	30	0	0	0	16	10	1983	7.8	7.8
	31	0	0	1	16	10	1983	1.6	1.6
	32	0	0	2	16	10	1983	0	0
	33	0	0	3	16	10	1983	0	0
	34	0	0	4	16	10	1983	1	1
	35	0	0	5	16	10	1983	2.2	2.2
	36	0	0	6	16	10	1983	1.6	1.6
*	37	0	0	7	16	10	1983	2.2	2.2

Figure 6.6 Interface for Tabular Data Entry Method for Clarkefield (After Data Entry)

6.2.1.3 Data Entry Using Single Record Entry from Interface (at Darraweit Guim)

Step 1 Select the Station

Click on the button **Station 10** on the interface of Figure 6.2 to select Darraweit Guim 10 as the active station.

Step 2 Start Data Entry

Click on the button **Add** on the interface of Figure 6.2, which displays the interface (Figure 6.7) that is used to add a record. Initially, all text boxes in Figure 6.7 are blank except the record number, which shows the new record number automatically generated by DSSFCMR. Figure 6.7 has SchemeNo as 37, which

states that there were 36 other records already in the database table. (A record is one row in Figure 6.6).

**Step 3** Enter Data

Enter 7, 0, 0 into text boxes of *Time(HH/MM/SS)*; 10, 16, 83 into text boxes of *Date(MM/DD/YY)*; 1 into text box of *Water Level(m)*, *Flow(m<sup>3</sup>/s)* and *Evaporation(mm)*; and 1.6 into text box of *Precipitation(mm)* (Figure 6.8). These are the relevant data for 0700 hours on 16 October 1983.

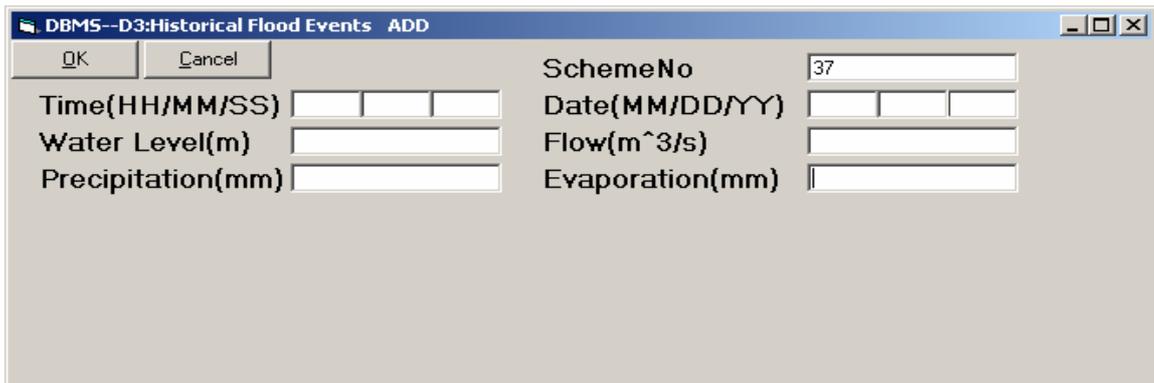


Figure 6.7 Interface for Adding a Record

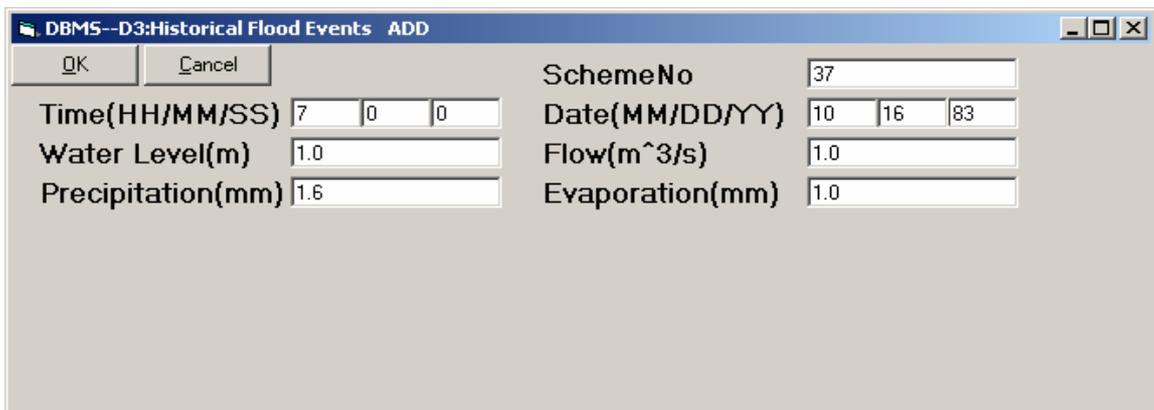


Figure 6.8 The Interface for Adding a Record (After Entering the Data)

**Step 4** Finish

Click on **OK** button in Figure 6.8 to save data in the database table *station10* and to close the interface of Figure 6.8.

**6.2.1.4 Entering Data into Database Table Directly (at Bulla)**

**Step 1** Open Relevant Database

Double click on the database *D3HFE.MDB* (and/or *D4RFE.MDB*) after searching for its directory using Window Explorer (e.g. *c:\dssfcmr\database\d3hfe.mdb*). This will open the database. The initial interface is similar to Figure 6.9 but without the two opened tables in the middle and right bottom parts of the interface.

**Step 2 Open Table**

Double click on the table *station2* to open. In this case, the database table is empty (middle part in Figure 6.9), since this was no data entered for the station. If there were data table in this database table, they were shown in Figure 6.9.

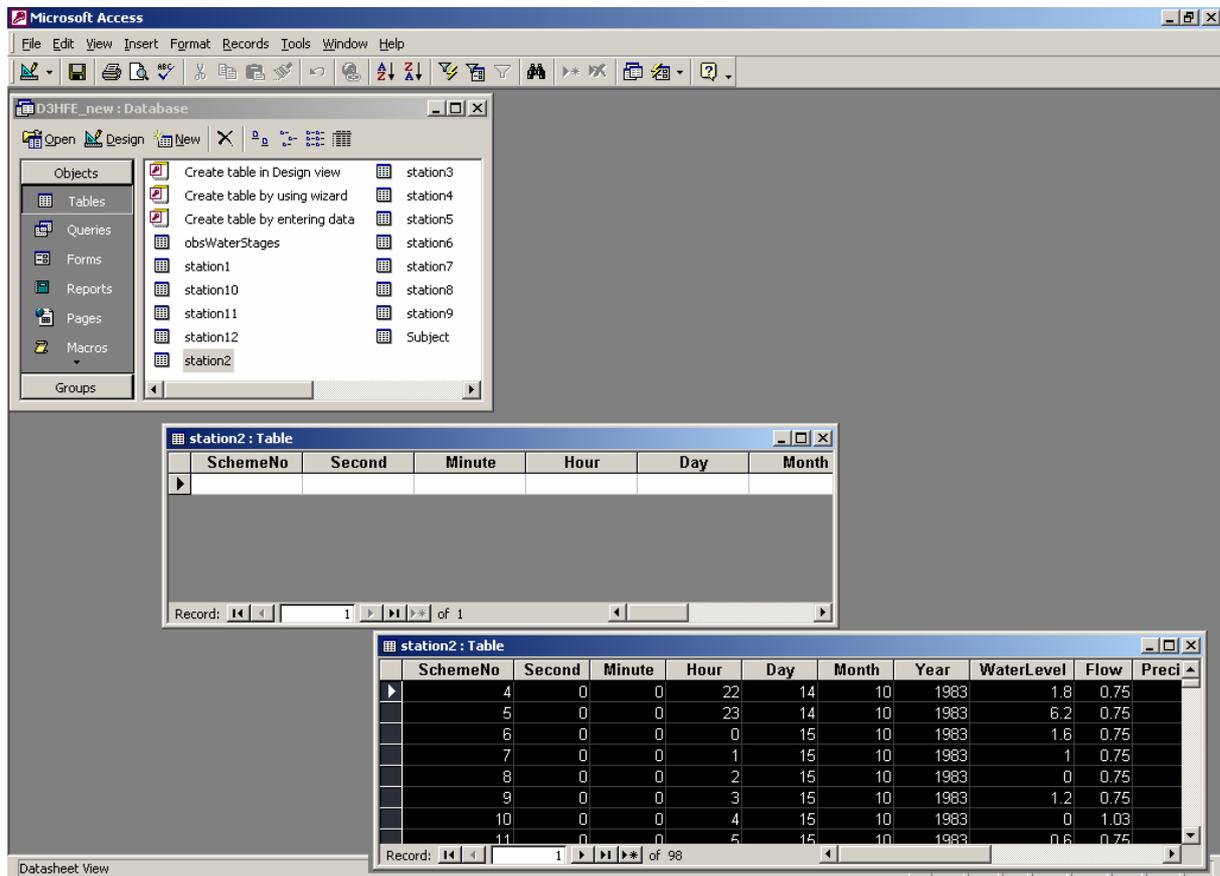


Figure 6.9 Interface for Entering Data from Database Directly for Bulla

**Step 3 Enter Data**

There are several methods to enter data into the database table such as entering data into the database table directly, converting from a text file, or copying data from a MS Excel sheet. In this example, data from a MS Excel sheet are copied to the database table. The copied data in the database table are shown in the bottom right part in Figure 6.9. Note that although two datasheet tables are shown in

Figure 6.9 (to illustrate what happens before and after data entry), there will be only one datasheet during the above operation. As noted earlier (Figure 6.2), these data entry operation can be only performed by a person with some experience in database operations and management.

Step 4      Finish

Close the interface by clicking on top right cross button in Figure 6.9.

## **6.2.2.      Data Management in Database Using Developed Functions**

This section describes how to use the developed functions in Database subsystem of DSSFCMR to perform the database management functions such as finding incorrect data, fixing incorrect data using update functions, deleting incorrect or unwanted data and so on. The user can refer to Chapter 5 for details of all relevant functions.

In Sections 6.2.2.1 and 6.2.2.2, it is assumed that there is an erroneous record in database table *station2*.

### **6.2.2.1      Check and Study the Entered Data by Tabular and Graphic View**

Step 1      Select the Station

Click on the button **Station 2** on the interface of Figure 6.2 to select Bulla 2 as the active station.

Step 2      Start View

Click on the button **View** on the interface of Figure 6.2. In this case, Figure 6.10 was displayed to indicate no data were found in the database for the specified period. Note that the default for specified period is set as from 0 hours of 01/01/99 to 0 hours of 01/01/99 (Figure 6.12). Clicking on the **OK** button in Figure 6.10 will display the Interface (Figure 6.11). As can be seen from Figure 6.11, *From Date/Time* and *To Date/Time* do not match with the information on records. This was the reason for displaying Figure 6.10, and also not showing a hydrograph above the data table in Figure 6.11. If data in the records were available for the period between *From Date/Time* and *To Date/Time*, Figure 6.10 will not be displayed and a hydrograph corresponding *From Date/Time* and *To Date/Time* will be displayed.

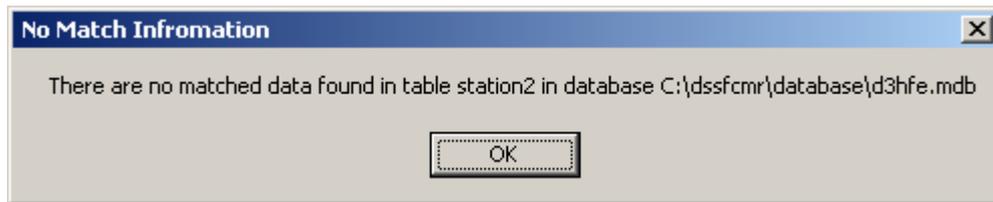


Figure 6.10 Interface showing 'No Matched Data Found' for Bulla

Step 3 View Requested Data

Enter start date and time of 10/14/83 and 21:00:00 in the text boxes of *From Date* and *From Time*, and end date and time of 10/16/83 and 07:00:00 in the text boxes *To Date* and *To Time* in Figure 6.11 respectively. Select **Rain and Flow** (Figure 6.12) in menu **Item** in Figure 6.11. The data for requested period is displayed in tabular and graphic forms as in Figure 6.13.

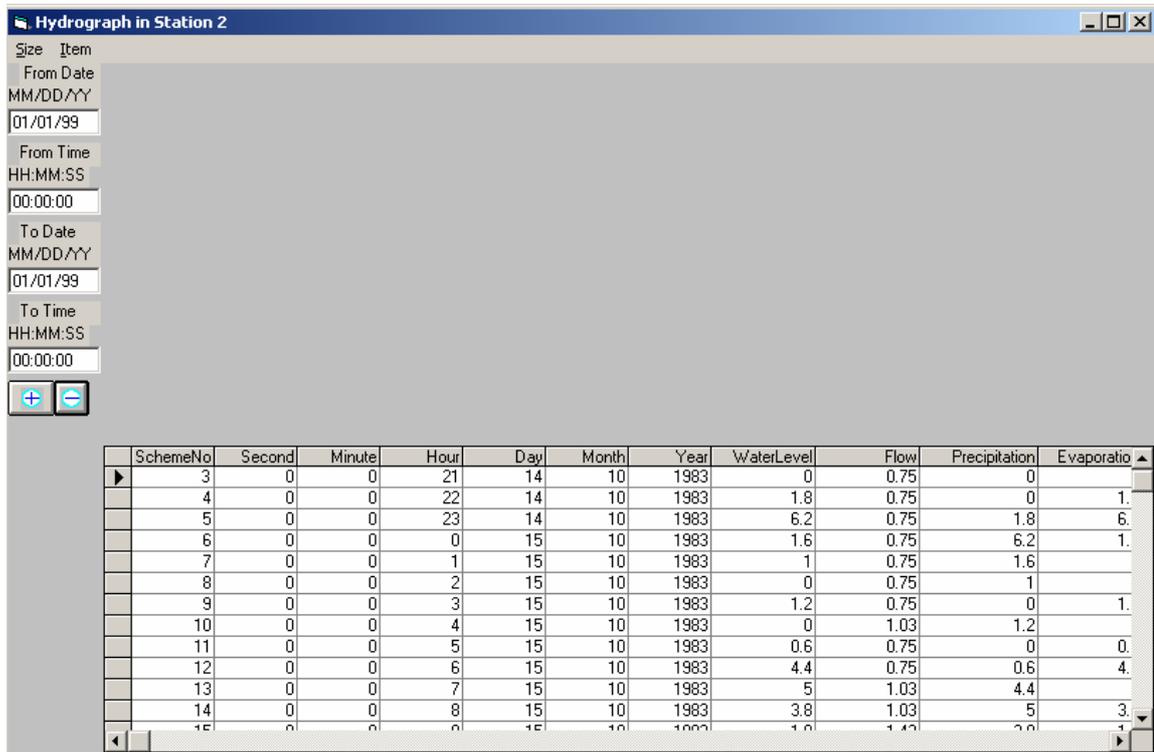


Figure 6.11 Interface to View Tabular and Graphic Data at Bulla

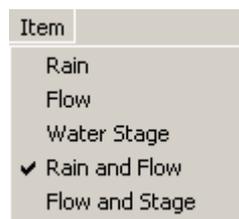


Figure 6.12 Menu of Item of Figure 6.11

**Step 4** Check the Data

It is observed from Figure 6.13 that the graph of rainfall and hydrograph at 0700 hours on 16 October 1983 was abnormal. The values in the table at the same time show a similar problem. The correct data should be 1.6 mm of rainfall and 255.2 m<sup>3</sup>/s of flow discharge instead of the current value of 106 mm and 25.52 m<sup>3</sup>/s respectively, and therefore a correction is necessary. Note that correction cannot be done under **View**, and the correction is done in Section 6.2.2.2.

**Step 5** Close and Reset

Close the interface in Figure 6.13 by clicking on the top right cross button. Figure 6.14 is then displayed. Clicking on the **Undo** button in Figure 6.14 to reset the relevant buttons available for use.

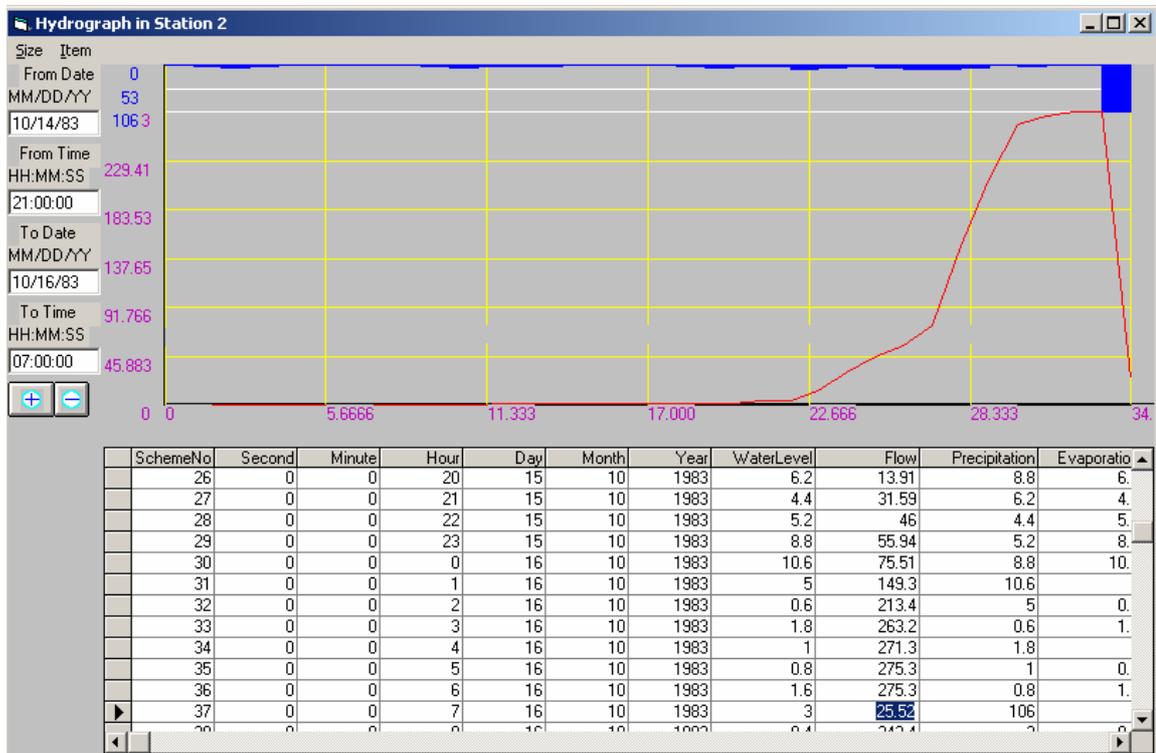


Figure 6.13 Viewing Data at Bulla

**6.2.2.2 Fixing Incorrect Data**

**Step 1** Start Updating

Click on the button **Station 2** and then on the **Update** button (which has become active after it was reset) on Figure 6.14. The interfaces of Figures 6.15 and 6.16 are displayed together.

Step 2 Find Record(s) Which Need Modifications

From Figure 6.16, select **Precipitation** from the combo box of *Variable Name*, and “>” from the combo box of *Operator*, enter **100** into the text box of *Value*, and click on the **OK** button. These operations display ”**Precipitation >=100**” in the text box of *Find Expression* and make the buttons of *Find By Variables* active (Figure 6.17). Clicking on the **F**irst button in Figure 6.17, the record 37 is displayed (Figure 6.18). This record is the record, which requires a correction.

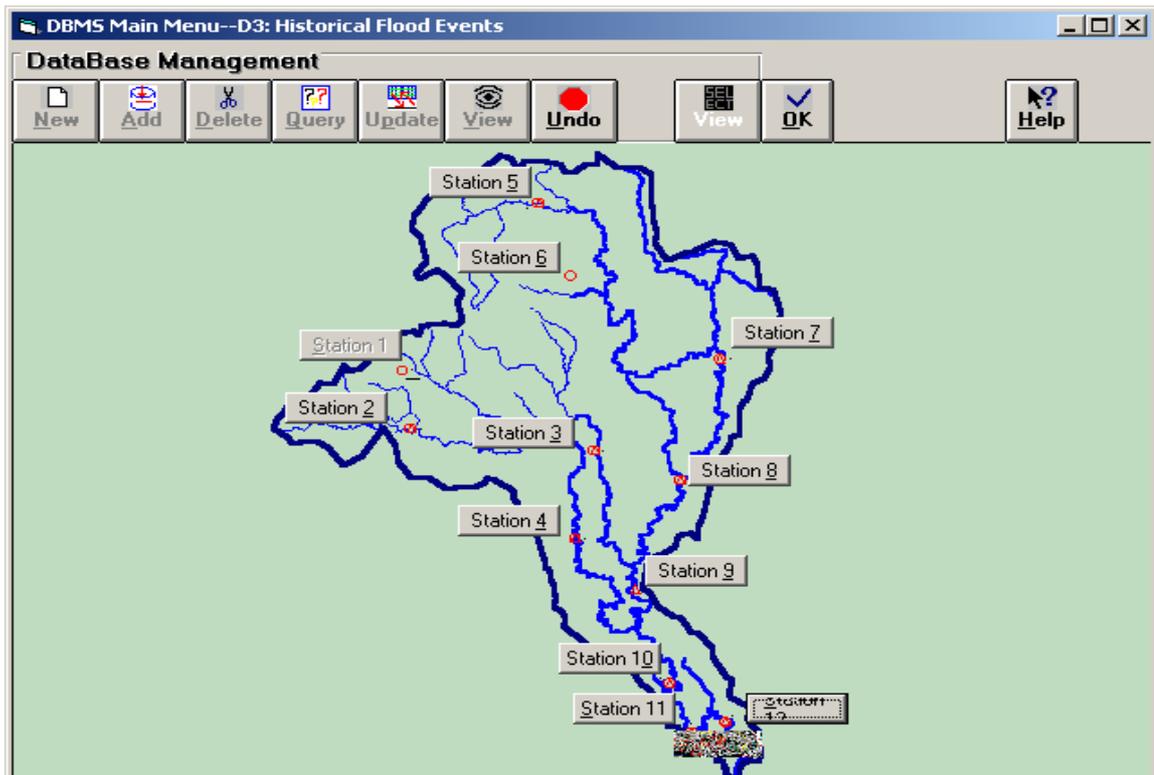


Figure 6.14 Interface for Historical Flood Events with Function Buttons Inactive

Step 3 Start Updating

Click on the button **Station 2** and then on the **Update** button (which has become active after it was reset) on Figure 6.14. The interfaces of Figures 6.15 and 6.16 are displayed together.

Step 4 Find Record(s) Which Need Modifications

From Figure 6.16, select **Precipitation** from the combo box of *Variable Name*, and “>” from the combo box of *Operator*, enter **100** into the text box of *Value*, and click on the **OK** button. These operations display ”**Precipitation >=100**” in the text box of *Find Expression* and make the buttons of *Find By Variables* active (Figure 6.17). Clicking on the **F**irst button in Figure 6.17, the record 37 is displayed (Figure 6.18). This record is the record, which requires a correction.

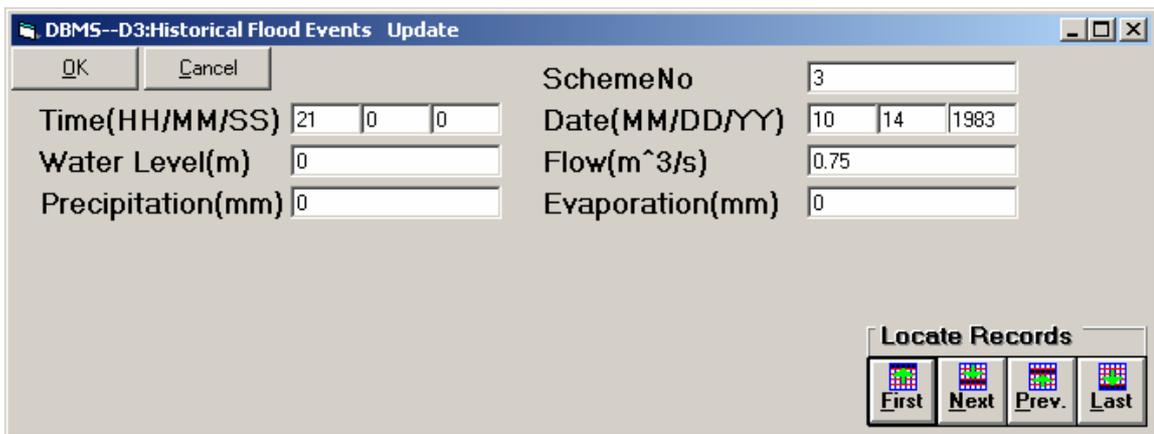


Figure 6.15 Interface for Updating Data

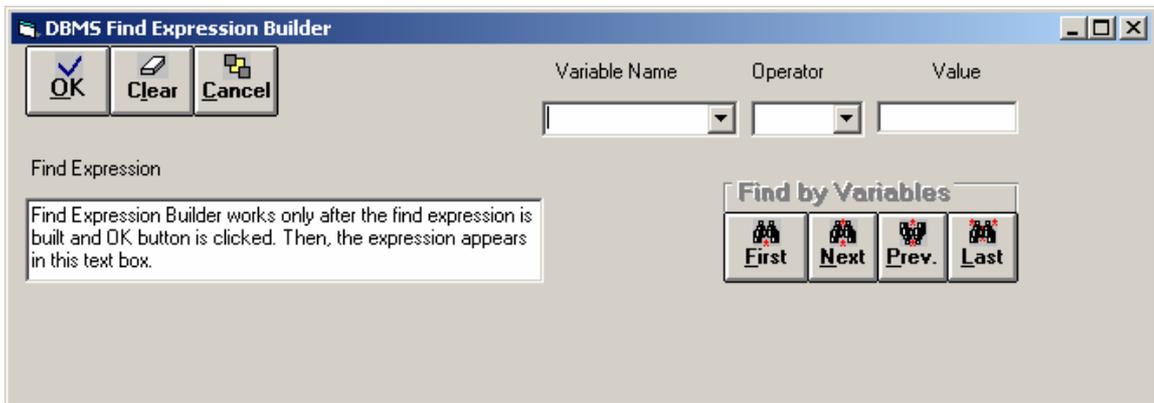


Figure 6.16 Interface for Searching Data for Updating

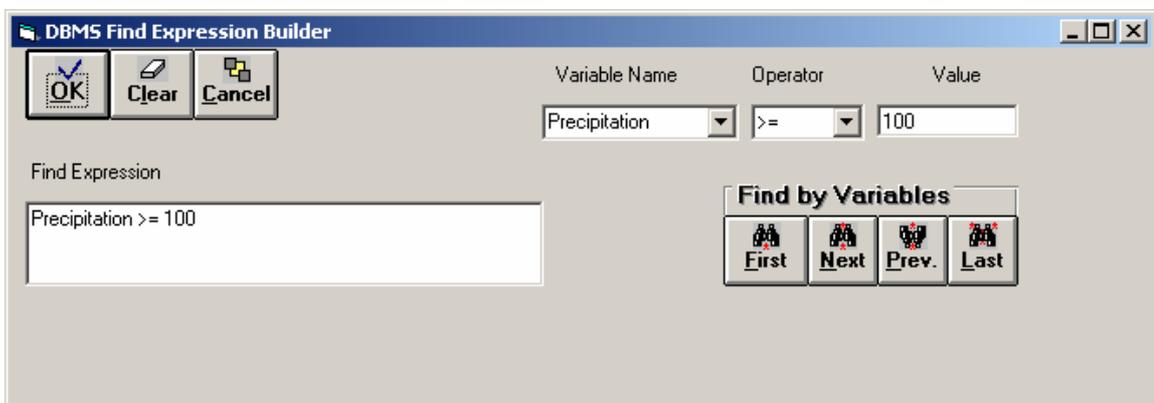


Figure 6.17 Searching Incorrect Data for Updating

Step 5 Update

Enter 1.6 and 255.2 into the text boxes of *Precipitation(mm)* and *Flow(m<sup>3</sup>/s)* in Figure 6.18 respectively, and click on the **OK** button to update data and close all data updating Windows (Figures 6.15 to 6.18). This takes the user back to Figure 6.14.

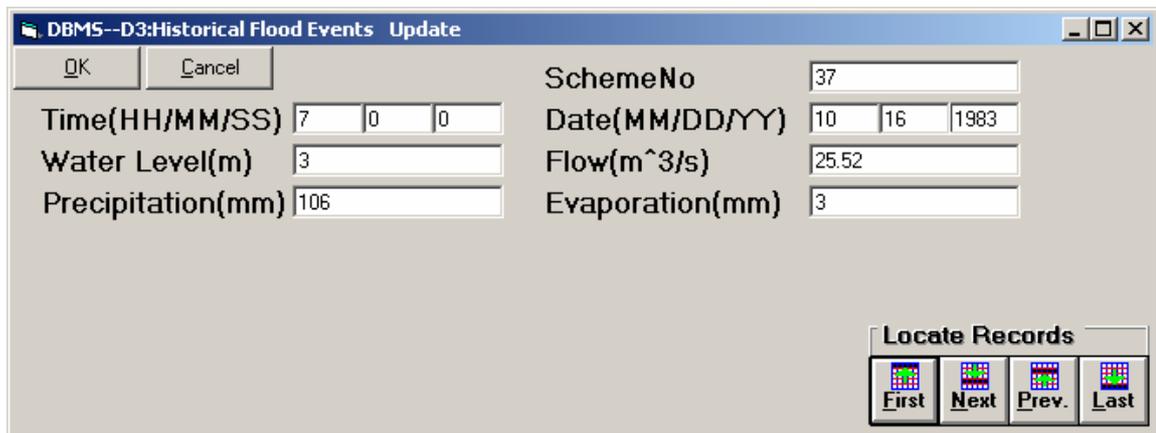


Figure 6.18 Erroneous Data Record Which Requires Updating

Step 6 Review Updating

Following the steps in Section 6.2.2.1 to review the updated data (or records) and show the updated data in tabular and graphical forms (Figure 6.19). The data in the table and the graph appear normal. Note the difference between Figure 6.13 and 6.19.

### 6.2.2.3 Delete Incorrect or Unwanted Data

In this case, it is assumed that it is necessary to delete the last record of Bulla 2 that has some unwanted data.

Step 1 Start Deletion

Click on the button **Station 2** and then on the button **Delete** on Figure 6.14 after it was reset. The interfaces (Figure 6.15 and Figure 6.16) are then displayed together, which 'Delete' instead of the 'Update' in the title of Figure 6.15.

Step 2 Find Record(s) Which Require Deletion

Click on the **Last** button of *Locate Records* buttons in Figure 6.15. The last record (No. 102) is displayed (Figure 6.20).

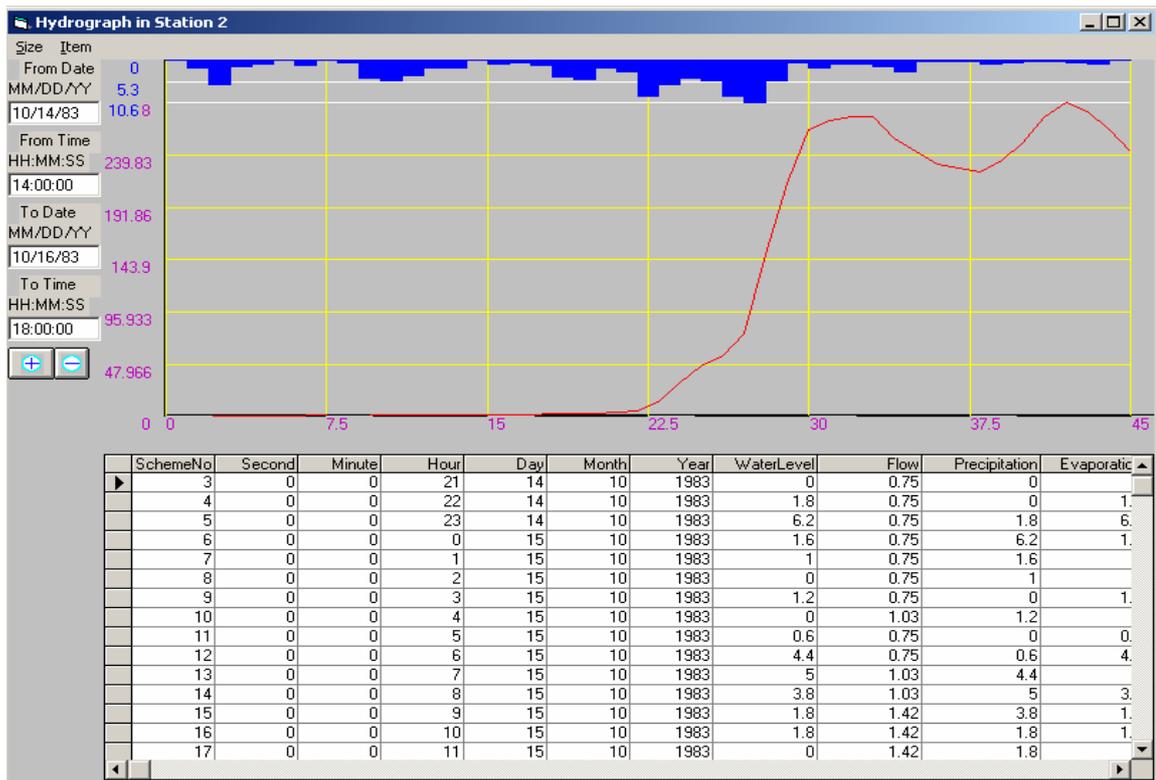


Figure 6.19 Tabular and Graphic Data Review for Updated Results

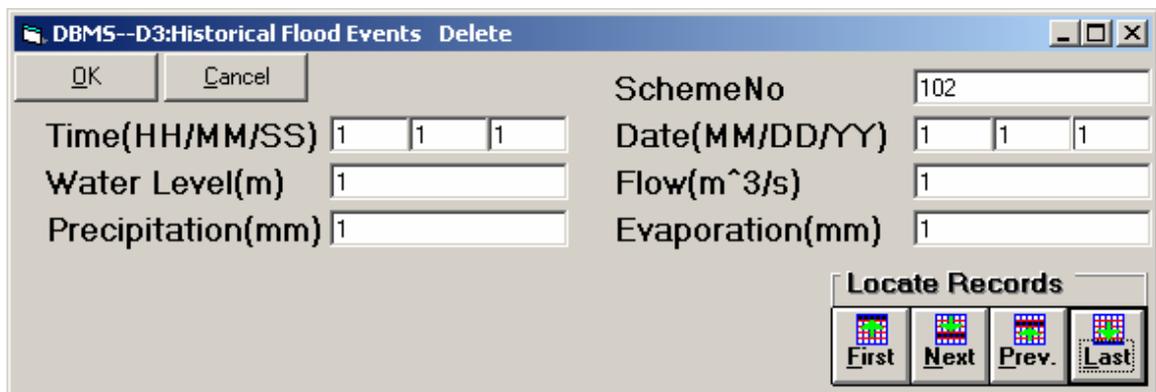


Figure 6.20 Last Record for Deletion

Step 3 Delete

Click on the **OK** button in Figure 6.20, which displays the Confirmation Window (Figure 6.21). Click on the **Yes** button in Figure 6.21 to delete this record, which also closes Figures 6.15 and 6.16.

Step 4 Review Deleting

Using Steps 1 to 3 of this section to review the deletion. It was found that the last record was No. 101 (Figure 6.22). Click **Cancel** button to close Figure 6.22.

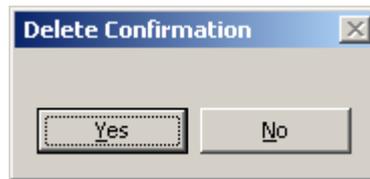


Figure 6.21 Delete Confirmation Window

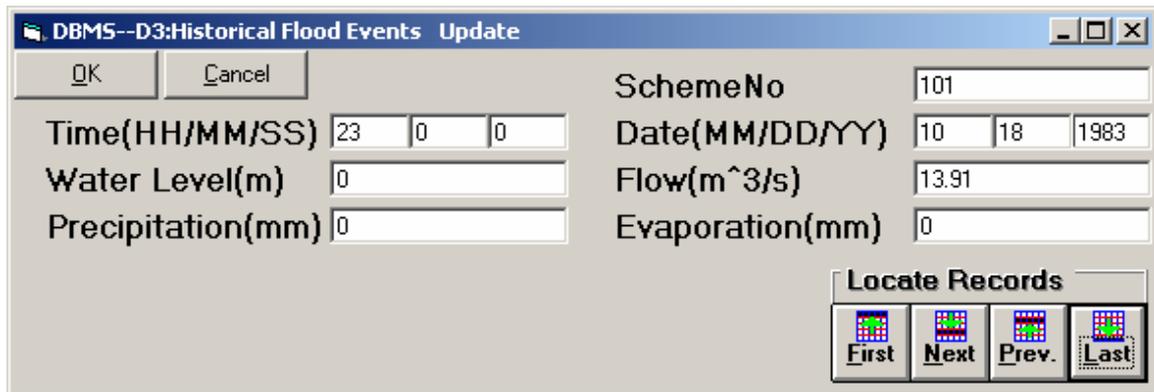


Figure 6.22 Interface for Checking Deletion

### 6.2.3 Final Remarks

Through the above operations in this application, it can be seen that the developed functions in DSSFCMR allow the user to enter data and perform database management operations (such as data searching, data updating, data deleting, etc.) for flood forecasting and warning easily, quickly and conveniently. These functions also help the decision maker to manage data and exchange information effectively.

## 6.3 Hydrological Model Calibration

The hydrological modelling calibration in this study was demonstrated through two methods. The first method uses different historical flood event data to calibrate the URBS hydrological model, and to determine parameters of *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow*. With the first method, it is possible to calibrate the model and validate it. This is demonstrated in Section 6.3.1. The second method uses the observed data in the current flood event to calibrate (or refine) the model, and in this case, only the event based parameters of *Initial Loss*, *Continuing Loss* and *Baseflow* were calibrated.

### 6.3.1 Calibration and Validation using Historical Flood Event Data

The flood event in October 1983 was used to derive five parameters of *Alpha*, *m*, *Initial Loss*, *Continuing Loss and Baseflow*, while the flood event in July 1987 was used to validate the derived parameters. The calibration steps are described below.

#### (a) Derive the parameters

##### Step 1 Connect Modelbase

Click on the item **Run-Models** in the **Main Menu** (Figure 5.2) of DSSFCMR, and then on **URBS** of item **Calibration**. As a result of this sequence of operations, Data Input Screen of Catchment Definition File of the URBS model is displayed (Figure 6.23). The parameters of *Alpha*, *m*, *Initial Loss*, *Continuing Loss and Baseflow* are “editable parameters”, which require calibration. This figure also shows the ‘display only’ parameters.

Display Only			
Total Subcatchments	18	Area (km ^2)	114.4
Subcatchment No	1	U (Urbanisation)	0
L (Reach Length)(km)	11.7	Reach Factor	0.5
		F (Forest)	0
Confluence at the Outlet of Subcatchment	No	UpCatchment	0
DownCatchment	2	Output Q	NO
Route L		Route U	
		Route F	
Total Pluviometers	5	Location	Bulla
Total Rating Curves	0	Location	" "
Total Gauging Stations	3	Location	bulla
		Covered Subcatchment by Pluviometer	11 12 17 18

Figure 6.23 Data Input Screen of Catchment Definition File in URBS Model Calibration

Step 2 Construct and Save Catchment Definition File (Details in Section 5.3.1.1a)

The displayed values in the text boxes of above-mentioned editable parameters in Figure 6.23 were 1.2, 0.8, 16, 0.45 and 0 respectively. Change the values of *Initial Loss* and *Continue Loss* to 20 and 0.25 respectively. Set the baseflow to 0, as this parameter is not critical to this flood event, because of low flow at the start.

Once the editable parameters are entered or changed, click on the button **OK** to save the catchment definition file and close the screen (Figure 6.23). This also displays the Data Input Screen for Rainfall Definition File (Figure 6.24).

Figure 6.24 Data Input Screen of Rainfall Definition File in URBS Model Calibration

Step 3 Enter Data for Rainfall Definition File (Details in Section 5.3.1.1b)

The user is required to set the following variables in Data Input Screen of Rainfall Definition File:

- *URBS\_DATE* (format: day/month/year). Enter 14/10/1983 as the start date of the flood event.
- *URBS\_Time* (format: Hour:Minute:Second). Enter 20:00:00 as the start time of the flood event.
- *Time Interval*. Use the default value of 1 hour.

- *Run Duration* (Hour). Enter 100
- *Total Rainfall Duration* (Hour). Enter 100. This value should be less than the value of *Run Duration* for calibration.
- *Observed Rainfall Start Time*. Enter 0.
- *Observed Rainfall Interval*. Use the default value of 1 hour.
- *Sub Catchment No.* Display only, but the *Rain on Sub Catchments* depends on this variable.
- *Rain on Sub Catchments*. In this case, the first method in Section 5.3.1.1b is used. Click on the **OK** button. The DSSFCMR then reads the observed rainfall data in pluviometers stored in D4RFE.MDB for relevant subcatchments, and stores these data in this combo box.
- *Hydrograph Start Time*. Enter 0.
- *Hydrograph Interval*. Use the default value of 1 hour.
- *Simulate Date* (format: day/month/year). No action is required, since it is automatically done.
- *Simulate Time* (format: Hour:Minute:Second). No action is required, since it is automatically done.

Step 4 Run Model and Store Results

Click on the **OK** button in Figure 6.24 to run the URBS model, store results and to display the **Main Menu** (Figure 5.2).

Step 5 View the Tabular Results of Calibration

Click on the item **Database** in **Main Menu** (Figure 5.2), and then click on the item **Forecast or Calibration URBS only** of **Simulated Flood Scenarios**. This displays the screen of D5: Simulated Flood Scenarios, as shown in Figure 6.25. The peak discharge ( $Q_{peak}$ ) is the maximum value of the discharge for this calibration scenario.

Step 6 View the Hydrograph for Calibration

Click on the **View** button on Figure 6.25 to compare calculated and observed hydrographs (Figure 6.26: Scheme No 1). If two hydrographs are matched well, the parameters of this scenario will be stored in the relevant database to forecast the hydrograph (Step 7 below). If they do not match, repeat Steps 1-6 with different values of *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* after exiting from Figure 6.26 by clicking on the right cross button at the top of the screen (which takes the user back to Figure 6.25) and then exiting from Figure 6.25 by clicking on the **OK** button to go back to the **Main Menu** (Figure 5.2).

After 12 calibration runs with different *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* values, the best calibration was obtained using the values of 1.2, 0.8, 1.6, 0.45 and 0 for *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* respectively. Figure 6.27 shows the results related to all 12 calibration runs, while Figure 6.26 shows the comparison of observed and calculated hydrographs for some selected runs of Scheme No 1, 2, 5, 8, 10 and 12.

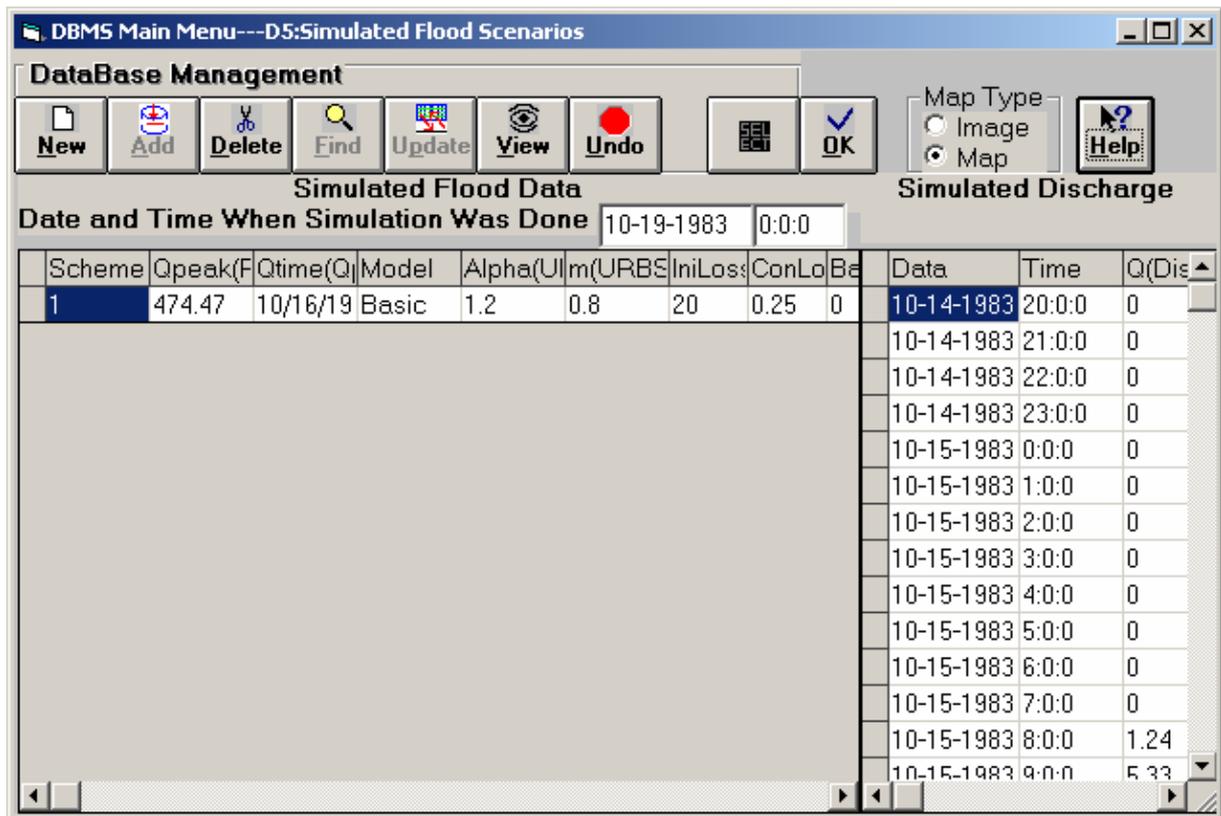
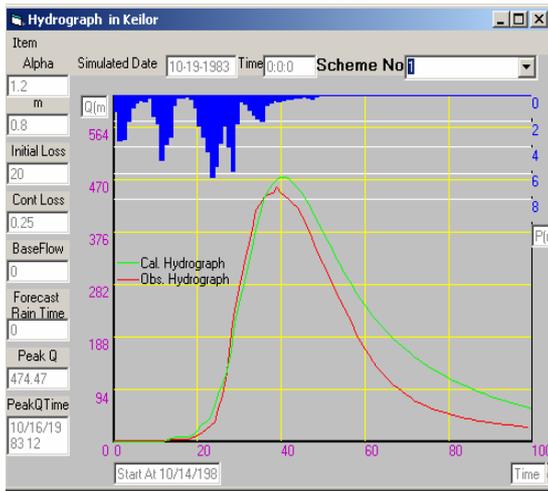
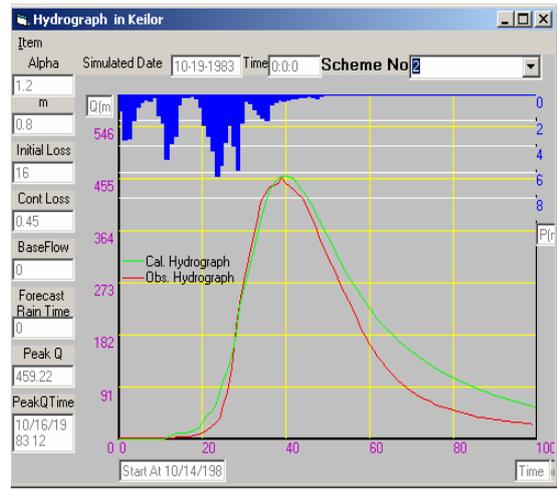


Figure 6.25 Screen of Simulated Flood Scenario for Calibration

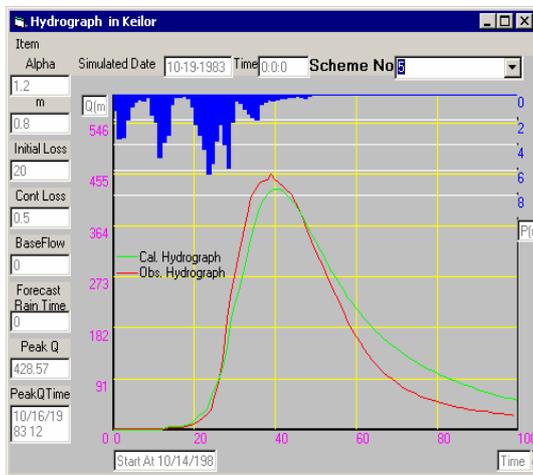
- Step 7 Save the Calibration Parameters
- Click on the item of **Database** in the **Main Menu** of DSSFCMR (Figure 5.2) and then on **Model Parameters**. Figure 6.28 is then displayed. Enter the values of 1.2, 0.8, 16, 0.45 and 0 in the text boxes of *Alpha*, *m*, *Initial Loss*, *Continue Loss* and *Baseflow*, and then click on the **Add** button to add these values into the corresponding combo boxes. These values will be added into the combo boxes, only if they are not already included in these boxes.
- Click on the **OK** button to save the changed data set of *edited parameters* into the database files and to close the interface of Figure 6.28.



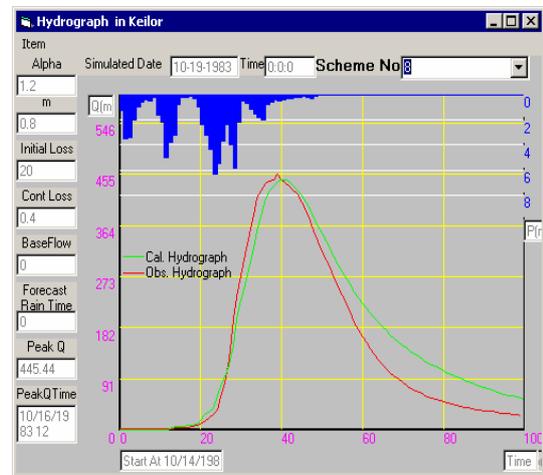
Scheme No 1



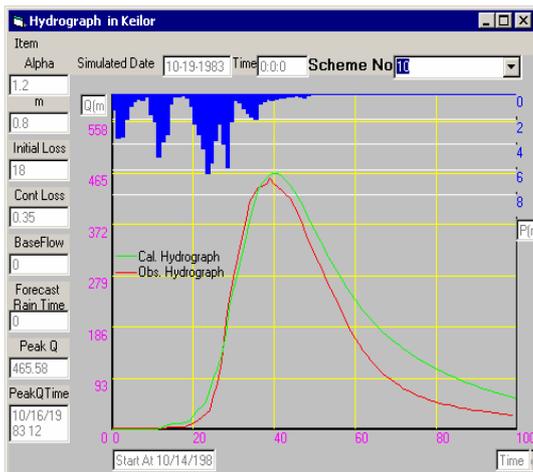
Scheme No 2



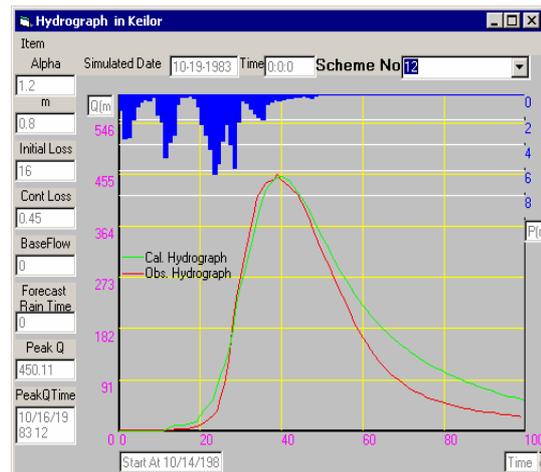
Scheme No 5



Scheme No 8



Scheme No 10



Scheme No 12

Figure 6.26 Observed and Calculated hydrographs for calibrating URBS model

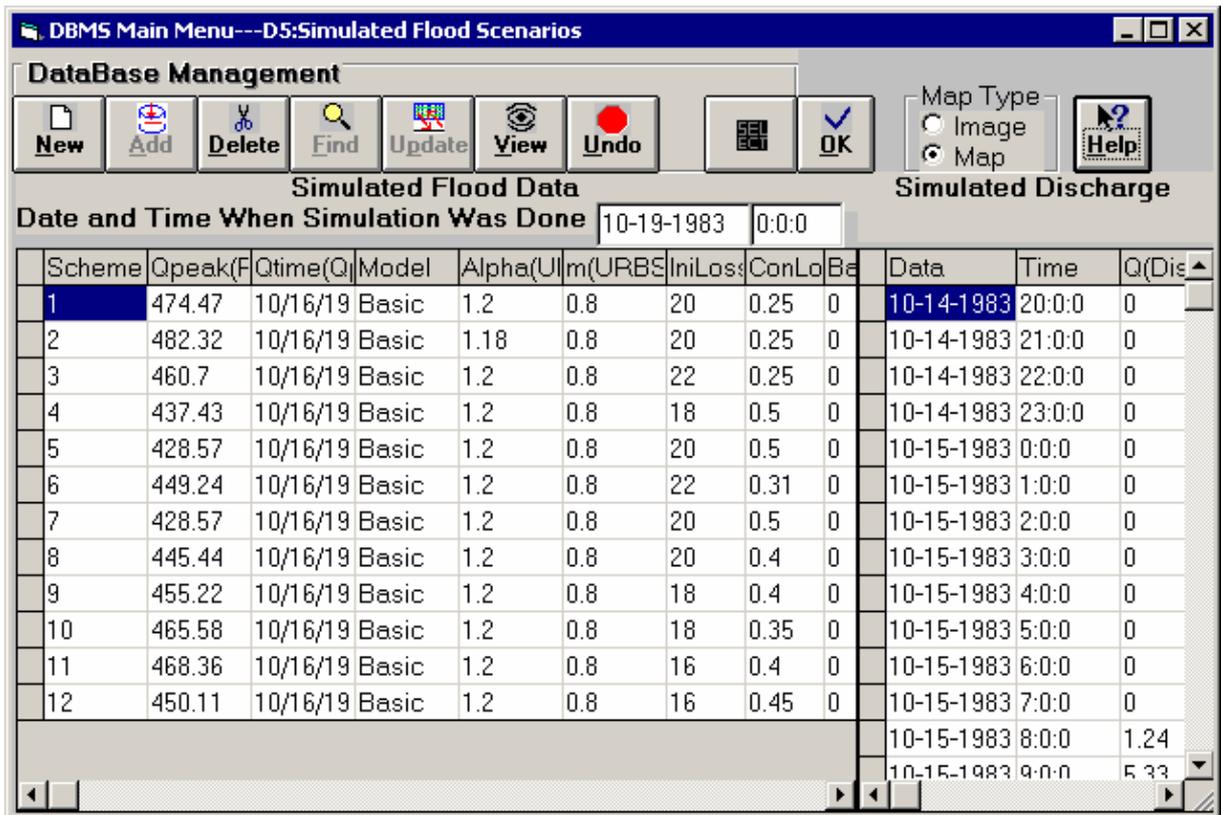


Figure 6.27 Results of Simulate Flood Scenarios

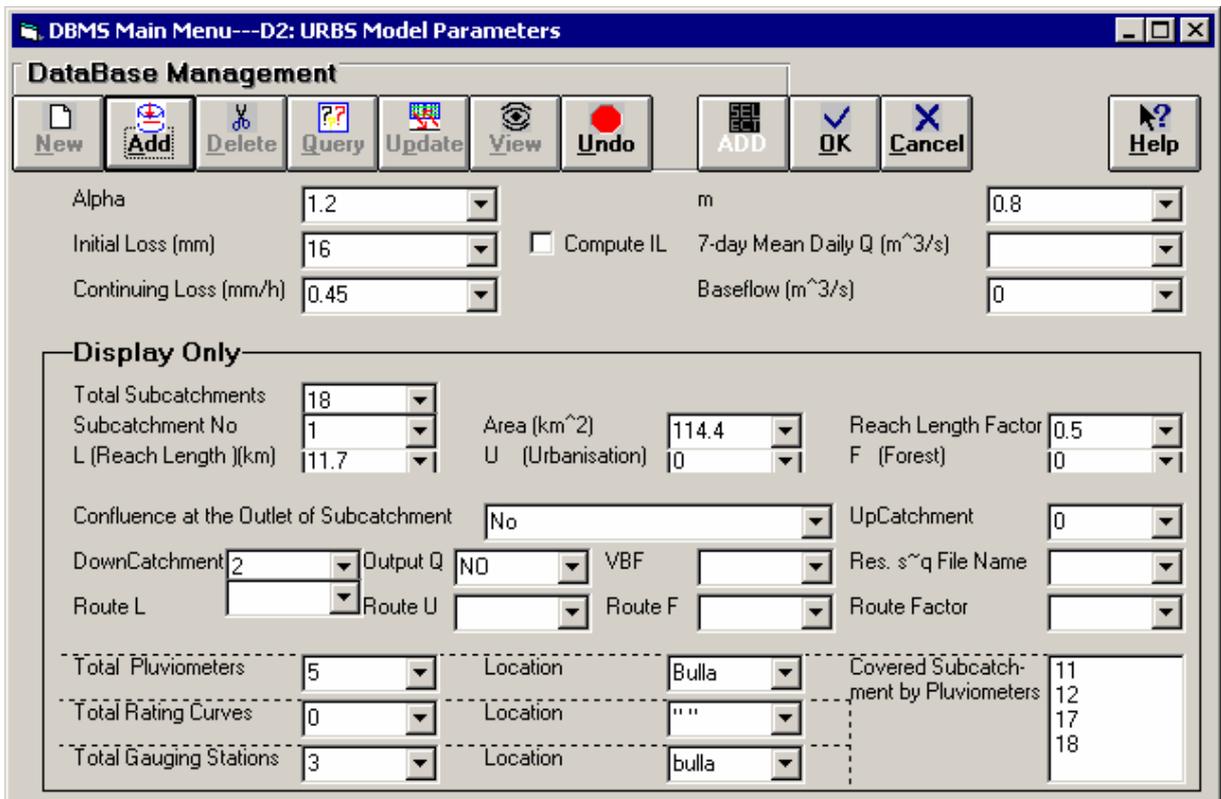


Figure 6.28 Screen of URBS Model Parameters in Database Menu

#### Step 8 Delete the Calibration Results

Once the calibration is completed and saved the model parameters in the database (Step 7 above), the calibration results displayed on Figure 6.27 can be deleted. This is necessary since the window in Figure 6.27 is also used for forecasting flood hydrographs. In any case, it is not necessary to store the calibration results since the model parameters related to calibration scenarios are already stored in the database.

Click on the item **D**atabase in **M**ain **M**enu (Figure 5.2), and then click on the item **F**orecast or **C**alibration **U**RBS only of **S**imulated **F**lood **S**cenarios. This will show all simulated flood scenarios generated during calibration, as shown in Figure 6.27. Click on the **D**elete button to delete all records from the database files and then on the **O**K button to return to the **M**ain **M**enu. The system is then ready for forecasting or calibration of hydrographs.

#### (b) Validate the parameters

The validation was done using the flood event in July 1987. The procedure is similar to (a) *Derive the parameters*, but the user may need to modify (i) 5 editable parameters in step 2 as those derived from (a) (Figure 6.29), if the parameters obtained from (a) do not produce hydrographs similar to the observed hydrograph (ii) *URBS\_DATE*, *URBS\_Time*, *Run Duration* and *Total Rainfall Duration* in Step 3 as follows (Figure 30):

- *URBS\_DATE* (format: day/month/year). Enter 28/07/1987 as the start date of the flood event.
- *URBS\_Time* (format: Hour:Minute:Second). Enter 16:00:00 as the start time of the flood event.
- *Run Duration* (Hour). Enter 100
- *Total Rainfall Duration* (Hour). Enter 98. This value should be less than the value of *Run Duration*.

The comparison of calculated and observed hydrograph in Step 6 is displayed as Figure 6.31. It is found that the calculated peak discharge ( $648 \text{ m}^3/\text{s}$ ) is about 98% of observed peak flood discharge, using parameter derived from 1983 flood event. Hence, in this case the parameters obtained from 1983 flood event seem to be satisfactory even for 1987 flood event, including the storm-dependent parameters, *Initial Loss*, *Continue Loss* and *Baseflow*. In most cases, it is

**Data Input Screen for Catchment Definition File**

River Basin: Maribyrnong River Basin  
 Model: Basic  
 Alpha: 1.2 m 0.8  
 Initial Loss (mm): 16  Compute IL 7-day Mean Daily Q (m<sup>3</sup>/s)  
 Continuing Loss (mm/h): 0.45 Baseflow (m<sup>3</sup>/s): 0

**Display Only**

Total Subcatchments: 18  
 Subcatchment No: 1 Area (km<sup>2</sup>): 114.4 Reach Factor: 0.5  
 L (Reach Length)(km): 11.7 U (Urbanisation): 0 F (Forest): 0

Confluence at the Outlet of Subcatchment: No UpCatchment: 0  
 DownCatchment: 2 Output Q: NO VBF: Res. s~q File Name:  
 Route L: Route U: Route F: Route Factor:

Total Pluviometers: 5 Location: Bulla Covered Subcatchment by Pluviometer: 11, 12, 17, 18  
 Total Rating Curves: 0 Location: ""  
 Total Gauging Stations: 3 Location: bulla

Figure 6.29 Derived Parameter Input Screen of Catchment Definition File to Check Calibration

**Data Input Screen for Rainfall Definition File**

River basin: Maribyrnong River Basin  
 Type of Model Run: CALIBRATION URBS\_DATE(MM/DD/YY): 07/28/1987  
 URBS\_Time(HH:MM:SS): 15:00:00  
 Time Interval (h): 1 Run Duration (h): 100  
 Total Rainfall Duration (h): 98

Observed Rainfall Start Time (h): 0 Observed Rainfall Interval (h): 1  
 Total Forecast RainTime (h): 0 %: 100  
 Total Forecast Rainfall (mm): Qty: 100  
 One Hour Rainfall / Total Forecast Rainfall (%): In First Hour: 100, In Second Hour: 100, In Third Hour: 100  
 Rain on Sub Catchments (mm): Sub Catchment No: \*

Hydrograph Start Time (h): 0 Hydrograph Time Interval (h): 1  
 Simulate Date(MM/DD/YY): 8/1/1987 Simulate Time (HH:MM:SS): 17:00:00  
 DownStream Water Level:

Figure 6.30 Data Input Screen of Rainfall Definition File for Flood Event in 1987 to Check Calibration

necessary to change the storm dependent parameters from event to event, but the catchment specific parameters *alpha* and *m* are constant.

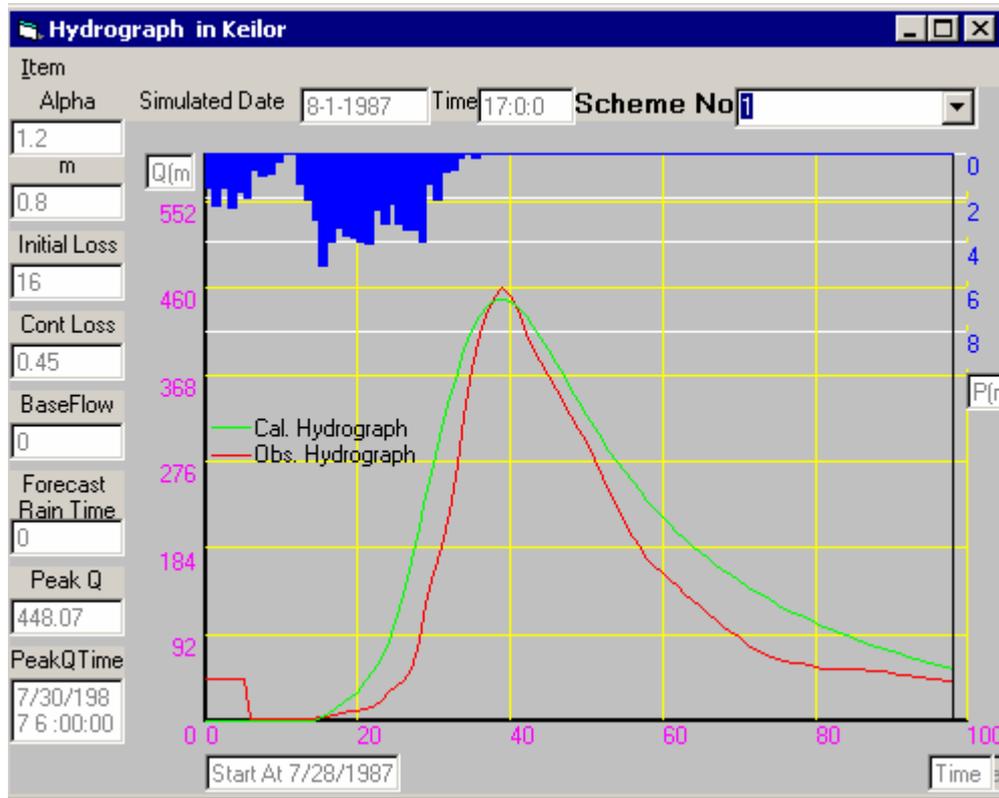


Figure 6.31 Hydrograph for Calibration in 1987 Flood Event

### 6.3.2 Calibration for Current Flood Event

The parameters of *Initial Loss*, *Continuing Loss* and *Based Flow* in the URBS model can vary for different flood events. It is considered here that the calibration of the URBS model is necessary at current time  $t_I$  (i.e. 0700 hours on 16 October 1983), which requires decisions to make on flood forecasting and warning. However, only the *Initial Loss*, *Continuing Loss* and *Based Flow* are considered needing calibration for this flood event (as these parameters vary with the flood event). The parameters *Alpha* and *m* are catchment parameters, which do not vary generally with the storm event. It is considered that they have already been calibrated using other historical data (Section 6.3.1). To do calibration at current time  $t_I$ , it is necessary to store the observed rainfall and flow data for the current flood event in relevant databases up to the current time  $t_I$ . There are 8 steps (same as those in Section 6.3.1 (a)) to follow for this calibration. The calibration steps, which are different to those in Section 6.3.1 (a), are described below.

Step 1 Connect Modelbase

The parameters of *Alpha*, *m*, *Initial Loss*, *Continuing Loss* and *Baseflow* are “editable parameters”, which require calibration. However, only the latter 3 parameters are considered in this calibration. This figure also shows the ‘display only’ parameters.

Step 2 Construct and Save Catchment Definition File (Details in Section 5.3.1.1a)

The displayed values in the text boxes of above-mentioned editable parameters in Figure 6.32 were 1.2, 0.8, 22, 0.01 and 10 respectively. Change the values of *Initial Loss* and *Continue Loss* to 30 and 0.1 respectively. Set the baseflow to 0, as this parameter is not critical to this flood event, because of low flow at the start.

Once the editable parameters are entered or changed, click on the button **OK** to save the catchment definition file and close the screen (Figure 6.32). This also displays the Data Input Screen for Rainfall Definition File (Figure 6.33).

Figure 6.32 Data Input Screen of Catchment Definition File in URBS Model Calibration

Step 3 Enter Data for Rainfall Definition File (Details in Section 5.3.1.1b)

The user is required to set the following variables in Data Input Screen of Rainfall Definition File:

Figure 6.33 Data Input Screen of Rainfall Definition File in URBS Model Calibration

- *URBS\_DATE* (format: day/month/year). Enter 14/10/1983 as the start date of the flood event.
- *URBS\_Time* (format: Hour:Minute:Second). Enter 20:00:00 as the start time of the flood event.
- *Time Interval*. Use the default value of 1 hour.
- *Run Duration* (Hour). Enter 50
- *Total Rainfall Duration* (Hour). Enter 35. This value should be less than the value of *Run Duration* for calibration.
- *Observed Rainfall Start Time*. Enter 0.
- *Observed Rainfall Interval*. Use the default value of 1 hour.
- *Sub Catchment No*. Display only, but the *Rain on Sub Catchments* depends on this variable.
- *Rain on Sub Catchments*. In this case, the first method in Section 5.3.1.1b is used. Click on the **OK** button. The DSSFCMR then reads the observed rainfall data in pluviometers stored in D4RFE.MDB for relevant subcatchments, and stores these data in this combo box.
- *Hydrograph Start Time*. Enter 0.

- *Hydrograph Interval*. Use the default value of 1 hour.
- *Simulate Date* (format: day/month/year). No action is required, since it is automatically done.
- *Simulate Time* (format: Hour:Minute:Second). No action is required, since it is automatically done.

Step 4 Run Model and Store Results

Step 5 View the Tabular Results of Calibration

This displays the screen of D5: Simulated Flood Scenarios, as shown in Figure 6.34.

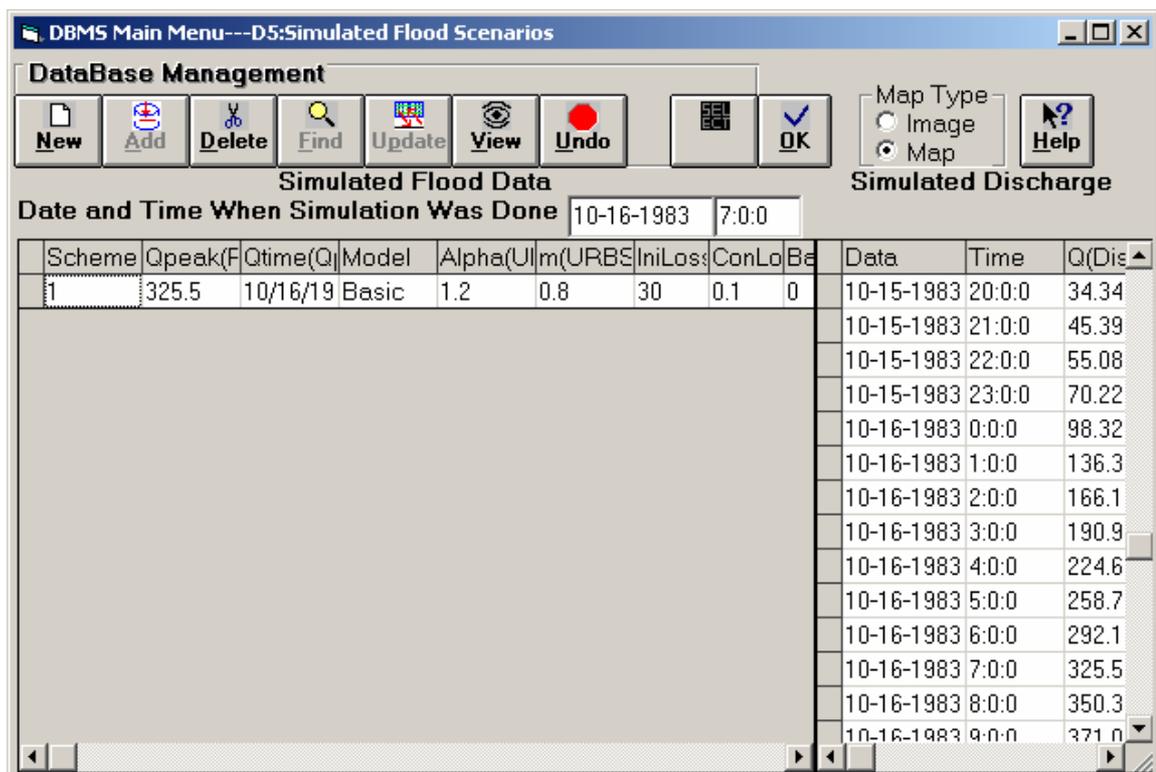
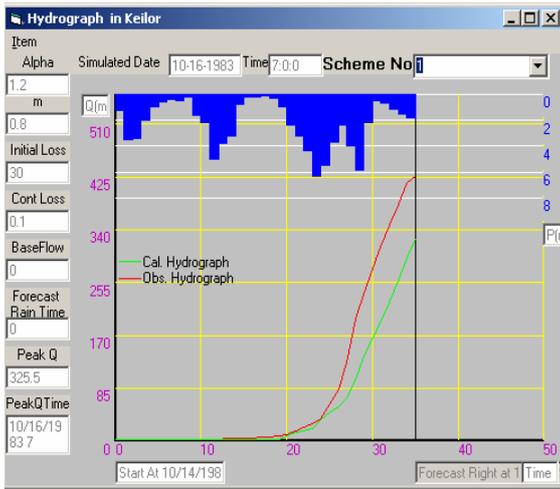


Figure 6.34 Screen of Simulated Flood Scenario for Calibration

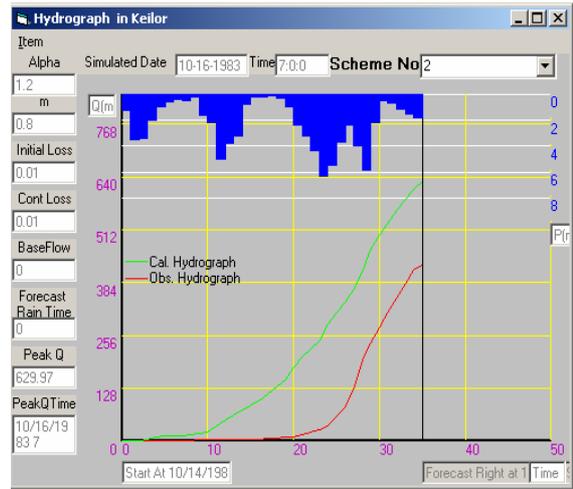
Step 6 View the Hydrograph for Calibration

Click on the **V**iew button on Figure 6.34 to compare calculated and observed hydrographs (Figure 6.35: Scheme No 1).

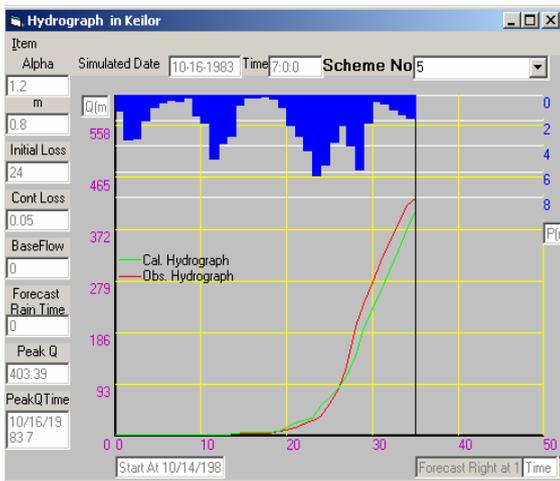
After 8 calibration runs with different *Initial Loss* and *Continuing Loss* values, the best calibration was obtained using the values of 22 and 0.01 for *Initial Loss* and *Continuing Loss* respectively. Figure 6.36 shows the results related to all 8 calibration runs, while Figure 6.35 shows the comparison of observed and calculated hydrographs for some selected runs of Scheme No 1, 2, 5, 7 and 8.



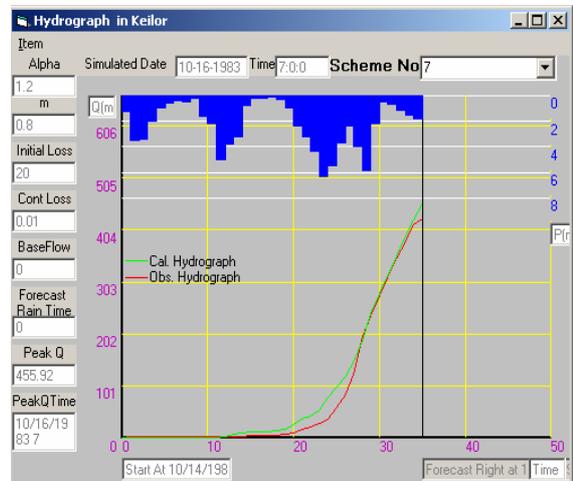
Scheme No 1



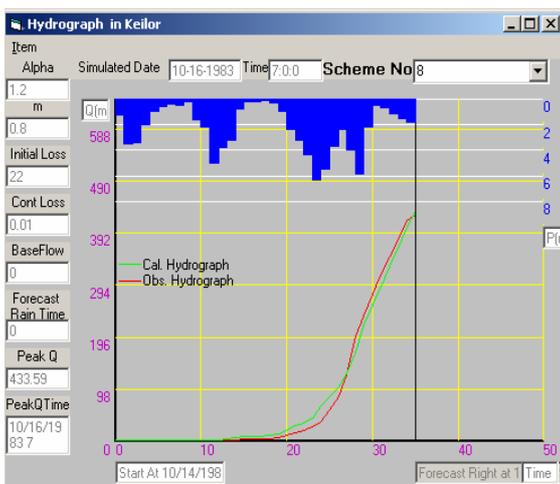
Scheme No 2



Scheme No 5



Scheme No 7



Scheme No 8

Figure 6.35 Observed and Calculated hydrographs for calibrating URBS model

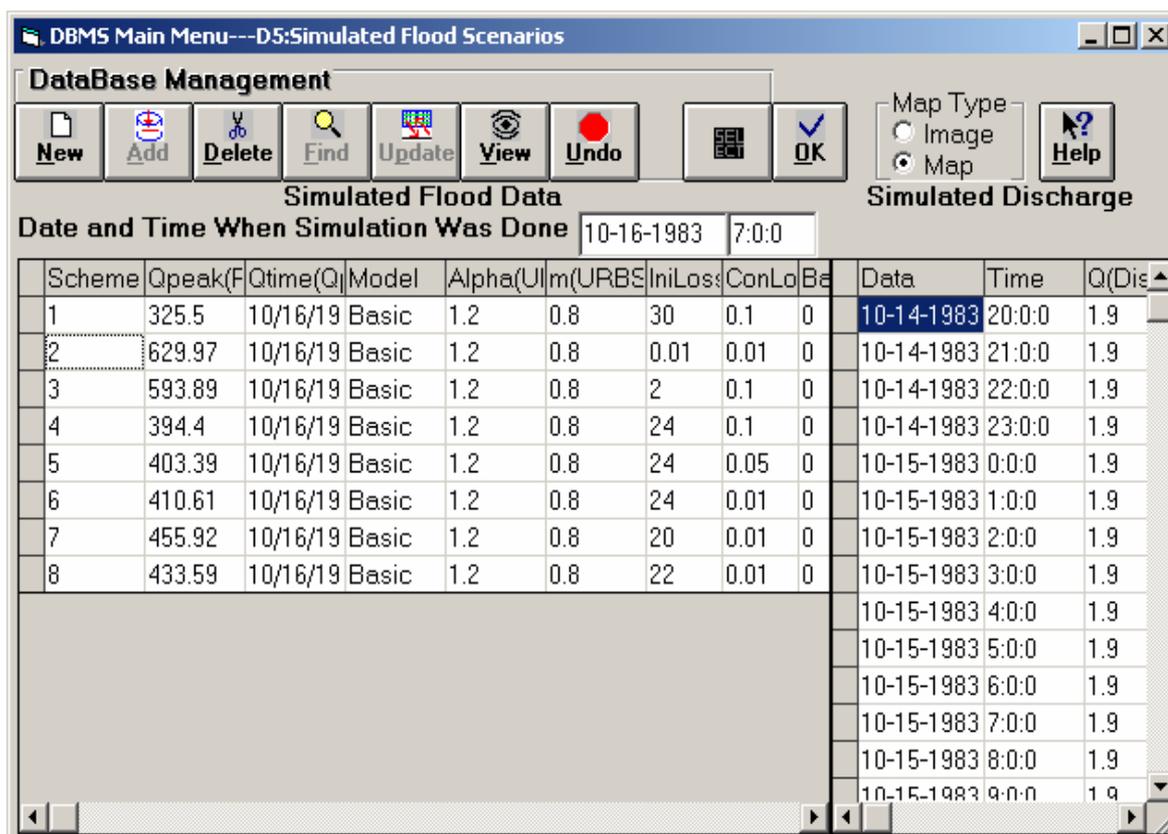


Figure 6.36 Results of Simulate Flood Scenarios

The above description shows how the user can easily edit the URBS model parameters interactively using the stored parameter values in DSSFCMR, and how the major processes of calibration (such as constructing the input files for the URBS model, running the URBS model and writing the model parameters and model output into appropriate database tables) are automatically done. The developed functions in the Database subsystem allow the user to effectively view and compare the calculated hydrographs with the observed hydrographs. In summary, the user can effectively, interactively and conveniently calibrate the URBS hydrological model through the developed DSSFCMR interface.

#### 6.4 Hydraulic Model Calibration

The water levels of four flood events (i.e. events occurred on 14 May 1974, 14 October 1983, 30 July 1987 and 16 September 1993) had been stored in the database D3HEF.MDB. The event on 14 October 1983 was used for the HEC-RAS model calibration since it had more comprehensive data available for observed flood levels compared to the other three events. It should be noted that the URBS model calibration should be done using the data of the real-

time flood event, which is currently occurring, as some parameters such as the *Initial Loss*, *Continuing Loss* and *Base Flow* are considered to vary with the flood event. However, this is not necessary for the HEC-RAS model calibration, since the HEC-RAS model parameters do not vary from flood event to flood event. The following steps describe the calibration procedure of the HEC-RAS model.

**Step 1**      **Connect Modelbase**

Click on the item **Run-Models** in the **Main Menu** (Figure 5.2) of DSSFCMR, and then on **HEC-RAS** of item **Calibration**. This shows the interface for calibrating the HEC-RAS model (Figure 6.37). The roughness coefficients (in left bank, main channel and right bank), contraction coefficients and expansion coefficients at each cross section are editable for calibration, together with the downstream water level. Initially, the default values of these parameters are displayed. The default parameter values are the parameter values used in the previous calibration for this flood event or other events.

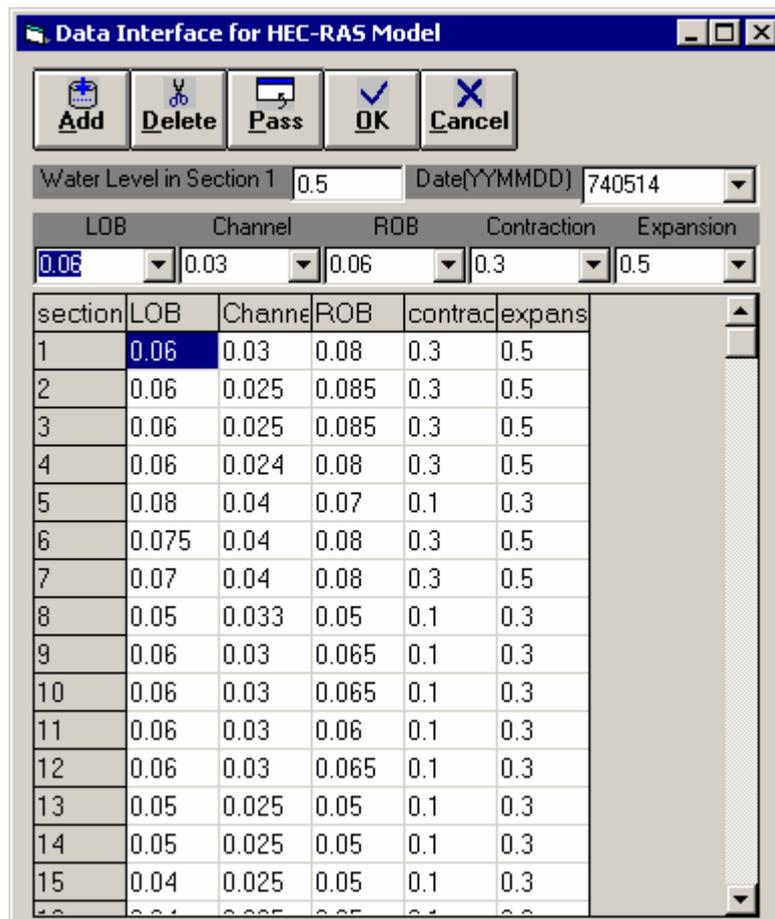


Figure 6.37 Interface for Calibrating HEC-RAS model

- Step 2      Select the Specific Event for Calibration  
 Select 831014 from the combobox of *Date(YYMMDD)*, which indicates that the flood event on 14 October 1983 is used to calibrate the model.
- Step 3      Enter the Downstream Water Level  
 Enter 0.5 into the text box of *Water Level in Section 1*, which is the observed maximum water level for this flood event at the most downstream cross section of the flood prone area of the lower part of the catchment.
- Step 4      Enter the Model Parameters for Calibration Run  
*LOB*, *Channel*, *ROB*, *Contraction* and *Expansion* in Figure 6.37 represents Manning's roughness coefficients in left bank, main channel and right bank, contraction and expansion loss coefficients respectively. They are the calibration parameters and these parameters need to be entered for each cross section for each calibration run. The parameters used for the first calibration scenario are given in Table 6.2. Enter data as described below.
- Select 0.06 from the combo box of *LOB*, click on the field *LOB* of section 1, and then on the button **PASS**. This will display 0.06 in the field *LOB* of section 1.
  - Similarly, enter values of 0.03, 0.08, 0.3 and 0.5 for *Channel*, *ROB*, *Contraction* and *Expansion* respectively.
  - Repeat the above procedure for all other cross sections using data in Table 6.2.
- Step 5      Save Data into HEC-RAS Data Files and Run HEC-RAS  
 Click on the **OK** button in Figure 6.37. This will write the peak discharge and the downstream water level of the calibration event into the flow file (i.e. *C:\HEC\RAS\temp.f01*), and the Manning's roughness coefficients in left bank, main channel and right bank, and contraction and expansion loss coefficients at each cross section into the geometric file (i.e. *C:\HEC\RAS\ temp.g01*). These files are stored in the HEC-RAS home directory (*C:\HEC\RAS*). During this process, several screens appear and disappear, as explained in Section 5.3.1.2. Finally, the results are stored in the database *D5SFS.MDB*.
- Step 6      Further Calibration Runs  
 Repeat Steps 4 and 5 with several other reasonable parameters sets. However, in this case, only one other calibration run was considered for demonstration purposes. The parameters for this calibration scenario are given in Table 6.3.

Table 6.2 Model Parameters Used for the 1<sup>st</sup> Calibration Scenarios

Cross Section	Manning's Roughness Coefficients			Contraction Coefficient	Expansion Coefficient
	Left Bank	Channel	Right Bank		
1	0.06	0.03	0.08	0.3	0.5
2	0.06	0.025	0.085	0.3	0.5
3	0.06	0.025	0.085	0.3	0.5
4	0.06	0.024	0.08	0.3	0.5
5	0.08	0.04	0.07	0.1	0.3
6	0.075	0.04	0.08	0.3	0.5
7	0.07	0.04	0.08	0.3	0.5
8	0.05	0.033	0.05	0.1	0.3
9	0.06	0.03	0.065	0.1	0.3
10	0.06	0.03	0.065	0.1	0.3
11	0.06	0.03	0.06	0.1	0.3
12	0.06	0.03	0.065	0.1	0.3
13	0.05	0.025	0.05	0.1	0.3
14	0.05	0.025	0.05	0.1	0.3
15	0.04	0.025	0.05	0.1	0.3
16	0.04	0.025	0.05	0.1	0.3
17	0.04	0.025	0.05	0.1	0.3
18	0.04	0.025	0.05	0.3	0.5
19	0.07	0.045	0.07	0.3	0.5
20	0.06	0.045	0.05	0.3	0.5
21	0.075	0.03	0.06	0.3	0.5
22	0.075	0.03	0.06	0.1	0.3
23	0.05	0.025	0.035	0.1	0.3
24	0.05	0.025	0.035	0.1	0.3
25	0.05	0.025	0.035	0.1	0.3
26	0.05	0.025	0.04	0.1	0.3
27	0.05	0.025	0.04	0.3	0.5
28	0.05	0.025	0.04	0.3	0.5
29	0.05	0.025	0.04	0.3	0.5
30	0.05	0.025	0.04	0.3	0.5
31	0.05	0.025	0.04	0.3	0.5
32	0.1	0.05	0.095	0.3	0.5
33	0.08	0.04	0.055	0.3	0.5
34	0.06	0.025	0.04	0.1	0.3
35	0.05	0.025	0.05	0.05	0.25
36	0.05	0.025	0.05	0.1	0.3
37	0.05	0.025	0.04	0.1	0.3
38	0.04	0.025	0.04	0.1	0.3
39	0.05	0.025	0.04	0.1	0.3
40	0.07	0.033	0.06	0.3	0.5
41	0.07	0.033	0.07	0.3	0.5
42	0.07	0.033	0.06	0.3	0.5
43	0.06	0.033	0.06	0.3	0.5
44	0.06	0.033	0.06	0.3	0.5
45	0.06	0.04	0.06	0.1	0.3
46	0.06	0.033	0.06	0.1	0.3
47	0.06	0.033	0.06	0.1	0.3

Table 6.3 Model Parameters Used for the 2<sup>nd</sup> Calibration Scenarios

Cross Section	Manning's Roughness Coefficients			Contraction Coefficient	Expansion Coefficient
	Left Bank	Channel	Right Bank		
1	0.04	0.025	0.04	0.1	0.3
2	0.04	0.025	0.04	0.1	0.3
3	0.04	0.025	0.04	0.1	0.3
4	0.04	0.025	0.04	0.1	0.3
5	0.04	0.025	0.04	0.1	0.3
6	0.04	0.025	0.04	0.1	0.3
7	0.04	0.025	0.04	0.1	0.3
8	0.04	0.025	0.04	0.1	0.3
9	0.04	0.025	0.04	0.1	0.3
10	0.04	0.025	0.04	0.1	0.3
11	0.04	0.025	0.04	0.1	0.3
12	0.04	0.025	0.04	0.1	0.3
13	0.04	0.025	0.04	0.1	0.3
14	0.04	0.025	0.04	0.1	0.3
15	0.04	0.025	0.04	0.1	0.3
16	0.04	0.025	0.04	0.1	0.3
17	0.04	0.025	0.04	0.1	0.3
18	0.04	0.025	0.04	0.1	0.3
19	0.04	0.025	0.04	0.1	0.3
20	0.04	0.025	0.04	0.1	0.3
21	0.04	0.025	0.04	0.1	0.3
22	0.04	0.025	0.04	0.1	0.3
23	0.04	0.025	0.04	0.1	0.3
24	0.04	0.022	0.04	0.1	0.3
25	0.04	0.02	0.04	0.1	0.3
26	0.04	0.015	0.03	0.01	0.3
27	0.01	0.01	0.01	0.01	0.01
28	0.06	0.03	0.06	0.1	0.8
29	0.005	0.001	0.005	0.01	0.01
30	0.005	0.001	0.005	0.01	0.01
31	0.005	0.001	0.005	0.01	0.01
32	0.03	0.03	0.03	0.1	0.3
33	0.03	0.03	0.03	0.1	0.3
34	0.06	0.05	0.06	0.1	0.3
35	0.03	0.015	0.03	0.1	0.3
36	0.03	0.02	0.03	0.1	0.3
37	0.03	0.015	0.03	0.1	0.3
38	0.03	0.015	0.03	0.1	0.3
39	0.03	0.015	0.03	0.1	0.3
40	0.03	0.015	0.03	0.1	0.3
41	0.03	0.015	0.03	0.1	0.3
42	0.03	0.015	0.03	0.1	0.3
43	0.03	0.015	0.03	0.1	0.3
44	0.03	0.015	0.03	0.1	0.3
45	0.03	0.015	0.03	0.1	0.3
46	0.03	0.015	0.03	0.1	0.3
47	0.03	0.015	0.03	0.1	0.3

Step 7 Viewing calibration results

Click on the **Calibration HEC-RAS only** of **Simulated Flood Scenarios** under **Database** (Figure 5.2) to display the interface shown in Figure 6.38. This interface is used to view the calibration results. Each calibration run has three rows of records in the left table. The first row shows the calculated water level at each cross section used in the HEC-RAS model. The second row shows the observed water levels at cross section where data were available. Finally, the third run shows is the differences between calculated water levels and observed water levels at cross section where these observed water levels were available. Considering acceptable differences between observed and calculated water levels for different calibration runs, the user can select the calibration parameters for the HEC-RAS model. In this case, the calibration scheme 2 produced the calibration model parameters set.

Scheme	Sec01H	Sec02H	Sec03H	Sec04H	Sec05H	Sec06	Sec07	Sec08	sections	LOB	Chan
1	0.5	0.75	0.75	0.92	1.01	1.44	1.51	1.5	1	0.06	0.03
							1.22		2	0.06	0.025
							0.28		3	0.06	0.025
2	0.5	0.71	0.71	0.88	0.95	1.16	1.14	1.2	4	0.06	0.024
							1.22		5	0.08	0.04
							-0.09		6	0.075	0.04
									7	0.07	0.04
									8	0.05	0.033
									9	0.06	0.03
									10	0.06	0.03
									11	0.06	0.03
									12	0.06	0.03
									13	0.05	0.025
									14	0.05	0.025

Figure 6.38 Results of Calibration HEC-RAS Model

Step 8 Ready for Forecasting

Enter the parameters of the best calibration run (i.e. scheme No 2) in Figure 6.37 again and then run HEC-RAS. This is required only if the last HEC-RAS run of

Step 6 has not used the final calibration parameter set. The parameters from last run are always set as the default values for the HEC-RAS model during its next run.

As can be seen from above operations, the HEC-RAS calibration is different to that of the URBS. In URBS calibration, the model parameters are changed after viewing the calibration results, and then the final calibration parameter set is selected. However, in HEC-RAS calibration, several runs are considered before viewing the results of all these calibration runs to get the final calibration parameter set. The reason for using these two approaches is that in URBS calibration, only two parameters are considered for calibration and therefore a systematic calibration can be done after viewing the results of the calibration. However, in HEC-RAS, there are many parameters used in calibration (i.e. 5 parameters at each cross section) and therefore the systematic approach used in URBS calibration cannot be used for HEC-RAS calibration.

## **6.5 Flood Forecasting**

Flood forecasting is used to answer the "what if" question in flood warning decision making. For example, if the forecast rainfall in the next three hours is  $X$  mm under the downstream water level of  $Y$  meters (i.e. this is the water level of the river downstream of the flood inundation area, which is estimated by other means such as tidal conditions), what will be the flood inundation area and the possible damage, and what kind of flood warning needs to be issued?

Twelve flood forecasting scenarios were considered in the demonstration to illustrate the power of DSSFCMR in flood forecasting. Different conditions of zero, low, medium, and high forecast rainfalls under normal and high downstream water levels were considered in these 12 scenarios and are listed in Table 6.4 (with their values given in tables 6.5 and 6.6). It should be noted that the terms of low, medium and high used for different rainfalls were examples only. They were not related any 'probabilities' or 'risks'. However, the user can consider other different flood forecasting scenarios as applicable. Note that these forecast rainfalls and downstream water levels are not calculated within DSSFCMR, but obtained from elsewhere. The estimation of forecast rainfalls and downstream water levels are beyond the scope of this study.

Step 1 Start Forecasting

Click on **Run-Models** in the **Main Menu** of DSSFCMR (Figure 5.2) and then on the item of **Forecasting**. The Data Input Screen of Catchment Definition File in the URBS model is displayed as Figure 6.39.

Table 6.4 Twelve Flood Forecasting Scenarios Used in This Application

Scheme	Forecast Period (h)	Forecast Rainfall				Downstream Water Level	
		Zero	Low	Medium	High	Normal	High
1	0	✓				✓	
2	1		✓			✓	
3	1			✓		✓	
4	1				✓	✓	
5	0	✓					✓
6	1		✓				✓
7	1			✓			✓
8	1				✓		✓
9	3		✓			✓	
10	3				✓	✓	
11	3		✓				✓
12	3				✓		✓

Figure 6.39 Data Input Screen of Catchment Definition File – Forecasting

Step 2 Construct Catchment Definition File  
 Check the values in the text boxes of *Alpha*, *m*, *Initial Loss*, *Continue Loss* and *Baseflow*. These should be same as the results of calibration (i.e. 1.2, 0.8, 22, 0.01 and 0). If the values are different to the above, change them to the calibrated parameters using the methods described in Section 5.3.1.1a. Click on the button **OK** in Figure 6.39 to save the catchment definition file and close the screen. This will also display the Data Input Screen for Rainfall Definition File shown in Figure 6.40.

Figure 6.40 Data Input Screen of Rainfall Definition File – Forecasting

Step 3 Forecast with Zero Forecast Rainfall under Normal Downstream Water Level (Scenario 1)

Set parameters in the interface of Figure 6.40 as described below:

- *River Basin* is hardwired as Maribyrnong River Basin.
- *Type of Model Run* is hardwired as FORECASTING
- *URBS\_DATE* (format: Day/Month/Year): Enter 14/10/1983.
- *URBS\_Time* (format: Hour:Minute:Second ): Enter 20:00:00.
- *Time Interval (h)*: Enter 1.

- *Run Duration (h)*: Enter 50.
- *Total Rainfall Duration (h)*: Enter 35.
- *Observed Rainfall Duration*: Enter 35.
- *Pluviometer Name*: Enter \*.
- *Observed Rainfall Start Time (h)*. Enter 0.
- *Observed Rainfall Interval (h)*: Enter 1.
- *Total Forecast Rain Time*: Enter 0.
- *Total Forecast Rainfall*: No action required.
- *One Hour Rainfall / Total Forecast Rainfall: in First Hour*: No action required.
- *One Hour Rainfall / Total Forecast Rainfall in Second Hour*: No action required.
- *One Hour Rainfall /Total Forecast Rainfall in Third Hour*: No action required.
- *Sub Catchment No*: No action required.
- *Rain on Sub Catchments*: No action required.
- *Gauging Station Name*: No action required.
- *Hydrograph Start Time*: Enter 0.
- *Hydrograph Interval*: Enter 1.
- *Simulate Date* (format: Month/Day/Year): No action required.
- *Simulate Time* (format: Hour:Minute:Second): No action required.
- *Downstream Water Level*: Enter 0.5 (as the normal water level).

Click on the **OK** button in the interface of Figure 6.40 to close the screen, write the rainfall definition file, run the URBS model, read the URBS model results from DOS based files, save the calculated results and parameters to relevant database files, write peak discharge and downstream water level into the flow file of the HEC-RAS project file, run the HEC-RAS model, modify the relevant database records and finally display the **Main Menu** (Figure 5.2).

Step 4 Forecast with 1-hour low, medium and high forecast rainfalls under normal downstream water level (Scenarios 2, 3 and 4)

Repeat the Steps 1 to 3 except some parameters related forecast rainfall in Step 3, which are described below. The forecast 1-hour low, medium and high rainfalls are given in Table 6.5

Table 6.5 Forecast 1-hour Low, Medium and High Rainfalls

Station	Forecast Rainfall (mm)		
	Low	Medium	High
<b>Bulla</b>	<b>3</b>	<b>3.8</b>	<b>22.2</b>
<b>Clarkefield</b>	<b>2.2</b>	<b>3.2</b>	<b>16.2</b>
<b>Darraweit Guim</b>	<b>1</b>	<b>1.8</b>	<b>9</b>
<b>Macedon</b>	<b>1.4</b>	<b>3.8</b>	<b>18</b>
<b>Romsey</b>	<b>2.6</b>	<b>4.2</b>	<b>20.4</b>

- *Total Rainfall Duration (h)*: Enter 36 (i.e. observed 35 hours plus forecast 1 hour).
- *Total Forecast Rain Time*: Enter 1.
- Enter low forecast rainfalls (Scenario 2) – Enter one rainfall value first for all stations, and then change the rainfall values from the above value, if changes are required at certain stations. In this case, initially Bulla rainfall values are entered first and then the procedure is explained to change the value of Romsey to its forecast rainfall. The details are given below.
  - Set forecast rainfall as 3 initially for all stations (which is only required for Bulla) - enter \* in the text box of the combo box of *Pluviometer Name*, enter 3.0 in *Qty* box, click on *Total Forecast Rainfall* and then on the **ADD** button. All 5 elements in the combo box of *Total Forecast Rainfall* become 3.0. Change these rainfall values then to reflect the low rainfalls in Table 6.5 at different stations, except Bulla.
  - For station Romsey - select Romsey from the combo box of *Pluviometer Name*, enter 2.6 in *Qty* box; Click on *Total Forecast Rainfall* and then on the **ADD** button. The fifth element in the combo box of *Total Forecast Rainfall* becomes 2.6.
  - Repeat the procedure used for Romsey for other stations, except Bulla, which does not require changes. These rainfall stations and corresponding forecast rainfall screens are shown Figure 6.41.

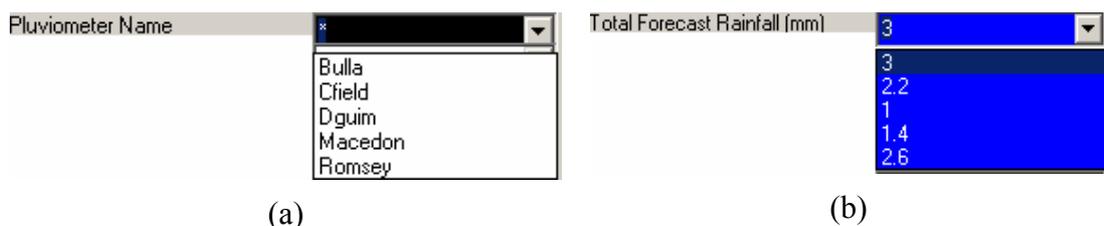


Figure 6.41 Pluviometer Names and Corresponding Forecast Rainfalls

Repeat the above procedure for Scenarios 3 and 4 (in Table 6.4) using the data in Table 6.5.

Step 5 Forecasting with Zero Forecast Rainfall under High Downstream Water Level (Scenario 5)

Repeat Steps 1 to 3, but with the downstream water level of 1.5 meters as the high water level.

Step 6 Forecast with 1-hour Low, Medium and High Forecast Rainfalls under High Downstream Water Level (Scenarios 6, 7 and 8).

Repeat Step 4, with the downstream water level of 1.5 meters as the high downstream water level.

Step 7 Forecast with Low 3-hour Forecast Rainfall under Normal Downstream Water Level (Scenario 9)

Repeat Steps 1 to 3 except some parameters related to 3-hour low forecast rainfall, as described below. The 3-hour forecast rainfalls together with their hourly percentages are given in Table 6.6.

- *Total Rainfall Duration (h)*: Enter 38 (i.e. observed 35 hours plus forecast 3 hours).
- *Total Forecast Rain Time*: Enter 3.
- *Downstream Water Level*: Enter 0.5.
- Enter low forecast rainfalls (Scenario 9) – Enter one rainfall value first for all stations, and then change the rainfall values from the value in Table 6.6, if changes are required at certain stations. In this case, Macedon and Bulla rainfall values are entered first (which have the same forecast rainfalls) and then the procedure is explained to change the value of Romsey to its forecast rainfall. The details are given below

Table 6.6 Forecast 3-hour Low and High Rainfalls

Station	Forecast Rainfall							
	Low				High			
	Depth (mm)	1 <sup>st</sup> Hour Rainfall (%)	2 <sup>nd</sup> Hour Rainfall (%)	3 <sup>rd</sup> Hour Rainfall (%)	Depth (mm)	1 <sup>st</sup> Hour Rainfall (%)	2 <sup>nd</sup> Hour Rainfall (%)	3 <sup>rd</sup> Hour Rainfall (%)
<b>Bulla</b>	3.8	80	10	10	22.2	80	10	10
<b>Clarkefield</b>	3.2	70	25	5	16.2	70	25	5
<b>Darraweit Guim</b>	1.8	60	20	20	9	60	20	20
<b>Macedon</b>	3.8	40	20	40	18	40	20	40
<b>Romsey</b>	4.2	60	30	10	20.4	60	30	10

- Set forecast rainfall as 3.8 initially for all stations, which is the rainfall for Macedon and Bulla: enter \* into *Pluviometer Name*, enter 3.8 in *Qty* box, and click on *Total Forecast Rainfall* and then on the **ADD** button. All 5 elements in the combo box of *Total Forecast Rainfall* become 3.8.
- For station Romsey: select Romsey from the combo box of *Pluviometer Name*, enter 4.2 in *Qty* box, and click on *Total Forecast Rainfall* and then on the **ADD** button. The fifth element in the combo box of *Total Forecast Rainfall* becomes 4.2.
- Repeat the procedure used for Romsey for other stations, except Macedon and Bulla, which does not require changes.
- Set percentages of forecast rainfall in each hour – Enter one set of percentages for all stations, and then the change these percentages as required for certain stations. In this case, Romsey percentages are entered first and then the procedure is explained for Darraweit Guim to its percentages. The details area given below.
  - Set these percentages for all stations as in Romsey: enter \* into *Pluviometer Name* and then
    - o Enter 60 in % box, click on *One Hour Rainfall / Total Forecast Rainfall(%) in First Hour* and then click on the **ADD** button. All 5 elements in the combo box of *One Hour Rainfall / Total Forecast Rainfall(%) in First Hour* become 60.
    - o Follow the above procedure for the second and third hour with 30 and 10 in % box.
  - For station Darraweit Guim (display on the interface as Dguim): select Dguim from the combo box of *Pluviometer Name* and then enter values of percentages as in Table 6.6.
  - Repeat the above procedure for Clarkefield, Macedon and Bulla. After entering above data, the combo boxes of *One Hour Rainfall / Total Forecast Rainfall(%) in First Hour*, *One Hour Rainfall / Total Forecast Rainfall(%) in Second Hour*, and *One Hour Rainfall / Total Forecast Rainfall(%) in Third Hour* are displayed as Figure 6.42.

Step 8 Forecast with High 3-Hour Forecast Rainfall under Normal Downstream Water Level (Scenario 10)

Repeat Step 7 above, but with forecast for high rainfalls in Table 6.6.

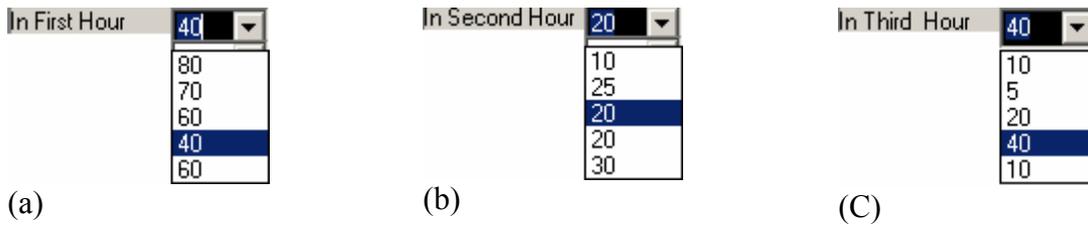


Figure 6.42 Rainfall Percentages in First, Second and Third Hour at Each Station

Step 9 Forecast with Low 3-hour Forecast Rainfall under High Downstream Water Level (Scenario 11)

Repeat Step 7, but with the downstream water level of 1.5 meters.

Step 10 Forecast with High 3-hour Forecast Rain under High Downstream Water Level

Repeat Step 8, but with the downstream water level of 1.5 meters.

Step 11 View the Tabular Results of Forecast Hydrographs and Flood Water Levels

Click on the item of **Dat**abase in the **Main Menu** of DSSFCMR and then on **F**orecast or Calibration URBS only of **S**imulated Flood Scenarios (Figure 5.2).

The forecast results are then displayed as shown in Figure 6.43. *Q<sub>peak</sub>* is the maximum discharge during the period from the end time of observed data (i.e. current time) to the end of run duration. The right table of Figure 6.43 gives the details of forecast hydrograph corresponding to a flood scenario (or Scheme). If there is more than one row of data in the left table (as in Figure 6.43), click on the field of *SchemeNo* corresponding to a flood scenario to display the corresponding forecast hydrograph details on the right table.

If the user clicks on the **V**iew button of Figure 6.43, the hydrograph only up to the current time is displayed in Figure 6.44. This hydrograph is same as the hydrograph of the calibration stage (Section 6.3). Forecast hydrograph can be seen only after the forecast event is transferred to database D6RFW.MDB (Section 6.7).

## 6.6 Flood Inundation Area Display and Spatial Analysis

The spatial analysis of flood inundation can be performed during both flood forecasting and decision support stages. Twelve flood forecasting scenarios had already been considered with different forecast rainfalls of different periods at time  $t_I$  (i.e. 07:00 16 October 1983) under different downstream water levels (Section 6.5). These flood results are stored in database D5SFS.MDB. The following steps describe the flood inundation area display and spatial analysis operations.

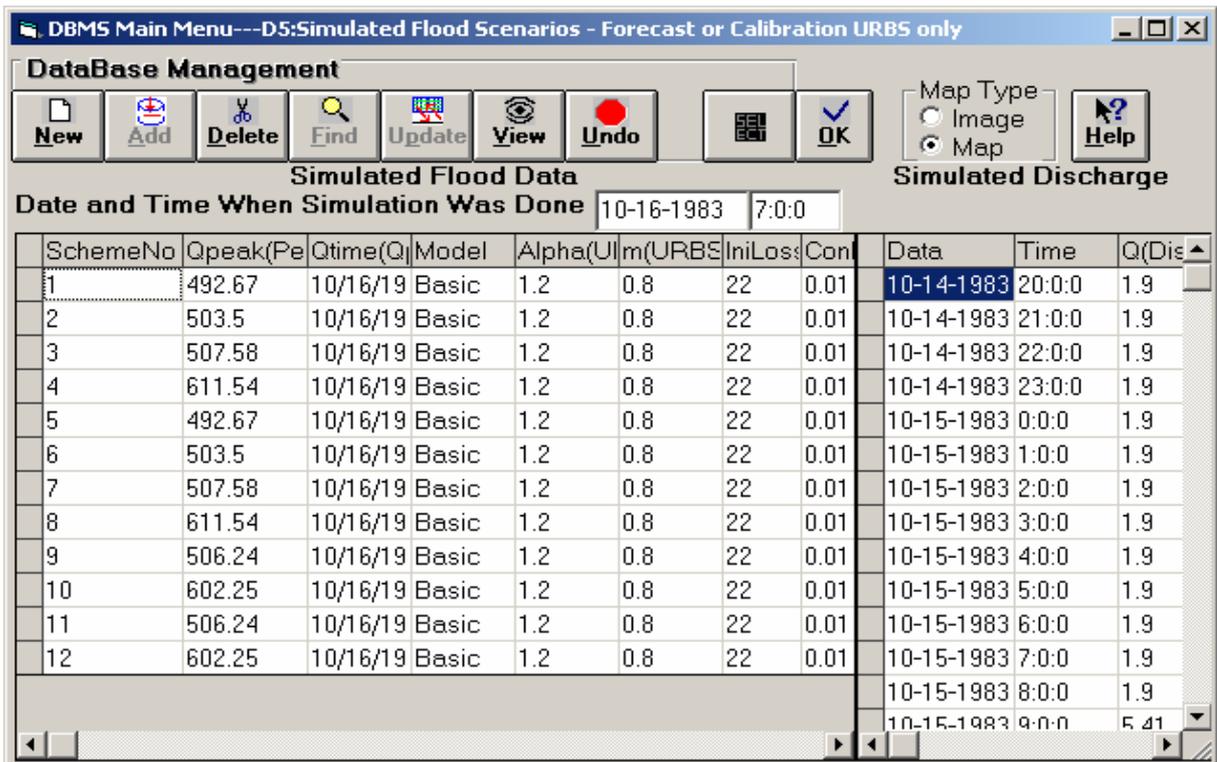


Figure 6.43 Results for All Flood Forecasting Scenarios

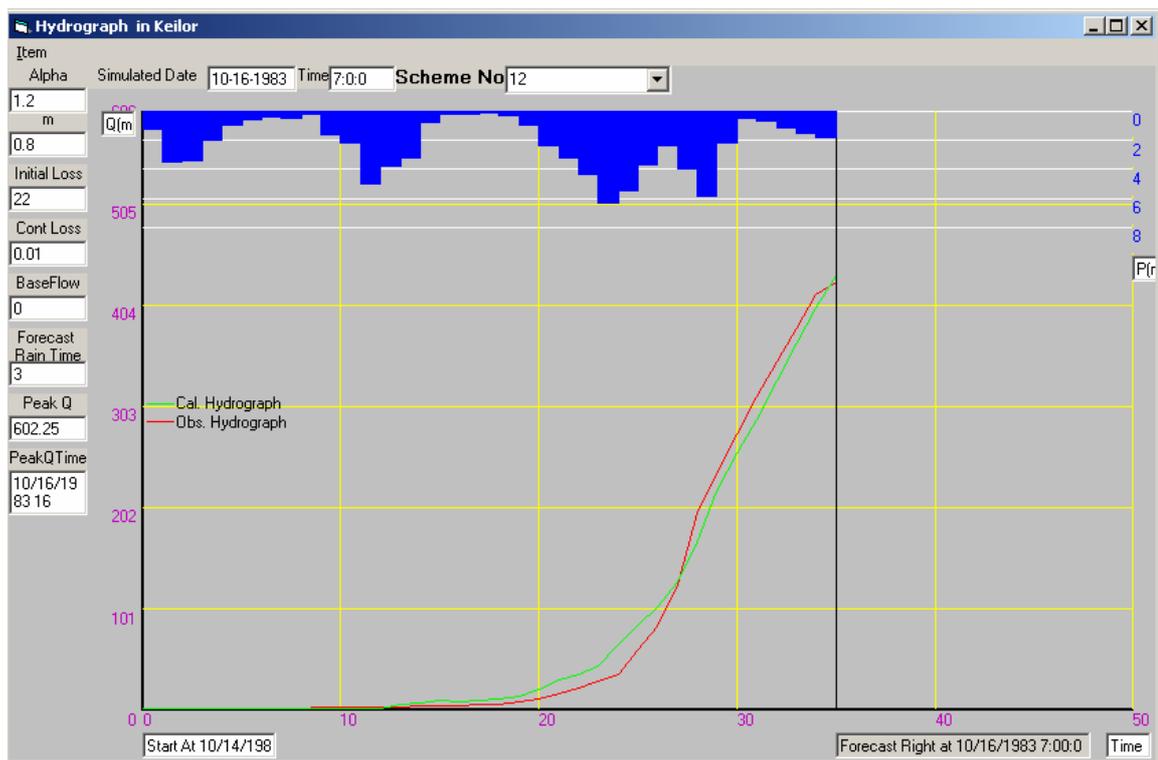


Figure 6.44 Hydrograph Display During Flood Forecasting Stage without Forecasts

Step 1 Start

Click on **Database** in the **Main Menu** of DSSFCMR and then click on **Forecast or Calibration URBS only** of **Simulated Flood Scenarios** (Figure 5.2). The interface shown in Figure 6.43 is displayed then. The option buttons **Image** and

**Map** (i.e. the buttons dealing with the first and second methods respectively in spatial and graphical display and data analysis - SGDDA described in Section 5.2.4.2) in Figure 6.43 are developed to display the flood area image and the interactive map interface for flood area spatial analysis respectively for a selected record. In this application, both methods are illustrated as Steps 2 and 3.

Step 2 Display of the Flood Area Image

- Select the first method of SGDDA: Click on the option button **Image**.
- Select the flood forecasting scenario: Click on the last record in the left table to select the simulated flood scenario 12, as an example. Click on *QProcess(ForecastFlowFile)* field of this row (record). This will display the flood prone area image map as shown in Figure 6.45 (without any flood lines).
- Overlay the flood line: Click on the flood prone area image in Figure 6.45 to draw the flood line (in red) on the image map (Figure 6.46). The area inside the red line represents the flood inundation area for the selected flood scenario.
- Find the position: Click on any point on the image also to display the Easting and Northing of that point (or the cursor point).
- Close the Window: Close the window of Figure 6.46 by clicking on the cross button at the top right of Window.
- Repeat above procedure of step 2 to display the flood area images for other scenarios, as required. Figures 6.47 and 6.48 show these images for flood forecasting scenarios of 1 and 11 respectively.



Figure 6.45 Flood Prone Area Without Flood Lines Figure 6.46 Flood Area Image for Forecasting Scenario 12

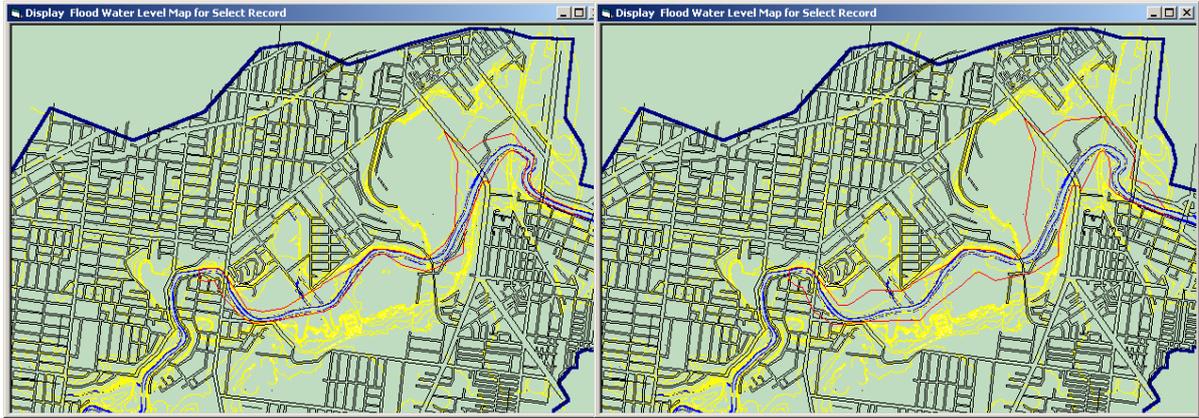


Figure 6.47 Flood Area Image for Forecasting Scenario 1

Figure 6.48 Flood Area Image for Forecasting Scenario 11

### Step 3 Spatial Analysis of Flood Inundation Area

- Select the second method of SGDDA: Click on the option button of **Map** (in Figure 6.43).
- Select the flood forecasting scenario and perform spatial analysis operations: Click on the last record in the left table to select the simulated flood scenario 12, as an example, and then click on the field *QProcess(ForecastFlowFile)* of this row (record). This will display the interface for spatial flood area analysis shown in Figure 6.49. The topographical details of Figure 6.45 (or 6.46) and 6.49 are the same. However, in Figure 6.45 (or 6.46), the full image of flood prone area is shown, while in Figure 6.49, only a section is shown. Although only the flood forecasting scenario 12 is considered in this section, the user can analyse any other flood forecasting scenario for which data are stored in database D5SFS.MDB. Following spatial analysis operations are performed for illustration purposes.
  - Showing full extent of Map - Click on the button  to show the whole catchment including the flood prone lower part of the river (Figure 6.50).
  - Zoom in and Zoom out operations - Click on the Zoom in button  to make it active, and then use mouse to select a rectangle area from the map as in (Figure 6.51). The detailed map as selected in Figure 6.51 is then displayed in Figure 6.52. Repeating this process again and again gives more detailed maps (e.g. Figure 6.53). Clicking on the Zoom out button  and then clicking on the map can perform the zoom out operation, which gives Figures 6.52, 6.51 and finally 6.50.

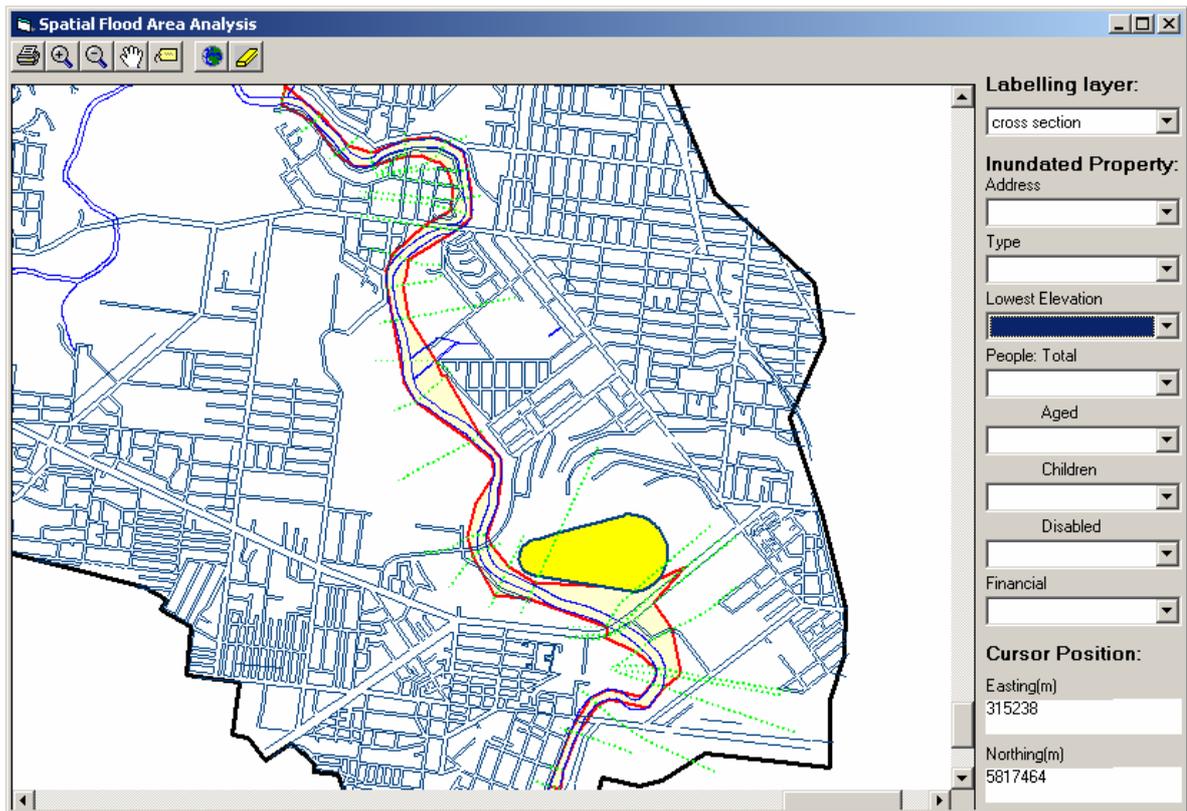


Figure 6.49 Interface for Spatial Analysis of Flooded Area

- Moving the current map - Clicking on the button  to make it active. Then drag the current map (e.g. Figure 6.53) up, which shows Figure 6.54. Dragging can be done in any direction to see required areas within the map.
- Showing cross section number and its water level – Click on the button  and then select “cross section” from the combo box of *Labelling layer* in Figure 6.53. Then click on a cross section to show its cross section number (Figure 6.55). Repeat the operation to show the cross section number of any other cross section. Click on the button Clean (i.e. ) to clean the current cross section numbers and this operation also make all buttons ready for use. Select the “water level” from the combo box of *Labelling layer* in Figure 6.55, and click on a cross section to show the water level of this cross section (Figure 6.56) (Note that this screen is not exactly same as Figure 6.55 as the map is moved up for details). Water levels of other cross sections can be displayed using operations similar to the cross section number.
- Easting and Northing of location – Move the cursor on the map. This displays the Easting and Northing of the cursor position under *Cursor Position* fields. Figure 6.41 shows them as 315238 and 5817464.

- Find the details of the inundated properties: At the start, the contents of combo boxes (Figure 6.49) under *Inundated Property* are empty. These combo boxes are used to store the data on inundated properties. When the user selects a rectangle area on Figure 6.49 using the mouse, all properties (the user can refer the property shapefile in Section 4.1 for details) within this rectangular area (either flooded in part or full) are detected as shown in Figure 6.57. In addition, with in the rectangular area, the colour of flood area boundary within inundated properties is changed from red to pink, and the flooded property boundary is changed from a solid line to a dotted line and the flooded property becomes transparent so that the flood line can also be seen, as shown in Figure 6.57. These features will help the user to locate the inundated properties. The information on inundated properties within the rectangular area will also be stored in combo boxes of Figure 6.58; the information includes property (house) address; type (i.e. school, hospital, etc.); number of persons (total within the flood inundation area, aged, children and disabled; and financial data. This information will help the decision maker for flood warning. The whole flood prone area showing the inundation properties are shown in Figure 6.58.

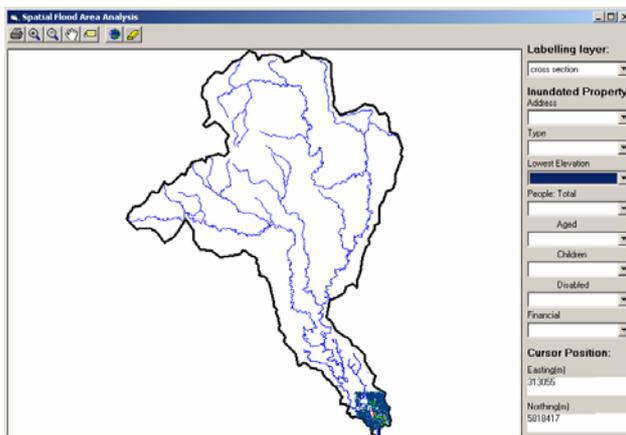


Figure 6.50 Full Extent of Catchment Map

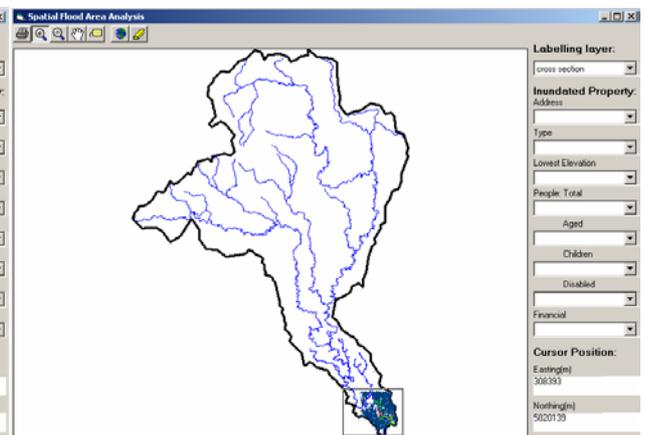


Figure 6.51 Selecting a Rectangle Area for Zoom In

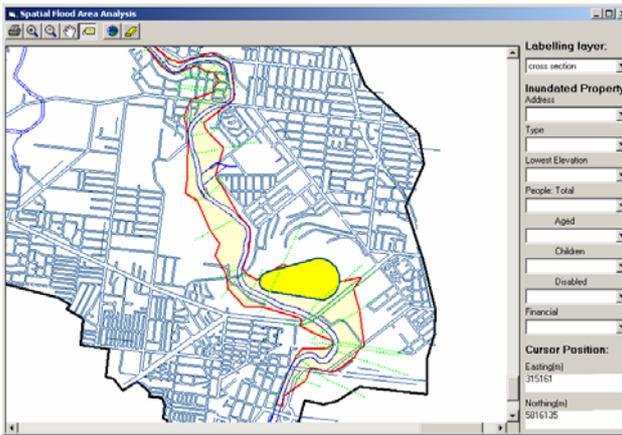


Figure 6.52 Zoom In Result for Selected Area

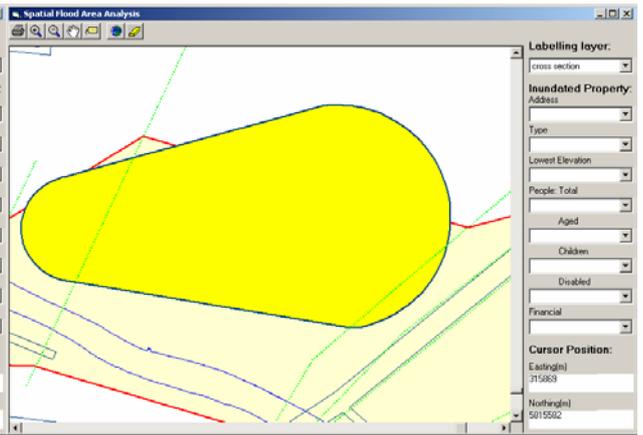


Figure 6.53 Further Zoom In Results for Selected Area

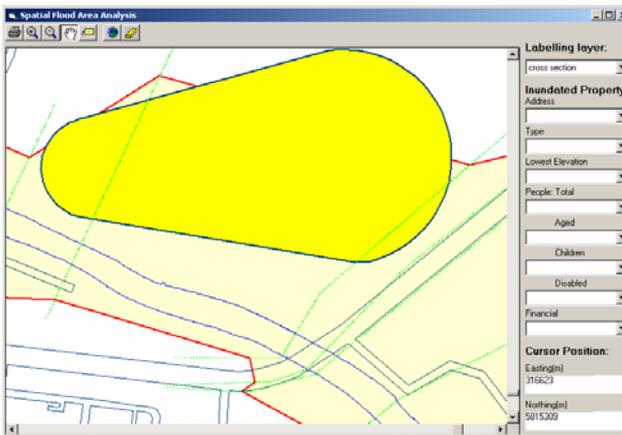


Figure 6.54 Results for Dragging the Map

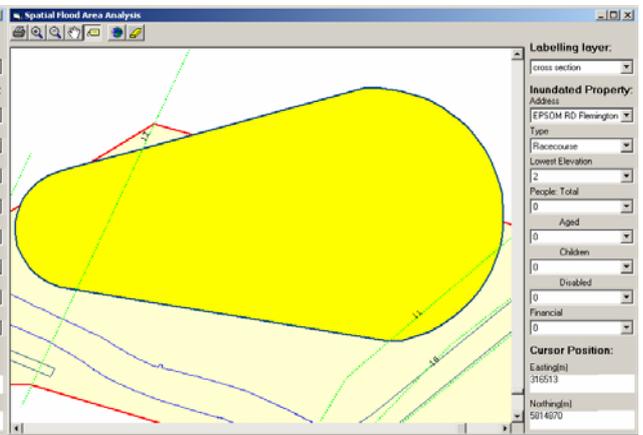


Figure 6.55 Map Showing Cross Section Numbers

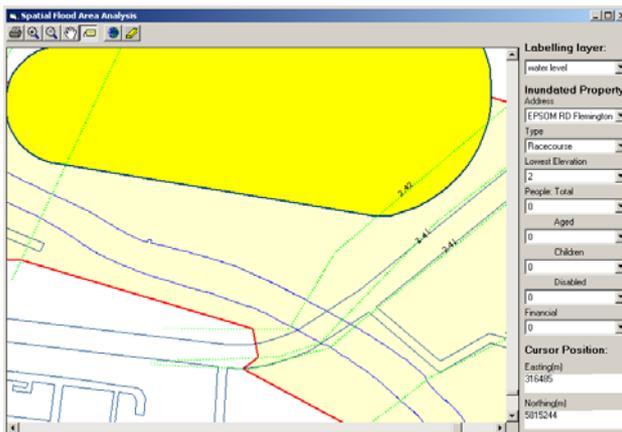


Figure 6.56 Map Showing Water Levels at Cross Sections

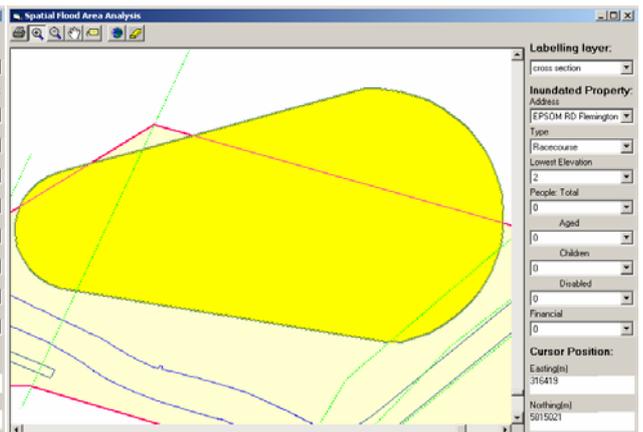


Figure 6.57 Selected Flooded Area Showing Inundated Properties

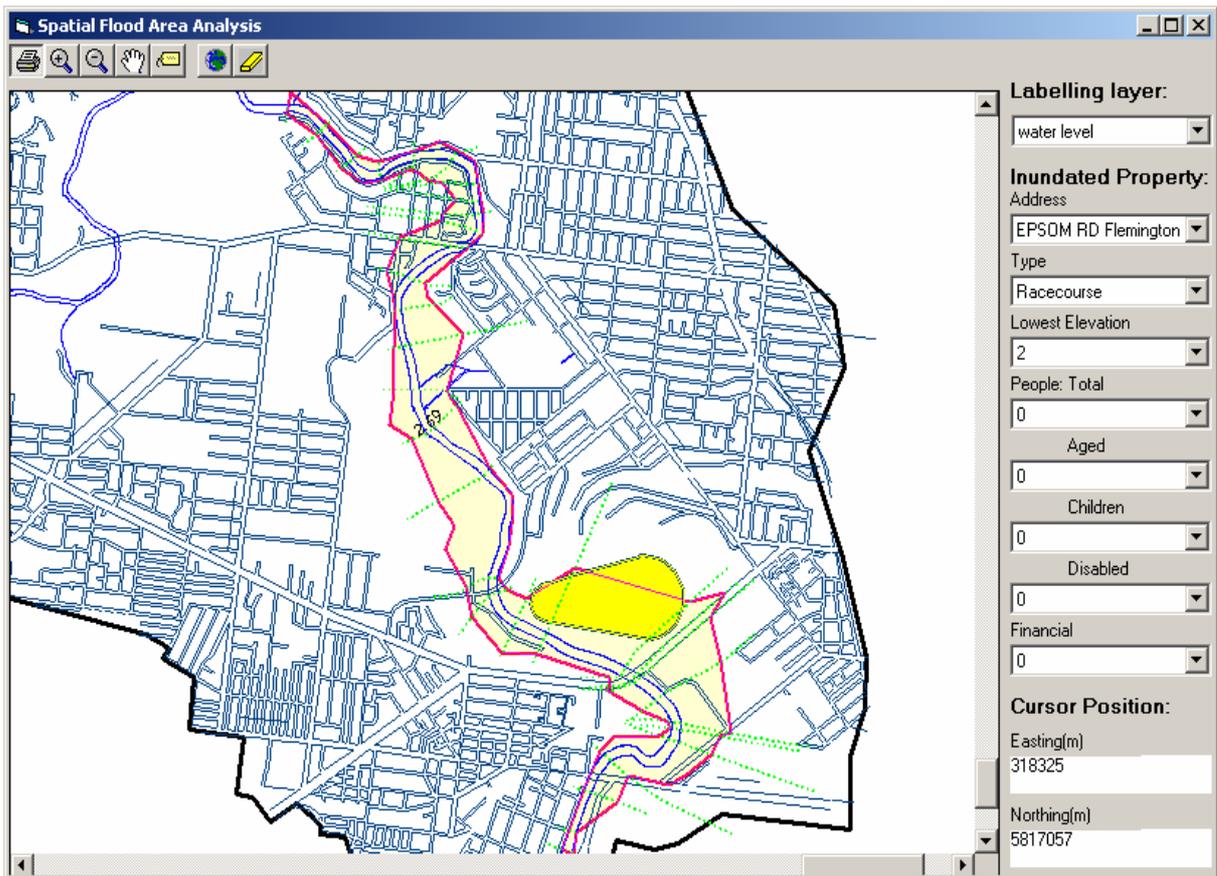


Figure 6.58 Whole Flood Prone Area Showing Inundated Properties

In this section, the two methods of SGDDA that were developed and described in Section 5.2.4.2 were demonstrated for spatial data display and analysis of flooded areas. All flood forecasting scenarios can be spatially displayed and analysed with these methods, which allow the decision maker to make the decisions effectively.

## 6.7 Decision Support

As stated in Sections 2.6 and 3.1.1, the decision support subsystem was developed for the user to select a small number of appropriate flood forecasting scenarios from the database D5SFS.MDB to build acceptable decisions at time  $t_1$ . The following steps describe this procedure.

### Step 1 Find a Small Number of Scenarios

Click on the item of **Decision** of the **Main Menu** in Figure 5.2. This displays the Window of **Form to Find Some Solutions** (Figure 6.59). Initially, this form does not contain any data. In this example, it is assumed that the decision maker is

interested in the flood scenarios using forecast rainfall greater than 5 mm in each station for forecasting periods of 1 and 3 hours with the downstream water level from 0.8 to 1.5. Set these data in Figure 6.59 as described below (to select the required flood forecasting scenarios).

**Form to Find Some Scenarios**

Buttons: Add, OK, View, Cancel

Field	Operator	Value1	Operator	Value2
Alpha	*	*	and	*
m	*	*	and	*
Initial Loss (mm)	*	*	and	*
Continuing Loss	*	*	and	*
Baseflow	*	*	and	*
Pluviometer Name	*	Qty 5	%	100
Forecast Rain Period	>=	1	and	
Forecast Rainfall(mm)	>=	5	and	
Rainfall / Total Forecast Rainfall (%)				
In 1st Hour	*	*	and	*
In 2nd Hour	*	*	and	*
In 3rd Hour	*	*	and	*
DownStream Water	Between	0.8	and	1.5

SQL Query: Select \* from SFS1 where ForecastStormPeriod >= 1 and ForecastStormQty01 >= 5 and ForecastStormQty02 >= 5 and ForecastStormQty03 >= 5 and ForecastStormQty04 >= 5 and ForecastStormQty05 >= 5 and Sec01H Between 0.8 and 1.5

Figure 6.59 Interface of the Form to Find Some Solutions

- Set forecast rainfall period: select “>=” from the comb box of *Operator* for *Forecast Rain Period*. This selection makes its combo box of *Value2* disappear. Select 1 from the combo box of *Value1*.
- Set forecast rainfall: select “>=” from the comb box of *Operator* for *Forecast Rainfall(mm)*. This selection makes its combo box of *Value2* disappear. Keep “\*” for the comb box of *Operator* for *Pluviometer Name*, enter 5 into the text box of *Qty*, and then click on the button **Add**. All values corresponding to all 5 pluviometers in the combo box of *Value1* become 5.
- Set downstream water level: select “between” from the comb box of *Operator* for *Downstream Water*, and then enter 0.8 into the text box of the combo box of *Value1* and 1.5 into the text box of the combo box of *Value2*.

- View the Structured Query Language (SQL) statement: click on the button **View**. The SQL statement “Select \* from SFS1 where ForecastStormPeriod >=1 and ForecastStormQty01 >= 5 and ForecastStormQty02 >= 5 and ForecastStormQty03 >= 5 and ForecastStormQty04 >= 5 and ForecastStormQty05 >= 5 and Sec01H Between 0.8 and 1.5 ” is displayed in the text box at the bottom of the form. The SQL statement states that a search will be made for flood scenarios, which have forecast storm period greater than 1 hour, storm depth of more than 5 mm during the forecast storm period and downstream water levels between 0.8 and 1.5m, and the flood scenario data are stored in the database table *SFS1*.
- Find the scenarios: click on the button **OK** to find the required scenarios. The interface (Figure 6.59) is then closed and the scenarios that are found, are displayed in the standard interface for database D5SFS.MDB (Figure 6.60). In this case, only two scenarios (i.e. scenario 8 and 12) are selected based on the above SQL statement.

Scheme	Qpeak	FQtime	Model	Alpha	m(URBS)	IniLoss	ConLo	Ba	Data	Time	Q(Dis)
8	611.54	10/16/19	Basic	1.2	0.8	22	0.01	0	10-14-1983	20:0:0	1.9
12	602.25	10/16/19	Basic	1.2	0.8	22	0.01	0	10-14-1983	21:0:0	1.9
									10-14-1983	22:0:0	1.9
									10-14-1983	23:0:0	1.9
									10-15-1983	0:0:0	1.9
									10-15-1983	1:0:0	1.9
									10-15-1983	2:0:0	1.9
									10-15-1983	3:0:0	1.9
									10-15-1983	4:0:0	1.9
									10-15-1983	5:0:0	1.9
									10-15-1983	6:0:0	1.9
									10-15-1983	7:0:0	1.9
									10-15-1983	8:0:0	1.9
									10-15-1983	9:0:0	5.41

Figure 6.60 Interface of Selected Scenarios in Database D5SFS

- Step 2      Transfer the Selected Scenarios for Decision Making  
Click on the button **N**ew in Figure 6.60. This displays Figure 6.61. Click **Y**es (in Figure 6.61) to transfer these selected scenarios into database D6RFW.MDB as decisions at this time step. All 12 scenarios in database D5SFS.MDB are then deleted, and then Figure 6.60 is displayed again, but without any data on scenarios.

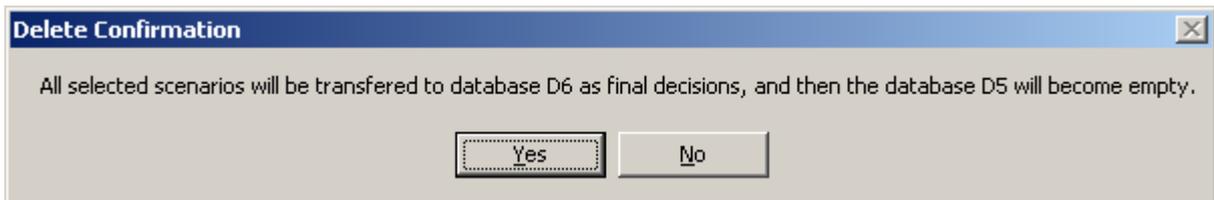


Figure 6.61 Window for Transferring Selected Scenarios for Decision Making

- Step 3      View the Tabular Results of Forecast Hydrograph  
Click on the item of **D**atabase in the **M**ain **M**enu of DSSFCMR and then on **R**eal **T**ime **F**lood **W**arning (Figure 5.2). The selected flood scenarios for decision making (from steps 1 and 2 above) are displayed again as in Figure 6.62. Other information in Figure 6.62 is same as in Figure 6.60 except *SchemeNo*, which is automatically reassigned by DSSFCMR and the additional columns of *Second*, *Minute*, *Hour*, *Day*, *Month* and *Year*, which are included to indicate the time when the forecasting was done and decision is being made.
- Step 4      View a Decision  
Click on the button **V**iew in Figure 6.62, which displays Figure 6.63 to view the forecast hydrographs for any flood forecasting decision scenario. Note the difference between this figure and Figure 6.44, which showed the calibration results. Figure 6.63 shows the forecast hydrograph, which consists of the observed hydrograph before the current forecast time and the calculated hydrograph after the forecasting time. The user can select any simulated flood scenario decisions from the combo box of *Scheme No* to show its forecast hydrograph.
- Step 5      Find the decision  
Note that Figure 6.62 contains selected flood forecasting scenarios based on contain criteria specified by the user. They can be in general for different floods occurred previously or for the current flood, which is under flood forecasting and warning. They can be further investigated to search for decision scenarios based on date and time of the flood, as flows:

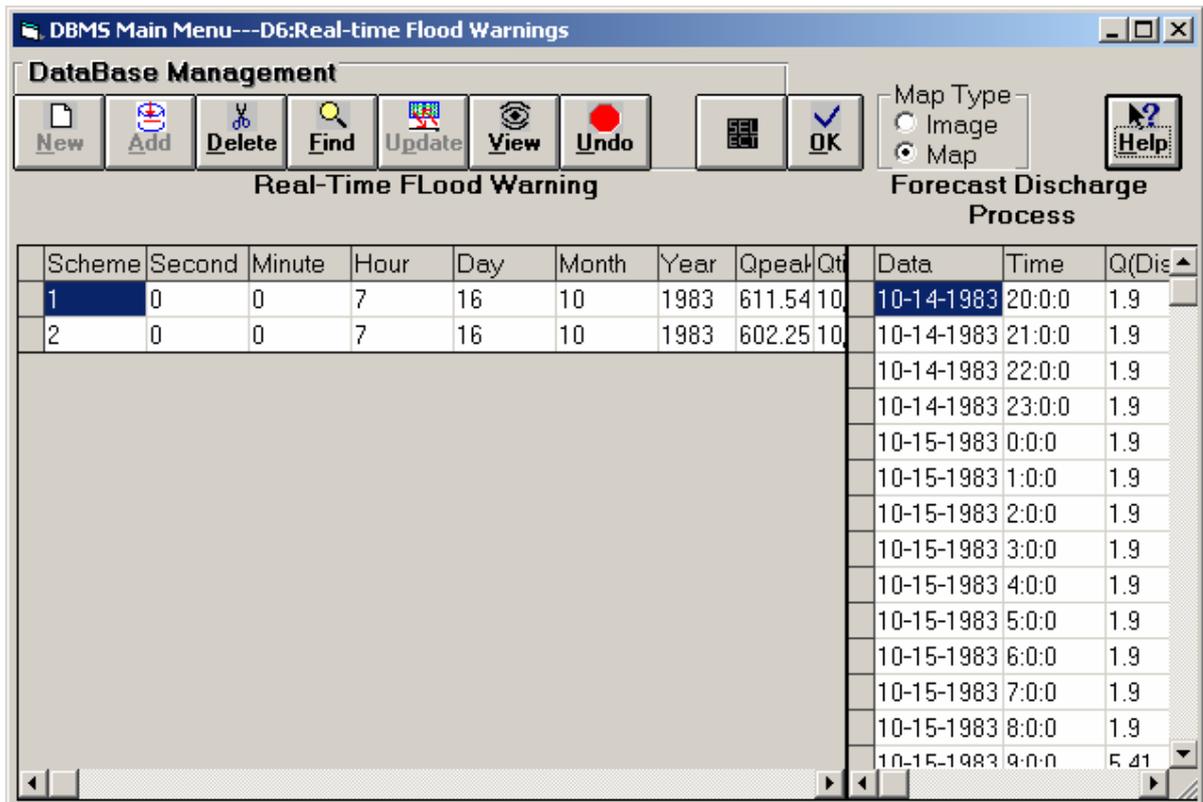


Figure 6.62 Interface Showing Decision Scenarios

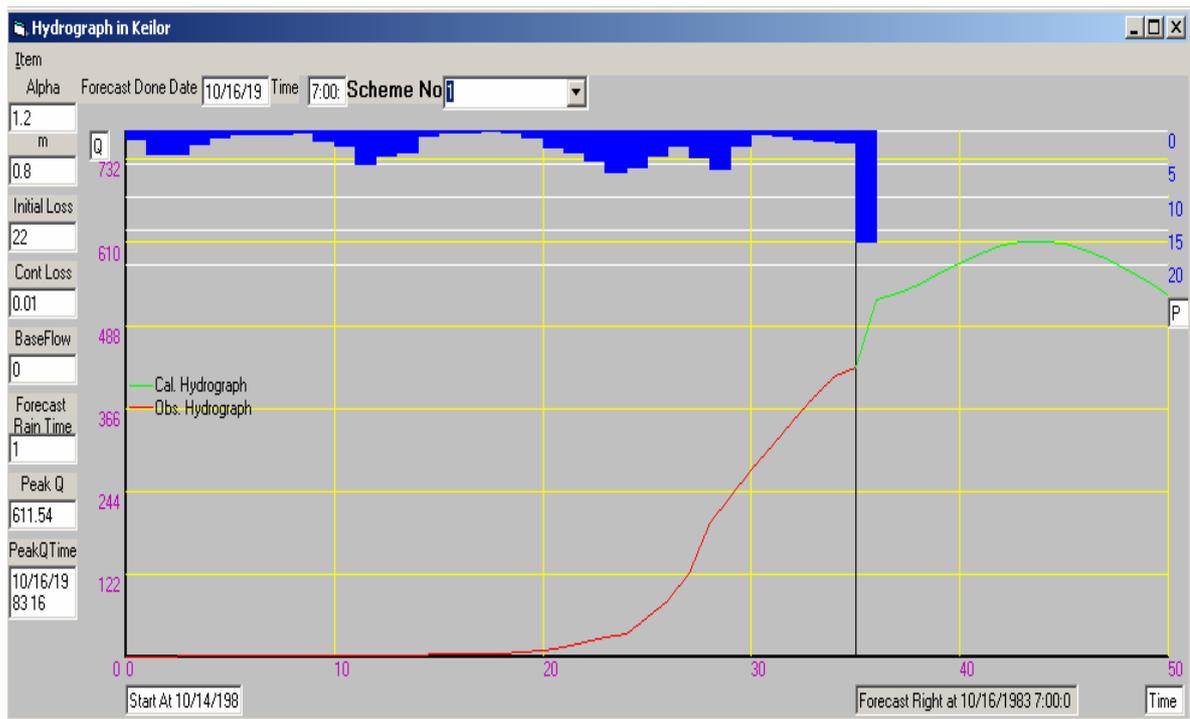


Figure 6.63 Forecast Hydrograph for Selected Decision Scenario 1

Click on the button **F**ind in Figure 6.62, which displays Figure 6.64. Initially, all variables in this interface is with \* symbol except *Qty* and % with 100. However,

the *Qty* and *%* values are not directly used in the search. Note the similarity between Figure 6.59 (which was for database D5SFS.MDB) and Figure 6.64 (which is for database D6RFW.MDB). They are almost the same except for *Time(HH:MM:SS)* and *Date(YY:MM:DD)* are added into Figure 6.64. These two lines are used to search the decisions that are/were made at different times. There can be decision scenarios stored in the database D6RFW.MDB for the current flood with forecasting done at the current time or previous times, or even decision scenarios of other floods studied previously. These decision scenarios will help the decision maker to compare the current decision scenario information (i.e. flood levels, inundation area, properties inundated etc.) with those of other decision scenarios stored in the database. However, in this example, only 2 scenarios are stored in D6RFW.MDB database (Figure 6.62).

**Find Some Final Decisions**

Add OK View Cancel

Time(HH:MM:SS) = 7 0 0 and  
 Date(YY:MM:DD) = 1983 10 16 and  
 Alpha \* and  
 m \* and  
 Initial Loss (mm) \* and  
 Continuing Loss \* and  
 Baseflow \* and  
 Pluviograph Name \* Qty 100 % 100  
 Forecast Rain Period \* and  
 Forecast Rainfall(mm) \* and  
 One Hour Rainfall / In 1st Hour \* and  
 Forecast Rainfall In 2nd Hour \* and  
 Sum (%) In 3rd Hour \* and  
 DownStream Water \* \* \*

Select \* from RfFw1 where Hour = 7 and Minute = 0 and Second = 0 and Year = 1983 and Month = 10 and Day = 16

Figure 6.64 Interface for Searching Stored Decision in Database D6RFW.MDB

The Enter =, 7, 0 and 0 into the text boxes of *Time(HH:MM:SS)*, and =, 83, 10 and 16 into text boxes of *Date(YY:MM:DD)*. Click on the button **View** to display SQL statement, as shown in Figure 6.64 and then click on the **OK** button. This displays an interface exactly same as Figure 6.62, since there were only two decisions corresponding to 07:00 hours on 16/10/1983.

Once the decision scenarios are selected as above, the operations described in Section 6.6 can be used to analyse the effect of these decision scenarios on flooding. These operations give the decision maker information on flood inundation area, depth of flooding, number of properties flooded under each scenario, etc. This information will help the decision maker to issue appropriate and well-informed flood warning and to take appropriate action for evacuation etc., if needed.

## **6.8 Summary**

The use of DSSFCMR to provide decision support for flood forecasting and warning in The Maribyrnong River basin was illustrated in this chapter. The application used the flood event that occurred on 14 October 1983, but forecasting was done under 1997 topographical conditions of the flood prone area of the lower part of the calibration. Essentially, the application concentrated on flood forecasting and warning decisions at a particular time during the event.

Three methods developed in DSSFCMR and one additional database method were demonstrated for entering hydrological and hydraulic data for observed flood events. It was seen that the developed functions for viewing data such as tabular and graphical methods were effective in studying data and identifying errors in data. The developed database functions such as delete, find and update were helpful for the user to locate the certain data records, delete the wrong entries and correct erroneous data. In addition, these functions help the user to manage the database efficiently, making data analysis and management of DSSFCMR effective and efficient.

The calibration of both the URBS hydrological model and the HEC-RAS hydraulic model showed that DSSFCMR can be used to calibrate these models easily and effectively. The developed tabular and graphical views effectively help the user to compare the observed data and calculated results to lead a good calibration outcome. The calibration parameters can be

stored in the database for further use. The additional functionality developed to link both models to DSSFCMR, made them more powerful in the use of flood forecasting and warning.

Twelve flood forecasting scenarios (with varying degrees of forecast rainfall for different forecast periods under different downstream water levels) were considered in this application for illustration purposes. It was demonstrated that flood forecasting was easy and convenient due to the automation of running the URBS model, writing the peak discharge of forecast hydrograph into the HEC-RAS project file, running the HEC-RAS model, and storing the forecast flood information (i.e. flood flows and levels) into the database. The user was then able to use the developed interfaces to effectively review the details of the flood forecasting scenarios including key parameters, forecast hydrographs from the URBS model and the relevant water levels calculated from the HEC-RAS model, using tabular and graphic formats.

Two separate methods developed within DSSFCMR for spatial data display and analysis of flood areas were demonstrated for all flood forecasting scenarios. All forecasting scenarios can be spatially displayed and analysed, which allow the decision maker to make the decisions effectively. The developed interfaces allowed the user to investigate spatial details of the flood inundation area and the potential flood damage extensively and interactively for all flood scenarios. The user can use DSSFCMR to investigate decision making variables related to flood warning such as people relocation from the second method conveniently and quickly.

The decision support was demonstrated by selecting a smaller number of acceptable and appropriate scenarios of many scenarios analysed, for making flood forecasting and warning decisions. Once the decision scenarios are selected as above, the spatial data display and analysis operations can be used to analyse the effect of these decision scenarios on flooding. These operations give the decision maker information on flood inundation area, depth of flooding, number of properties flooded under each decision scenario. This information will help the decision maker to issue appropriate and well-informed flood warning and to take appropriate action for evacuation etc., if needed.

# CHAPTER 7

## SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The Decision Support Systems (DSSs) have become popular in making decisions for complex water resources problems. The design and development of an effective DSS needs to incorporate both theory and knowledge in many different areas, such as DSS theory, computer science, GIS technology (when spatial analysis is required for decision making), and the knowledge in the specific application domain (i.e. hydrological and hydraulic knowledge for decisions in flood forecasting and warning, as in this particular application). However, the design and development of some previous applications were based on very old DSS theory and computer science, and not based recent theory. The literature on design and development of effective DSSs are also relatively few, while most DSSs are concentrated on their applications. Moreover, the applications of DSSs in flood forecasting and warning are very few.

The flood warning decision is based on the information on potential damage such as properties and persons in the flood inundated area for certain “what if” scenarios corresponding to a certain forecast rainfall and a certain downstream water level condition. The information transfer from forecast rainfall to final decision making objects (e.g. relocated persons) requires a unique system to perform an effective and correct process. A DSS is such a computer based system, which can be effectively use to answer “what if” questions and assist decision making. Therefore, the research into development of such a DSS helps the decision-maker to make decisions effectively. The above research will also help DSS studies in flood warning, water resources and other fields. Therefore, the goal of this thesis was to develop an effective DSS for flood forecasting and warning, specifically for use in the Maribyrnong River basin in Melbourne, Victoria in Australia.

Based on the goal, this thesis systematically reviewed the relevant past research on the topic, investigated and developed the methodology of the DSS, developed a detailed conceptual system design, and finally developed the DSS for flood forecasting and warning with appropriate functions. This chapter summarises the achievements in this research, discusses the strengths and limitations of this research work, points out the future research opportunities and finally presents general conclusions from this research project.

## 7.1 Achievements

A detailed review of the relevant topics, which assists the development of an effective DSS for flood forecasting and warning, was completed in this research. The reviewed topics included the DSS theory (such as definition, components, design, and development); the flood mitigation strategies in the Maribyrnong River basin; the topics relevant to the application area of flood forecasting and warning (e.g. hydrological models, hydraulic models, rainfall forecast technologies, spatial data display and analysis technologies, flood warning, and software development); decision support technologies; and applications of DSS for water resources issues.

Based on the literature review, the methodology for development of a DSS for flood forecasting and warning was investigated. As part of this research, the author defined the DSS as an interactive computer-based system that helps decision-makers to use data and models to solve semi-structured problems effectively. The DSS should allow the user to participate in principal steps of the decision making process, to simulate many steps in the process of decision making, to investigate alternative scenarios, to seek the overall goal for decision, and to improve the effectiveness of decision making. Based on modern developed technology and more powerful functions, the author suggested a DSS, which requires spatial data display and analysis (that is very common in water resources area) should include five essential components: a database subsystem, a Modelbase subsystem, an interface subsystem, a decision support subsystem, and a spatial and graphic data display and analysis (SGDDA) subsystem.

A Windows-based computer system called DSSFCMR (**D**ecision **S**upport **S**ystem for **F**lood **C**ontrol in **M**aribyrnong **R**iver) was designed and then developed to enhance the effectiveness of flood warning in the Maribyrnong River basin. Based on the current advanced technology and more powerful functions required for modern DSSs, DSSFCMR was designed to include the above five major subsystems. The functions of DSSFCMR included the database management functions such as data entry, data deletion and data extraction; calibration of the hydrological and hydraulic models, forecasting of flood hydrographs, calculation of flood water levels, spatial data display and analysis of flood inundated areas, and decision selection support for flood warning.

The developed Database subsystem can perform various tasks for general requirement in database management for flood warning. The Database subsystem was well designed to comprise six groups of databases, namely: Catchment Characteristics; Model Parameters; Historical Flood; Real-time Flood Events; Simulated Flood Scenarios and Real-time Flood Warning. Four methods were developed in DSSFCMR to enter the observed hydrological and hydraulic data, namely data entry from a text data file, tabular data entry directly from the interface, single record entry at a time from the interface (a record is a set of data at a particular time) and entering data directly into the database table. The developed interface of tabular and graphical view functions effectively helps the user to check the entered data and review them. The common graphical format in hydrological analysis such as display of hydrographs, hyetographs, water stage and discharge curves were developed. The user can also use the developed tabular and graphical functions to compare the results of the hydrological and hydraulic model calibrations. Other functions such as deleting data and searching data were also developed. These functions help the user to analyse and manage relevant data effectively and conveniently, and to exchange data quickly.

The DOS based URBS hydrological model was embedded in the Windows based DSSFCMR. URBS is a non-linear rainfall-runoff catchment routing model, which computes flood hydrographs due to rainfall events, giving due consideration to catchment losses. Although the URBS model is suitable for forecasting flood hydrographs, the model itself does not have the facility for adaptive parameter modifications. From the developed Windows Interface, the user is able to edit key parameters of the URBS model. DSSFCMR constructs the catchment and rainfall files for the URBS model based on the selected values of model parameters, and run the URBS model automatically, which creates DOS based output files. The data in these DOS based output files are then automatically entered into relevant database tables with all input parameters. This functionality was developed in DSSFCMR for both calibration of URBS model and forecasting using the URBS model. DSSFCMR allows the forecasting of flood hydrographs under scenarios of no forecast rainfall, 1-hour forecast rainfall and 3-hour forecast rainfall. The peak discharges from the forecast hydrographs are used to calculate flood water levels in the flood inundation area. The forecasting results such as the flood hydrograph details and the model parameters are stored in database files for further analysis. The procedure of calibration and forecasting can be updated at each time step during a flood event. The user can effectively calibrate the URBS model through the developed DSSFCMR interface and use the model to forecast the flood hydrographs effectively. The above functions

developed in DSSFCMR have made the URBS model more powerful compared to its stand-alone version.

Another major challenge was the integration of the Windows based DSSFCMR with the Windows based HEC-RAS hydraulic model. HEC-RAS performs one-dimensional hydraulic calculations, using the energy equation. It has been successfully used in Australia and overseas for flood modelling applications. Therefore, the HEC-RAS model was embedded in the Modelbase of DSSFCMR to calculate the flood water levels and the flood inundation area along the lower part of the Maribyrnong River. The steady and sub-critical flow mode in HEC-RAS was used in DSSFCMR, as it was appropriate for modelling the flood prone area of the lower part of the Maribyrnong River. The parameters (Manning's roughness coefficient and expansion/contraction loss coefficients at each river cross section of the flood prone area) were considered as calibration parameters of the HEC-RAS model. From the developed Windows Interface in DSSFCMR, the user can edit these parameters and downstream water level conditions, which are the key parameters for calibration of the HEC-RAS model and for forecasting of flood water levels. Once these key parameters are edited, DSSFCMR rewrites the flow data and geometric data files of the HEC-RAS project file. DSSFCMR manages the HEC-RAS model for running and outputting the results and then finally store the results (i.e. flood water levels) into the database. The computations and information transfer are automated in DSSFCMR. Each forecast flood scenario can be viewed in tabular format. Through DSSFCMR, the user can effectively use the HEC-RAS model for computation of potential flood water levels, which can be used in flood waning decision making in addition to calibration of the HEC-RAS model.

All available GIS data were originally in DXF data format and the data did not satisfy the specific requirement in this development. For example, the original contour data consisted of many segments of small lines and they do not link with each other systematically from river upstream to downstream and/or vice versa. Therefore, the data process and reproduction were necessary. A DOS based C++ program was separately developed to solve the above problem in this project. It was developed to read the vertex data from the DXF file, and to reorganize segments in one contour line in the order from upstream to downstream of the river and/or vice versa. The program also produced an output with the ordered vertex data in contours into an ASCII file, and these data was then used to derive the positions of other data such as cross section data. This technology had also the benefit developing of an integrated spatial system based on DXF spatial data exchange format. Although this particular integrated system was

once planned (in 1997) in this research project, it was decided not to use this technology, since the shapefile concept and GIS technology were used. The latter technology is far superior to the former due to existence of software tools for development (e.g. MapObjects), easy integration and development, easy spatial analysis, etc.

The shapefile originally developed by ESRI is a common GIS format. The generation of shapefile on line for the flood inundated area under each simulated flood is a significant achievement in DSSFCMR. After investigation of the shapefile structure, the shapefile of the flood inundated area was developed in this research. The water levels at cross sections and their geographical control points were used to generate the shapefile of the inundated area on line, which then interacts with the property boundary data to show the inundated properties (i.e. houses) and their data. The developed shapefile then can be used to perform spatial analysis of the flood inundated area for each simulated flood scenario through a developed interactive map interface where the MapObjects technology was used. This technology allows the user to analyse many different flood forecasting scenarios and show results using spatial analysis. This essentially helps to answer “what if” questions in flood forecasting and warning.

Two separate methods were developed in DSSFCMR to perform spatial data display and analysis of the flood inundation (computed area from the hydrological and hydraulic models) for different users with different computer literacy. The first method displays an image of pre-generated map showing flood affecting physical attributes such as river, roads and streets, and overlays the simulated flood area corresponding to a flood scenario using the Windows interface of DSSFCMR. The second method was to integrate the simulated flood inundated area with other geographical information data using MapObjects software in DSSFCMR. The shapefile of the flood area corresponding to a flood scenario is created instantly using the calculated flood water levels from the HEC-RAS model. The user can obtain the geographical information such as position and water level, and flood warning features such as the inundated properties (i.e. houses) and their attributes (e.g. property address, type such as school and hospital, number of persons, and financial data) related to flood warning. The advantage of the first method is that the user has a flood area map without extra expenses (such as having MapObjects software in the computer) and the user does not need to have extensive knowledge in computing. The advantage of the second method is that the user can investigate the spatial details of the flood inundation area and potential flood damage extensively. However, more resources such as MapObjects software are required to use this method. All

flood forecasting scenarios can be spatially displayed and analysed with both methods, which allow the decision maker to make the decisions effectively.

The Decision Support subsystem was developed to assist the decision-maker to issue flood warning, using the results of the analysis of many flood forecasting scenarios. An Interface was developed to query the valuable and relevant decisions for the current flood. The query results are displayed in a table for decision maker to make flood warning decisions. The database search technology was used in the Decision Support subsystem.

Based on a well-designed system, a unique decision support system, DSSFCMR, was developed in this study to help decision making in flood warning, from data entry to final decision search. The design of DSSFCMR includes various functions for various operations, interface development, database development, system status displays, error handling capabilities, safety systems, etc. It is much more detailed, systematic and wider than the three subsystems used in early definitions of DSSs (i.e. Interface, Database and Modelbase). Although DSSFCMR was specifically developed for the Maribyrnong River basin, the design of this system and the general concept of its application can be used for other DSS studies in water resources and other fields. The DSSFCMR software can also be used for flood forecasting and warning in other river basins using appropriate data and slight modifications of the code.

Application of DSSFCMR was illustrated for the Maribyrnong River basin. The system can effectively perform the calibration of the hydrological and hydraulic models, forecasting of flood hydrographs, calculation of flood water levels, spatial data display of flood inundated areas and decision selection support for flood warning. DSSFCMR can efficiently forecast flood hydrographs and calculate the flood water levels. The process of complex data transfer during the decision investigation is done automatically and quickly. The data can be displayed flexibly in various formats. The system is easy to use by different users with different computer skills. The user can use DSSFCMR to investigate decision making variables related to flood warning (e.g. people relocation) conveniently and quickly. In summary, DSSFCMR with above features helps the decision maker to make the decisions effectively.

## 7.2 Strengths and Limitations of This Research

As discussed in previous chapters in relevant places and in Section 7.1, the research in this thesis led to some important contributions to the theory and application of DSS in water resources, in particular in the area of flood forecasting and warning. The developed DSS shows some strengths in system design, development and application. At the same time, there are some limitations of these research works. The details of these strengths and limitations are described below.

### 7.2.1 Strengths

- Contribution to the theory of Decision Support Systems in water resources. Based on the spatial nature of the many water resource problems, the previous research work, the modern decision support system theory, the spatial technology and software, and the computer technology, the researcher developed a five-subsystem DSS. These five subsystems are Database Modelbase, Spatial and Graphic Data Display and Analysis (SGDDA), Decision Support, and Interface. This is a significant improvement from the early definition of DSS, which consist of only three subsystems (Interface, Database and Modelbase).
- Well designed and developed system. Most past applications of DSS in water resources rarely reported their system design and development and therefore could not see system design and development aspects. However, the system design and development is very important in DSS development. The researcher uses his knowledge and working experience in water resource, computer science, GIS and DSS to design and develop this system.
- Practice of software engineering theory. The researcher used recent software engineering theory for development to make DSSFCMR a general computer software tool. For example, DSSFCMR can be used by different users with different computer skills by having four methods of data entry. The error handling is properly handled without crashing the system.
- Advanced Integration technology. All subsystems in DSSFCMR are effectively integrated. For example, the DSSFCMR embedded the DOS based URBS hydrological model and Windows based HEC-RAS model in Modelbase as tools for hydrological and hydraulic analysis respectively. The simulated flood water levels from the HEC-RAS model in the Modelbase were used by the SGDDA subsystem to generate the

shapefile of flood inundation area and perform spatial analysis corresponding to each simulate flood scenario. The process of complex data transfer during the investigation (e.g. the peak discharge to the water level, then water level to the shapefile of flood inundation area) is automatically done by the developed system functions. A deep understanding of the model structures and operations, database, GIS and advanced integrated programming skills were necessary to develop DSSFCMR with these advanced capabilities..

- Instantaneous creation of inundated area shapefile. To analyse each flood forecasting scenario (due to a certain forecast rainfall and a downstream flood water level), the instantaneous creation of the inundation area shapefile is a critical step, since the spatial analysis can be done easily, quickly and effectively with a shapefile than working with database and/or database tables. DSSFCMR can create the flood inundation area shapefile instantly without any external software, using the water levels at each river cross section of the flood prone area generated from the HEC-RAS model.
- Spatial analysis tools to assist flood warning. Two methods of spatial data display and analysis were developed in DSSFCMR to provide details to assist flood warning by the decision maker. These methods were developed for users with different levels of computer skills and for organizations with different levels of resources.
- Conveniently and quickly access various data related to flood warning. The database was well designed and developed to perform database management functions. The data can be viewed in various ways. For example, several types of data such as flood water levels, inundated properties (houses) and relevant economic data in terms of flood damage can be shown together to assist flood warning by the decision maker.
- User-friendly interactive Interface. DSSFCMR uses some attractive and innovative methods for users to work easily and quickly within DSSFCMR to provide information for flood warning. For example, the display of rainfall hyetograph and corresponding hydrograph was developed similar to the traditional design (i.e. rainfall on top and hydrograph at the bottom), which the users are familiar. The knowledge of initial loss from previous research in the study area was facilitated for use in the URBS model, as an alternative method. The spatial and graphical data display and analysis interface is innovative where it uses GIS and shapefile concepts to easily, quickly and convenience display and analyse data interactively.
- Easily and directly involve in decision making. The developed functions in DSSFCMR allow the decision maker to easily and directly involve in the many steps of decision making process in flood warning. These steps are related to forecast rainfall, calibration

of hydrological model parameters, possible tidal influence (i.e. downstream water level), potential water damage (i.e. flood inundated houses and their related information, for example type, persons who need assistance, value of damage), etc. The decision is made by the decision makers themselves rather than the machine giving a single solution. Many ideas about the potential flood damage and related warning can be investigated through many scenarios using models in DSSFCMR, which provide information for final decision making. Such processes included in one system as in DSSFCMR are much faster and more accurate than the manual processes, or using several models running independently and transferring data from one model to another.

- DSSFCMR can be easily adopted for another flood warning system in a different location with slight modification to the computer code. DSSFCMR is developed in a structured way, corresponding to each subsystem, which can be easily modified to develop a similar DSS for another river basin with its own data.

### 7.2.2 Limitations

- The available historical flood data for this research were not sufficient to build alternative decision support tools such as an Expert system to help select decisions from a number of scenarios. The current decision support in DSSFCMR allows the user to query the relevant decision scenarios from all simulated flood scenarios, then display the selected decision scenarios for further investigation, and finally make the decision for flood warning.
- The spatial data for all property (house) boundaries in the study area were not available for this research. The property shapefile only included several properties to demonstrate the power of spatial data display and analysis module in DSSFCMR. However, any number of properties can be included easily in the DSSFCMR in its current form, but should be noted that when they are included, the spatial analysis algorithm of flood inundated properties would use more computer resources such as CPU and memory.
- Due to copyright, only an evaluation version of MapObjects was used in the development of DSSFCMR.
- Initially, DAO (an older method of connecting the database from computer programming) was used to connect to the database to DSSFCMR. However, most of these database connections were subsequently converted to use the ADO (an advanced method to connect database) method. Due to specific requirements of the version of

used MapObjects, which only allowed DAO to connect to the database, some databases are connected still using DAO method in DSSFCMR.

- As state in early chapters, HEC-RAS is a Windows programming. When HEC-RAS runs in DSSFCMR, the run process is automatically controlled by DSSFCMR. Interruption by keyboard during this run process could lead wrong operations and/or empty results, which could not be avoided. It should be noted that the stand-alone version of HEC-RAS was developed for the end user (rather than for the developer) and the developer in this research project could not get the source code of HEC-RAS. Therefore, DSSFCMR was designed to interact with HEC-RAS by its input/output interfaces. This is different to integration of the URBS model, where the interaction was achieved through input and output text files.

### **7.3 Future Research and Application**

The future research work, which are described below, could make DSSFCMR more powerful.

- When more data on historical floods are available, it is recommended to build an Expert system to help the decision maker to eliminate the flood scenarios which are less likely and to focus more on the flood scenario, which are more likely, to make quality decisions for flood warning considering both historical and simulated flood data.
- It is recommended to investigate alternative methods for spatial-searching the properties (houses) in the flood inundated area, when the number of properties in the shapefile becomes large. Due to limitations of the version of MapObjects in terms DAO method of database connection and the small size of currently used shapefile of properties, these alternative methods were not investigated in this research. However, these methods could make DSSFCMR more robust as latest database connection methods (e.g. ADO method) are usually more robust than those of GIS software tools (e.g. MapObjects).
- To investigate the updating software such ArcObjects (i.e. new version of MapObjects) to solve the MapObjects' disadvantages in database connection if the new software becomes available.
- It is also recommended to include alternative models in the Modelbase to provide more choice for the user. For example, RORB and/or WBNM model can be included as hydrological models.

## 7.4 Conclusions

This research project concentrated on the development of a DSS in the area of water resources in particular in flood forecasting and warning. The system was well designed and developed based on recent theory and practice of DSS, software engineering, GIS and water resources. The integration technology to interact DSSFCMR with other models or software (e.g. such as URBS model, HEC-RAS model, MapObjects) was advanced so that many steps in the process of complex decision investigation (e.g. the peak discharge to the water level, water level to the shapefile of flood area) can be done automatically, effectively and quickly. The instantaneous creation of inundated area shapefile was an outstanding method, since it is done within DSSFCMR without any external software and therefore the spatial analysis corresponding to each simulate flood scenario in DSSFCMR can be achieved effectively, efficiently, easily and quickly. Two methods of spatial data display and analysis were developed for analysis of flood inundated areas for users with different levels of computer literacy and for organization with different levels of resources. These methods provide decision selection support for flood warning.

The functions developed in DSSFCMR are very powerful and allow the decision maker to easily and directly involve in the decision making process. For example, the forecast rainfall can be considered within DSSFCMR; the hydrological model and hydraulic model can be calibrated; forecasting of flood hydrographs can be performed; and calculation of flood levels can be automatically computed.

The general concept and the design of this system can be used for DSS studies in water resources and other fields, and the DSSFCMR software can be used for other river basins using appropriate data and slight modifications to the computer code.

## REFERENCES

- Ackermann, T., Loucks, D.P., Schwanenberg, D. and Detering, M., 2000. Real-Time Modeling for Navigation and Hydropower in the River Mosel. *Journal of Water Resources Planning and Management*. Vol. 126, No. 5, pp. 298-303.
- Alter, S., 1978. Development Patterns for Decision Support Systems. *MIS Quarterly*, September, pp. 33-42.
- Alter, S., 1992. Why Persist with DSS when the Real Issue is Improving Decision Making, in "Decision Support System: Experiences and Expectations", Edited by Jelassi, T., Klein, M.R. and Mayon-White, W.M., Published by North-Holland, pp. 1-11.
- Alter, S., 1996. *Information Systems: A Management Perspective*, 2<sup>nd</sup> edition. Benjamin: Cummings, Menlo Park, California.
- Andersen, C., Dybkjaer, G., Jensen, K. H., Refsgaard, J. C. and Rasmussen, K., 2002. Use of Remotely Sensed Precipitation and Leaf Area Index in a Distributed Hydrological Model, *Journal of Hydrology*, Vol.264, No.1-4, pp.34-50.
- Andreu, J., Capilla, J. and Sanchis, E., 1996. AQUATOOL, A Generalised Decision Support System for Water Resources Planning and Operational Management. *Journal of Hydrology*, Vol. 177, pp. 269-291.
- Arnold, J.G. and Sammons, N.B., 1988. Decision Support System for Selecting Inputs to a Basin Scale Model. *Water Resources Bulletin*, Vol. 24, No. 4, pp. 749-759.
- Arnold, U. and Orlob, G.T., 1989. Decision Support for Estuarine Water Quality Management. *Journal of Water Resources Planning and Management*, ASCE, Vol. 115, No. 6, pp. 775-792.
- Arnaud, P., Bouvier, C., Cisneros, L. and Dominguez, R., 2002. Influence of Rainfall Spatial Variability on Flood Prediction. *Journal of Hydrology*, Vol. 260, No. 1-4, pp. 216-230.
- Aron, G., 1987, Penn State Runoff Model for IBM-PC, User's Manual, Depart of Civil Engineering, Pennsylvania State University, University Park, Pennsylvania, USA.
- Arumugam, N. and Mohan, S., 1997. Integrated Decision Support System for Tank Irrigation System Operation. *Journal of Water Resources Planning and Management*, ASCE, Vol. 123, No. 5, pp. 256-273.
- Autodesk. 2003. AutoCAD DXF File Format Documentation. (<http://usa.autodesk.com/adsk/servlet/ps/item?siteID=123112&id=2882295&linkID=2475323>)
- Barbosa, L.C. and Hirko, R.G., 1980. Integration of Algorithmic Aids into Decision Support Systems, *MIS Quarterly*, March, 1980, pp. 1-8.
- Bates, P.D. and De Roo, A.P.J., 2000. A Simple Raster-based Model for Flood Inundation Simulation, *Journal of Hydrology*, Vol. 236, No.1-2, pp. 54-77.
- Becchi, I., Caporali, E. Federici, G. and Palmisano, E., 1989. Un Modello Distribuito Per Lo Studio Del Bacino Dell'Arno: Analisi Idrologica Della Sieve. *Acqua-Aria*, 10, pp.1129-1144.

- Bennett, J. L., 1983. *Building Decision Support Systems*, Addison-Wesley Publishing Company, USA.
- Benoit, R., Schär, C., Binder, P., Chamberland, S., Davies, H. C., Desgagné, M., Girard, C., Keil, C., Kouwen, N., Lüthi, D., Maric, D., Müller, E., Pellerin, P., Schmidli, J., Schubiger, F., Schwierz, C., Sprenger, M., Walser, A., Willemsse, S., Yu, W. and Zala, E., 2002. The Real-Time Ultrafinescale Forecast Support during the Special Observing Period of the MAP. *Bulletin of the American Meteorological Society*, Vol. 83, No. 1, pp. 85-109.
- Beven, K., and Kirkby, M., 1979. A Physically Based, Variable Contributing Area Model of Basin Hydrology. *Hydrological Science Bulletin*, No. 24, pp. 43–69.
- Borga, M., 2002. Accuracy of Radar Rainfall Estimates for Streamflow Simulation. *Journal of Hydrology*, Vol. 267, No. 1-2, pp. 26-39.
- Bouchart, F.J.-C. and Goulter, I.C., 1997. Is Rational Decision Making Appropriate for Management of Irrigation Reservoirs? *Journal of Water Resources Planning and Management*, ASCE, Vol. 124, No. 6, pp. 256-273.
- Boyd, M.J., Rigby, E.H. and Van Drie, R., 1996. A Comprehensive Flood Model for Natural and Urban Catchments. *International Association for Hydraulic Research / International Association for Water Quality*. In *Proceedings 7<sup>th</sup> International Conference on Urban Storm Drainage*, Hanover. Vol. 2, pp. 329-334.
- Bracke, M.B.M., Metz, J.H.M. and Spruijt, B.M, 2001. Development of a Decision Support System to Assess Farm Animal Welfare, *Acta Agriculturae Scandinavica: Section A, Animal Science*, Vol. 51, No. 1, pp. 17– 20.
- Bradley, S.G., Dirks, K.N. and Stow, C.D., 1998. High Resolution Studies of Rainfall on Norfolk Island, Part III: A Model for Rainfall Redistribution. *Journal of Hydrology*, Vol. 208, No. 3-4, pp. 194-203.
- Brivio, P.A., Colombo, R., Maggi, R. and Tomasoni, R., 2002. Integration of Remote Sensing Data and GIS for Accurate Mapping of Flooded Areas. *International Journal of Remote Sensing*, Vol. 23, Issue 4, pp. 429-432.
- Brown, D.L. and Jones, D.R., 1998. Factors that Influence Reliance on Decision Aids: A Model and an Experiment. *Journal of Information Systems*, Vol. 12, No. 2, pp. 75-94.
- Burnash, R., Ferral, R. and Mcguire, 1973. *A Generalized Streamflow Simulation System—Conceptual Modeling for Digital Computers*. Technical Report, National Oceanic and Atmospheric Administration, NWS, and State of California, Department of Water Resources, Joint Federal-State River Forecast Center, Sacramento, California, USA.
- Bureau of Transport Economics, 2001. *Economic Costs of Natural Disasters in Australia*. Report 103, Canberra, ACT, Australia.
- Bureau of Transport and Regional Economics, 2002. *Benefits of Flood mitigation in Australia*. Report 106. Canberra, ACT, Australia.
- Camara, A.S., da Silvar, M.C., Rodrigues, A.C., Remedio, J.M., Castro, P.P., de Oliveira, M.J.S. and Fernandes, T.F., 1990. Decision Support System for Estuarine Water Quality Management. *Journal of Water Resources Planning and Management*, ASCE, Vol. 116, No. 3, pp. 417-432.

- Camara, D., Beven, B. and Tawn, J., 2000. An Evaluation of Three Stochastic Rainfall Models. *Journal of Hydrology*, Vol. 228, pp. 130-149.
- Carroll, D.G., 1995. URBS-CM Manual – Version 3.5, Gutteridge, Haskins and Davey Pty Ltd, Australia.
- Chan, C.W., Kritpiphat, W. and Tontiwachwuthikul, P., 2000. Knowledge Engineering of a Monitoring and Control Decision Support System. *International Journal of Software Engineering and Knowledge Engineering*, Vol. 10, No.3, pp. 301-318.
- Chang, F.J. and Chen, Y.C., 2001. A Counter Propagation Fuzzy-neural Network Modelling Approach to Real Time Stream Flow Prediction. *Journal of Hydrology*, Vol. 245, No. 1-4, pp. 153-164.
- Chen, X., Brimicombe, A. J., Whitting, B.M. and Wheeler, C., 1998. Enhancement of Three-dimensional Reservoir Quality Modelling by Geographic Information Systems. *Geographical and Environmental Modelling*, Vol. 2, No. 2, pp. 125-139
- Chen, C. W., Herr, J., Ziemelis, L., Goldstein, R. A., and Olmsted5, L., 1999. Decision Support System for Total Maximum Daily Load. *Journal of Environmental Engineering, ASCE*, Vol. 125, No. 7, pp. 653-655.
- .Chiueh, P.-T. and Lo, S.-L. Prototype SDSS for Using Probability Analysis in Soil Contamination. *Journal of Environmental Engineering, ASCE*, Vol. 123, No. 5, pp. 514-519.
- Cock, R.A. and Elliott, J.F., 1989. Flood Warning and Real-time Data Collection in Australia. *Proceedings of Hydrology and Water Resources Symposium, Christchurch, New Zealand*, pp. 86-89.
- Connolly T.M., Begg, C.E. and Strachan A., 1999. *Database System: a Practical Approach to Design, Implementation and Management*. Addison Wesley Longman Limited, England.
- Cortés, U., Sánchez-Marrè, M., Sangüesa, R., Comas, J., R.-Roda, I., Poch, M. and Riaño, D., 2001. Knowledge Management in Environmental Decision Support Systems. *AI Communications*, Vol. 14, No. 1, pp. 3-12.
- Cosgriff, G.O., Forte, P.E., Kennedy, M.A., Russell, J.V., Smith, R.D., and West, A.K., 1985. Interactive Computer Modelling, Monitoring, and Control of Melbourne's Water Supply System. *Water Resources Research*, Vol. 21, No. 2, pp. 123-129.
- Crapper G., 1989. Development of A Real-time Reservoir Routing Flood Warning Procedure Using the RORB Model. *Proceedings of Hydrology and Water Resources Symposium 1989, Christchurch, NZ*, pp. 86-89.
- Crapper, G., 1997. Personal Communication.
- Crawford, N.H. and Linsley, R.K., 1966. Digital Simulation in Hydrology: Stanford Watershed Model IV. Technical Report No. 39, Department of Civil Engineering, Stanford University, Stanford, California, USA.
- CRC for Catchment Hydrology, 1994. *Annul Report 1993-1994*. Melbourne, Australia.
- Crosetto, M. and Tarantola, S., 2001. Uncertainty and Sensitivity Analysis: Tools for GIS-based Model Implementation. *International Journal of Geographical Information Science*, Vol. 15, No. 5, pp. 415-437.

- Cunnane, C., 1989. Statistical Distributions for Flood Frequency Analysis. World Meteorological Organisation, Operational Hydrology Report, No. 33. Galway, Ireland.
- Davis, R.K., 1979. Strategic Tactical, and Operational Planning and Budgeting: A Study of Decision Support System Evolution. *MIS Quarterly*, December, pp. 1-19.
- Davis, J.R., Nanninga, P.M., Biggins, J. and Laut, P., 1991. Prototype Decision Support System for Analysing Impact of Catchment Policies. *Journal of Water Resources Planning and Management*, ASCE, Vol. 117, No. 4, pp. 399-414.
- de Azevedo, L.G.T., Gates, T.K., Fontane, D.G., Labadie, J.W. and Porto, R.L., 2000. Integration of Water Quantity and Quality in Strategic River Basin Planning. *Journal of Water Resources Planning and Management*, ASCE, Vol. 126, No. 2, pp. 85-97.
- DeGagne, M., Douglas, G.G., Hudson, H.R. and Simonovic, S.P., 1996. A Decision Support System for the Analysis and Use of Stage-Discharge Rating Curves. *Journal of Hydrology*, Vol. 184, pp. 225-241.
- Dirks, K.N., Hay, J.E., Stow, C. D. and Harris, D., 1998. High-Resolution Studies of Rainfall on Norfolk Island. Part II: Interpolation of High-Spatial-Resolution Rainfall Data. *Journal of Hydrology*, Vol. 208, No. 3-4, pp. 187-193.
- Dunn, S.M., Mackay, R., Adams, R. and Oglethorpe, D.R., 1996. The Hydrological Components of the NELUP Decision Support System: An Appraisal. *Journal of Hydrology*, Vol. 177, pp. 213-235.
- Eastman, J.R., 1992. IDRISI: A Grid-Based Geographical Analysis System. Graduate School of Geography, Clark University, Worcester, Massachusetts, USA.
- Environmental Systems Research Institute (ESRI), 1991. ARC/INFO User's Guide, Version 6.0. Redlands, California, USA
- Environmental Systems Research Institute (ESRI), 1999. ArcView (3.2a) User's Guide. Redlands, California, USA..
- Environmental Systems Research Institute (ESRI), 1998. ESRI Shapefile Technical Description, An ESRI White Paper—July 1998. Redlands, California, USA.
- Environmental Systems Research Institute (ESRI), 2003. Spatial Data Standards and GIS Interoperability, An ESRI White Paper-January 2003. Redlands, California, USA.
- Eschenbach, E.A., Magee, T., Zagona, E., Goranflo, M. and Shane, R., 2001. Goal Programming Decision Support System for Multiobjective Operation of Reservoir Systems, *Journal of Water Resources Planning and Management*, ASCE, Vol. 127, No.2, pp. 108-120.
- Fedra, K. and Loucks, D.P., 1985. Interactive Computer Technology for Planning and Policy Modelling. *Water Resources Research*, Vol. 21, No. 2, pp. 114-122.
- Fedra, K., 1993. Expert Systems in Water Resources Simulation and Optimisation, in *Stochastic Hydrology and its Use in Water Resources Simulation and Optimisation*, edited by J.B. Marco et al., pp. 397-412.
- Fedra, K. and Jamieson, D.G., 1996. The 'Water Ware' Decision - Support System for River-Basin Planning. 2. Planning Capability. *Journal of Hydrology*, Vol. 177, pp. 177-198.

- Finkl, C.W., 2000. Identification of Unseen Flood Hazard Impacts in Southeast Florida through Integration of Remote Sensing and Geographic Information System Techniques. *Environmental Geosciences*, Vol. 7, No. 3, pp. 119-136.
- Ford, D.T., 2001. Flood-Warning Decision-Support System for Sacramento, California. *Journal of Water Resources Planning and Management*, ASCE, Vol. 127, No. 4, pp. 254-260.
- Ford, D.T. and Killen, J.R., 1995. PC-Based Decision Support System for Trinity River, Texas. *Journal of Water Resources Planning and Management*, ASCE, Vol. 121, No. 5, pp. 375-381.
- Foxon, T.J., Mcilkenney, G., Gilmour, D., Oltean-dumbrava, C., Souter, N., Ashley, R., Butler, D., Pearson, P., Jowitt, P. and Moir, J., 2002. Sustainability Criteria for Decision Support in the UK Water Industry. *Journal of Environmental Planning and Management*, Vol. 45, No. 2, pp. 285-301.
- Fread, D.L., 1987. National Weather Service Operation Dynamic Wave Model, Appendix A: User's Manual, National Weather Service, National Oceanic and Atmospheric Administration, Silver Springs, Maryland, USA.
- Fredericks, J.F., Labadie, J.W. and Altenhofen J.M. 1998. Decision Support System for Conjunctive Stream-Aquifer Management. *Journal of Water Resources Planning and Management*, ASCE, Vol. 124, No.2, pp. 69-76.
- French, M.N., and Krajewski, W.F., 1994. A Model for Real-Time Quantitative Rainfall Forecasting using Remote Sensing, Part 1: Formulation. *Water Resources Research*, Vol. 30, No. 4, pp. 1075-1083.
- French, M.N., Andrieu, H. and Krajewski, W.F., 1994. A Model for Real-time Quantitative Rainfall Forecasting using Remote Sensing, Part 2: Case Studies. *Water Resources Research*, Vol. 30, No. 4, pp. 1085-1097.
- Gallus Jr., W.A. and Segal, M., 2000. Sensitivity of Forecast Rainfall in a Texas Convective System to Soil Moisture and Convective Parameterisation. *Weather and Forecasting*, Vol. 15, No. 5, pp. 509-525.
- Gabrys, B. and Bargiela, A., 1999. Neural Networks Based Decision Support in Presence of Uncertainties. *Journal of Water Resources Planning & Management*, Vol.125, No.5, pp.272-280.
- Garcia, L.A. and Strzepek, K.M., 1987. A Decision Support System for Design and Evaluation of Spillways. *Computational Hydrology'87*, Lingthouse Publications, Mission Viejo. pp. J14-J19.
- Garcia, S.G., 2004. GRASS GIS-embedded Decision Support Framework for Flood Simulation and Forecasting. *Transactions in GIS*, Vol. 8, No. 2, pp. 245-254.
- Garrote, L. and Becchi, I., 1997. Object-Oriented Software for Distributed Rainfall-Runoff Models. *Journal of Computing in Civil Engineering*, Vol. 11, No. 3, pp. 190-194.
- Garrote, L. and Bras, R. L., 1995. A Distributed Model for Real-Time Flood Forecasting Using Digital Elevation Models. *J. Hydro.*, Amsterdam, The Netherlands, 167, pp.279-306

- Georgakakos, K.P., 1986. On the Design of National, Real-Time Warning Systems with Capability for Site-Specific, Flash-Flood Forecasts. *Bulletin of the American Meteorological Society*, 67(10), pp.1233-1239.
- Georgakakos, K.P., and Smith, G.F., 1990. On Improved Hydrologic Forecasting: Results from a WMO Real-time Forecasting Experiment. *Journal of Hydrology*, Vol. 114, pp. 17-45.
- Georgakakos, K.P., and Krajewski, W.F., 1991. Worth of Radar Data in the Real-time Prediction of Mean Areal Rainfall by Nonadvective Physically Based Models. *Water Resources Research*, Vol. 27, No. 2, pp. 185-197.
- Germann, U., and Zawadzki, I., 2002. Scale-Dependence of the Predictability of Precipitation from Continental Radar Images. Part I: Description of the Methodology. *Monthly Weather Review*, Vol. 130, No. 12, pp. 2859-2873.
- Ginzberg, M.J., 1978. Redesign of Managerial Tasks: A Requisite for Successful Decision Support Systems. *MIS Quarterly*, March, pp. 39-52.
- Ginzberg, M.J. and Stohr, E.A., 1982, Decision Support System: Issues and Perspectives, in *Decision Support Systems*, edited by Ginzberg, M.J., Reitman, W. and Stohr, E.A., published North-Holland Publishing Company, pp. 9-27.
- Gorr, W., Johnson, M. and Roehrig, S., 2001. Spatial Decision Support System for Home-Delivered Services. *Journal of Geographic System*, No. 3, pp. 181-197.
- Gorry, G.A. and Morton, M.S., 1971. A Framework for Management Information Systems, *Sloan Management Review*, Vol. 13, No. 1, pp. 55-70.
- Goonetilleke, A. and Jenkins, G., 1994. The Use of Geographical Information Systems in Hydrological Modelling. Physical Infrastructure Centre Research Report 94-5, Queensland University of Technology, Brisbane, Australia.
- Goulter, I.C. and Forrest, D., 1987. Use of Geographic Information Systems (GIS) in River Basin Management. *Water Science and Technology*, Vol. 19, No. 9, pp. 81-86.
- Goyen, A.G., 1987. RAFTS: Runoff Analysis and Flow Training Simulation (Version 2.5): Detailed Documentation and User Manual. W.P. Software, Curtin, Canberra, ACT, Australia.
- Grobler, D.C., Rossouw, J.N., van Eeden, P. and Oliveria, M., 1987. Decision Support System for Selecting Eutrophication Control Strategies, in "System Analysis in Water Quality Management", published by Pergamon Press, New York, USA.
- Greco, M. and Krajewski, W.F., 2000. Simulation Study of the Effects of Model Uncertainty in Variational Assimilation of Radar Data on Rainfall Forecasting. *Journal of Hydrology*, Vol. 239, No. 1-4, pp. 85-96.
- Hashino, M., Yao, H. and Yoshida, H., 2002. Studies and Evaluations on Interception Processes During Rainfall Based on a Tank Model. *Journal of Hydrology*, Vol. 255, No. 1-4, pp. 1-11.
- Heller, U. and Struss, P., 2002. Consistency-Based Problem Solving for Environmental Decision Support. *Computer-Aided Civil and Infrastructure Engineering*, Vol. 17, No. 2, pp. 79-92.

- Hendriks, P. and Vriens, D. 2000. From Geographical Information Systems to Spatial Group Decision Support Systems: A Complex Itinerary. *Geographical & Environmental Modelling*, Vol. 4, No. 1, pp. 83-104.
- Holsapple, C. W., 1995. Knowledge Management in Decision Making and Decision Support. *Knowledge and Policy*, Vol. 8, No.1, pp. 5-22.
- Hopple, G.H., 1986. Psychological Issues in the Design and Development of Decision Support Systems, in "Microcomputer Decision Support Systems: Design, Implementation, and Evaluation", edited by Andriole, S. J., published by North-Holland, QED Information Science, Inc, Massachusetts, USA.
- Hopple, G.H., 1988. The State of the Art in Decision Support Systems. QED Information Sciences, Inc., Wellesley, Massachusetts, USA.
- Horritt, M.S. and Bates, P.D., 2002. Evaluation of 1D and 2D Numerical Models for Predicting River Flood Inundation. *Journal of Hydrology*, Vol. 268, No. 1-4, pp. 87-99.
- Huber, G.P., 1981. The Nature of Organizational Decision Making and the Design of Decision Support Systems. *MIS Quarterly*, June, pp. 1-10.
- Huber, W.C., Heaney, J.P., Nix, S.J., Dickonson, R.E. and Polman, D.J., 1982. Storm Water Management Model. User's Manual, Version III, U.S. Environmental Protection Agency, Cincinnati, Ohio, USA.
- ICIM, 1991. WAQUA UNIX-version, User Guide I. ICIM, Den Haag.
- Imrie, C.E., Durucan, S. and Korre, A., 2000. River Flow Prediction Using Artificial Neural Networks: Generalisation Beyond the Calibration Range. *Journal of Hydrology*, Vol. 233, No. 1-4, pp. 138-153.
- Inmon, W.H., 1991. Database Machines and Decision Support Systems. QED Information Sciences, Inc., Wellesley, Massachusetts, USA.
- Ito, K., Xu, Z.X., Jinno, K., Kojiri, T. and Kawamura, A., 2001. Decision Support System for Surface Water Planning in River Basins. *Journal of Water Resources Planning and Management*, Vol. 127, No. 4, pp. 272-276.
- James, W.P., Robinson, C.G. and Bell, J.F., 1993. Radar-Assisted Real-time Flood Forecasting. *Journal of Water Resources Planning and Management*, ASCE, Vol. 119, No. 1, pp. 32-44.
- Jamieson, D.G and Fedra, K., 1996a. The 'Water Ware' Decision - Support System for River-basin Planning. 1. Conceptual Design. *Journal of Hydrology*, Vol. 177, pp. 163-175.
- Jamieson, D.G and Fedra, K., 1996b. The 'Water Ware' Decision - Support System for River-basin Planning. 3. Example Applications. *Journal of Hydrology*, Vol. 177, pp. 199-211.
- Jasper, K., Gurtz, J. and Lang, H., 2002, Advanced Flood Forecasting in Alpine Watersheds by Coupling Meteorological Observations and Forecasts with a Distributed Hydrological Model. *Journal of Hydrology*, Vol. 267, No. 1-2, pp. 40-52.
- Jinno, K., Kawamura, A., Berndtsson, R., Larson, M. and Niemczynowicz, J., 1993. Real-Time Rainfall Prediction at Small Space-Time Scales Using a Two-Dimensional Stochastic Advection-Diffusion Model. *Water Resources Research*, Vol. 29, No. 5, pp. 1498-1504.

- Jinwon, K., Miller, N. L., Guetter, A.K. and Georgakakos, K.P., 1998. River Flow Response to Precipitation and Snow Budget in California during the 1994/95 Winter. *Journal of Climate*, Vol. 11, No. 9, pp. 2376-2386.
- Johnson, L.E., 1986. Water Resources Decision Support Systems. ASCE, *Journal of Water Resources Planning and Management*, ASCE, Vol. 112, No. 3, pp. 308-325.
- Johnson, M.P., 2001. A Spatial Decision Support System Prototype for Housing Mobility Program Planning. *Journal of Geographical Systems*, 2001, Vol. 3 Issue 1, pp. 49-67.
- Kalay, P. and Chen, D., 2002. Integrating a Decision Support System into a School: The Effects on Student Functioning. *Journal of Research on Technology in Education*, Vol. 34, No. 4, pp. 435-452.
- Keen, P.G.W., and Morton, M.S., 1978. Decision Support System: An Organizational Perspective. Addison-Wesley Publishing Company, Inc., Reading, Massachusetts, USA.
- Kelly, K.S., and Krzysztofowicz, R., 1994a. Probability Distributions for Flood Warning Systems. *Water Resources Research*, Vol. 30, No.4, pp.1145-1152.
- Kelly, K.S., and Krzysztofowicz, R., 1994b. Synergistic Effect of Dam and Forecast on Flood Probabilities: a Bayesian Analysis, in *Engineering Risk in Natural Resources Management*, edited by L. Duckstein and E. Parent, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp.131-143.
- Kelly, K.S., and Krzysztofowicz, R., 1994c. Regional Reliability Envelopes of Flood Warning Systems, in *Stochastic and Statistical Methods in Hydrology and Environmental Engineering*, edited by K.W. Hipel and L. Fang, Kluwer Academic Publishers, Dordrecht, The Netherlands, Vol. 4, pp.259-265.
- Koch, R.W. and Allen, R.L., 1986. Decision Support System for Local Water Management. ASCE, *Journal of Water Resources Planning and Management*, ASCE, Vol. 112, No. 4, pp. 527-542.
- Kouwen, N., 1988. WATFLOOD: A Micro-Computer based Flood Forecasting System based on Real-Time Weather Radar. *Canadian Water Resources Journal*, Vol.13, No.1, pp. 62-77.
- Krajewski, W.F., Lakshmi, V., Georgakakos, K.P. and Jain, S.C., 1991. A Monte Carlo study of Rainfall Sampling Effect on a Distributed Catchment Model, *Water Resources Research*, Vol. 27, No. 1, pp. 119-128
- Kroenke, D. and Hatch, R., 1994. *Management Information Systems*. Third Edition, Mitchell McGraw-Hill. Watsonville, California, USA.
- Krzysztofowicz, R., 1992. Performance Trade off Characteristic of A Flood Warning System, *Water Resources Bulletin*, Vol. 28, No.1, pp.193-200.
- Krzysztofowicz, R., 1993. A Theory of Flood Warning Systems, *Water Resources Research*, Vol. 29, No. 12, pp. 3981-3994.
- Krzysztofowicz, R., 1994. Recent Advances Associated with Flood Forecast and Warning Systems (<http://www.agu.org/revgeophys/krzysz00/node1.html>).

- Krzysztofowicz, R., and Davis, D.R., 1983. A Methodology for Evaluation of Flood Forecast-Response Systems, Part 1: Analyses and Concepts, *Water Resources Research*, Vol. 19, No. 6, pp. 1423-1429.
- Krzysztofowicz, R., Kelly, K.S. and Long, D., 1994. Reliability of Flood Warning Systems. *Journal of Water Resources Planning and Management*, ASCE, Vol. 120, No. 6, pp. 906-926.
- Kumar, C.N. and Douglas, J., 1997. Peak-flow Forecasting with Genetic Algorithm and SWMM. *Journal of Hydraulic Engineering*, ASCE, Vol. 123, No. 6, pp. 585-586.
- Kunreuther, H. and Miller, L. 1985. Interactive Computer Modelling for Policy Analysis: The Flood Hazard Problem. *Water Resources Research*, Vol. 21, No. 2, pp. 105-113.
- Labadie, J.W. and Sullivan, C.H., 1986. Computerised Decision Support Systems for Water Managers. ASCE, *Journal of Water Resources Planning and Management*, ASCE, Vol. 112, No. 3, pp. 299-307.
- Laboratoire d'Hydraulique de France (LHF), 1997. Telemac System – Presentation Document.
- Lardet, P., and Obled, C., 1994. Real-Time Flood Forecasting Using a Stochastic Rainfall Generator. *Journal of Hydrology*, Vol. 162, pp. 391-408.
- Laurenson , E.M., and Mein, R.G., 1995. RORB-Version 5 Runoff Routing Program User Manual. Department of Civil Engineering, Monash University, Victoria, Australia.
- Lehmann, A. and Lachavanne, J.-B., 1999. Changes in the Water Quality of Lake Geneva Indicated by Submerged Macrophytes. *Freshwater Biology*, Vol. 42, No. 3, pp. 457-456.
- Li, D., Y.Y. Haines, E.Z. Stakhiv and D.A. Moser, 1992. Optimal Flood Warning Threshold: A Case Study in Connellsville, Pennsylvania, in *Risk-Based Decision Making in Water Resources V*, edited by Y.Y. Haines, D.A. Moser and E.Z. Stakhiv, American Society of Civil Engineers, New York, pp. 260-283.
- Liong, S.Y., Chan, W.T. and ShreeRam, J., 1995. Peak-Flow Forecasting with Genetic Algorithm and SWMM. *Journal of Hydraulic Engineering*, ASCE, Vol. 121, No. 8, pp. 613-617.
- Lotov, A.V., Bushenkov, V.A. and Chernykh , O.L., 1997. Multicriteria DSS for River Water-Quality Planning. *Microcomputers in Civil Engineering*, No. 12, pp. 57–67.
- Loucks, D.P., 1995. Developing and Implementing Decision Support Systems: A Critique and a Challenge. *Water Resources Bulletin*, Vol. 31, No. 4, pp. 571-582.
- Loucks, D.P., Kindler, J. and Fedra, K., 1985a. Interactive Water Resources Modelling and Model Use: An Overview. *Water Resources Research*, Vol. 21, No. 2, pp. 95-102.
- Loucks, D.P., Taylor, M.R. and French, P.N., 1985b. Interactive Data Management for Resources Planning and Analysis. *Water Resources Research*, Vol. 21, No. 2, pp. 131-142.
- Loucks, D.P., and da Costa, J.R., 1991, Computer-Aided Decision Support in Water Resources Planning and Management. In “Decision Support Systems: Water Resources Planning”, edited by Loucks, D. P., and da Costa, J. R, NATO ASI Series, published by Springer-Verlag, Berlin, Germany.

- Lupo, A.R. and Market, P.S., 2002. The Application of a Simple Method for the Verification of Weather Forecasts and Seasonal Variations in Forecast Accuracy. *Weather and Forecasting*, Vol. 17, No. 4, pp. 891-897.
- MacLean, R.F., 1986, User-System Interface Requirements for Decision Support Systems, in "Microcomputer Decision Support Systems: Design, Implementation, and Evaluation", edited by Andriole, S. J., published by North-Holland, QED Information Science, Inc, Massachusetts, USA.
- MacLean, D.A. and Porter, K.B., 1994, Development of a Decision Support System for Spruce Budworm and Forest Management Planning in Canada, in "GIS Application in Natural Resources 2", edited by Heit, M., Parker, H. D. and Shortreid, A, published by GIS World, Inc, Fort Collins, Colorado, USA.
- Madsen, H., Wilson, G. and Ammentorp, H.C., 2002. Comparison of Different Automated Strategies for Calibration of Rainfall-Runoff Models. *Journal of Hydrology*, Vol. 261, No. 1-4, pp. 48-59.
- Makropoulos, C.K., Butler, D. and Maksimovic, C., 2003. Fuzzy Logic Spatial Decision Support System for Urban Water Management. *Journal of Water Resources Planning and Management*, ASCE, Vol. 112, Vol. 129, No. 1, pp. 69-77.
- Malone, T., 1999. Using URBS for Real Time Flood Modelling. *Proceeding of Water 99 Joint Congress - Brisbane, Australia*, 6-8, July 1999, pp. 603-608.
- Mann, R.I. and Watson, H.J., 1984. A Contingency Model for User Involvement in DSS Development. *MIS Quarterly*, March, pp. 27-38.
- Marquínez, J., Lastra, J. and García, P., 2003. Estimation Models for Precipitation in Mountainous Regions: the Use of GIS and Multivariate Analysis. *Journal of Hydrology*, Vol. 270, No. 1-2, pp. 1-11.
- Marr, A, and Martin J., 1999. Lower Balonne Floodplain Decision Support Tool (DST). *Proceeding of Water 99 Joint Congress*, 6-8 July, Brisbane, Australia, pp. 257-261.
- Marshall Shepherd, J., Pierce, H.; Negri, A.J., 2002. Rainfall Modification by Major Urban Areas: Observations from Spaceborne Rain Radar on the TRMM Satellite. *Journal of Applied Meteorology*, Vol. 41, No. 7, pp. 689-701.
- Mathworks, 1999. *Matlab R.5.3.b User's Manuel*. Coleman, Branch, and Grace, Mathworks Inc.
- Mays, L.W., 1996, *Water Resources Handbook*. McGraw-Hill, Inc.
- McLeod, R. Jr., 1995. *Management Information Systems*, Sixth Edition. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.
- McClellan, C.J., Watson, P. M., 1995. Land Use Planning: A Decision Support System. *Journal of Environmental Planning and Management*, Vol. 38, No.1, pp.77-92.
- Meikle, T., 2002. Towards a New MODDE of Improving Legal Decision Support Design. *Information and Communications Technology Law*, Vol. 1, No. 1, pp. 87-98.
- Melbourne and Metropolitan Board of Works, 1975. *Report on Flood of May 1974 Maribyrnong River Basin*, Melbourne, Australia.

- Melbourne and Metropolitan Board of Works, 1976. Report on Flood Mitigation in the Maribyrnong River Basin - A Preliminary Hydrological Study, Melbourne, Australia.
- Melbourne and Metropolitan Board of Works, 1984. Report on Flooding in Metropolitan Watercourses on 15-16 October 1983, Melbourne, Australia.
- Melbourne and Metropolitan Board of Works, 1986. Maribyrnong River Flood Mitigation Study, Melbourne, Australia.
- Melbourne and Metropolitan Board of Works, 1988. Flood Prone Property Details for Lower Maribyrnong River, Melbourne, Australia.
- Melching, C.S., Yen, B.C. and Wenzel, H.G. Jr., 1991. Output Reliability as Guide for Selection of Rainfall-Runoff Models. ASCE, Journal of Water Resources Planning and Management, ASCE, Vol. 117, No. 3, pp. 383-398.
- Mennecke, B.E., Crossland, M.D. and Killingsworth, B.L., 2000. Is a Map More than a Picture? The Role of SDSS Technology, Subject Characteristics, and Problem Complexity on Map Reading and Problem Solving. MIS, Vol. 24, No. 4, pp. 601-629.
- Michaud, J.D., and Sorooshian, S., 1994a. Comparison of Simple Versus Complex Distributed Runoff Models on a Midsized Semiarid Watershed. Water Resources Research, Vol. 30, No. 3, pp. 593-605.
- Michaud, J.D., and Sorooshian, S., 1994b. Effect of Rainfall Sampling Errors on Simulations of Desert Flash Floods. Water Resources Research, Vol. 30, No. 10, pp. 2765-2775.
- Middelkoop, H. and Van Der Perk, M., 1998. Modelling Spatial Patterns of Overbank Sedimentation on Embanked Floodplains. Geografiska Annaler Series A: Physical Geography, Vol. 80A, No. 2, pp. 95-109.
- Mimikou, M.A. and Baltas, E.A., 1996. Flood Forecasting Based on Radar Rainfall Measurements. ASCE, Journal of Water Resources Planning and Management, ASCE, Vol. 122, No. 3, pp. 151-155.
- Morton, M.S., 1971. Management Decision Systems: Computer Based Support for Decision Making. Division of Research, Harvard, Cambridge, Massachusetts, USA.
- Mowrer, T.H., 1997, Decision Support System for Ecosystem Management: An Evaluation of Existing Systems. General Technical Report RM-GTR-296. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado, US.
- Newell, C.J., Haasbeek, J.F. and Bedient, P.B. 1990, OASIS: A Graphical Decision Support System for Ground-Water Contaminant Modelling. GroundWater, Vol. 28, No. 2, pp. 224-234.
- Nico, G., Pappalepore, M., Pasquariello, G. and Refice, A., 2000. Comparison of SAR Amplitude vs. Coherence Flood Detection Methods – A GIS Application. International Journal of Remote Sensing, Vol. 21, No. 8, pp. 1619-1631.
- Niehoff, D., Fritsch, U. and Bronstert, A., 2002. Land-Use Impacts on Storm-runoff Generation: Scenarios of Land-use Change and Simulation of Hydrological Response in a Mesoscale Catchment in SW-Germany. Journal of Hydrology, Vol. 267, No. 1-2, pp. 80-93.

- Or, I., 1991. Development of a Decision Support System for Maintenance Planning. In "Recent Developments in Decision Support System", Edited by Holsapple, C. W. and Whinston, A. B, Published by Springer-Verlag, pp. 505-520.
- Özelkan, E.C. and Duckstein, D., 2001. Fuzzy Conceptual Rainfall-runoff Models. *Journal of Hydrology*, Vol. 253, No. 1-4, pp. 41-68.
- Parker, D.J. and Handmer, J.W., 1998. The Role of Unofficial Flood Warning Systems. *Journal of Contingencies and Crisis Management*, Vol. 6, No.1, pp. 45-60.
- Parsaye, K. and Chignell, M., 1988. *Expert Systems for Experts*. John Willey and Sons, New York, USA.
- Perera, B.J.C. and Shipton, R. ECF3841 Engineering Hydrology Class Notes, School of Architectural, Civil and Mechanical Engineering, Victoria University, Victoria, Australia.
- Philp, T., 1985. *Improve Your Decision Making Skills*. McGraw-Hill, UK.
- Pingry, D. E., Shaftel, T.L. and Boles, K. E., 1991. Role for Decision Support System in Water Delivery Design. *ASCE, Journal of Water Resources Planning and Management*, Vol. 117, No. 6, pp. 629-643.
- Power, D.J., 1997. Tips for Choosing Enterprise-Wide DSS Software. *The On-Line Executive Journal for Data-Intensive Decision Support*, Vol. 1, No. 7.
- Power, D. J., 2002. *Decision Support Systems: Concepts and Resources for Managers*. Quorum Books.
- Prajamwong, S., Merkley, G.P. and Allen, R.G., 1997. Decision Support Model for Irrigation Water Management. *Journal of Irrigation and Drainage Engineering*, Vol. 123, No. 2, pp. 106-113.
- Pressman, R.S., 1997. *Software Engineering: A Practitioner's Approach*. Fourth Edition. McGraw-Hill. ISBN 0-07-052182-4.
- Rowney, A.C., and Wisner, P.E., 1984. *QUALHYMO User Manual Release 1.0*. Ministry of the Environment, Toronto, Canada.
- Sample, D.J., Heaney, J.P., Wright, L.T., and Koustas, R., 2001. Geographic Information Systems, Decision Support Systems, and Urban Storm-Water Management. *Journal of Water Resources Planning and Management, ASCE*, Vol. 127, No. 3, pp. 143-201.
- Sauter, V., 1997. *Decision Support Systems: An Applied Managerial Approach*. John Wiley and Sons, Inc, USA.
- Schoolmaster, F.A. and Marr, P.G., 1992. Geographic Information System as a Tool in Water Use Data Management. *Water Resources Bulletin*, Vol. 28, No. 2, pp. 331-336.
- Schultheis, R. and Sumner, M., 1995. *Management Information Systems - The Manager's View*, Richard D. Irwin, Inc.
- Schumann, A.H., Funke, R., and Schultz, G.A., 2000. Application of a Geographic Information System for Conceptual Rainfall-runoff Modelling. *Journal of Hydrology*, Vol. 240, No. 1-2, pp. 45-61.
- See, R.B., Naftz, D.L. and Qualls, C.L., 1992. GIS-Assisted Regression Analysis to Identify Sources of Selenium in Streams. *Water Resources Bulletin*, Vol. 28, No. 2, pp. 315-330.

- Seuffert, G., Gross, P., Simmer, C. and Wood, E.F., 2002. The Influence of Hydrologic Modelling on the Predicted Local Weather: Two-Way Coupling of a Mesoscale Weather Prediction Model and a Land Surface Hydrologic Model. *Journal of Hydrometeorology*, Vol. 3, No. 5, pp. 505-524.
- Shamsi, U.M., 1996. Storm-Water Management Implementation through Modeling and GIS. *Journal of Water Resources Planning and Management*, ASCE, Vol. 122, No. 2, pp. 114-127.
- Sharma, T., Kiran, P.V.S., Singh, T.P., Trivedi, A.V. and Navalgund, R.R., 2001. Hydrologic Response of a Watershed to Land Use Changes: a Remote Sensing and GIS Approach. *International Journal of Remote Sensing*, Vol. 22, No. 11, pp. 2095-2108.
- Shelly, G.B., Cashman, T.J. and Rosenblatt, H.J., 2001. *Systems Analysis and Design*. Fourth Edition. Course Technology, Boston, USA.
- Shim, K.-C., Fontane, D. G. and Labadie, J. W., 2002. Spatial Decision Support System for Integrated River Basin Flood Control. *ASCE, Journal of Water Resources Planning and Management*, ASCE, Vol. 128, No. 3, pp. 190-201.
- Silver, M.S., 1991. *Systems That Support Decision Makers*. Wiley, New York, USA.
- Simon, H.A., 1976. *Administrative Behaviour, A Study of Decision-making Processes in Administrative Organization* (3rd edition). The Free Press, New York, USA.
- Simonovic, S.P., 1998. *Decision Support System for Flood Management in the Red River Basin*. Report prepared for the International Joint Commission Red River Basin Task Force, Winnipeg, Canada.
- Simonovic, S.P. and Bender, M.J., 1996. Collaborative Planning-support System: an Approach for Determining Evaluation Criteria. *Journal of Hydrology*, Vol. 177, pp. 237-251.
- Sivakumar, B., Jayawardena, A.W. and Fernando, T.M.K.G., 2002. River Flow Forecasting: Use of Phase-space Reconstruction and Artificial Neural Networks Approaches. *Journal of Hydrology*, Vol. 265, No. 1-4, pp. 225-245.
- Smith, J. and Eli, R.N., 1995. Neural-Network Models of Rainfall-Runoff Process. *Journal of Water Resources Planning and Management*, ASCE, Vol. 121 No. 6, pp. 499-508.
- Sprague, Jr., R.H., 1980. A Framework for the Development of Decision Support Systems, *Management Information Systems Quarterly*, No. 4, pp. 1-26.
- Sprague, Jr., R.H. and Carlson, E.D., 1982. *Building Effective Decision Support Systems*. Prentice-Hall, Englewood Cliffs, New Jersey, USA.
- Sprague, Jr., R.H., and Watson, H.J., 1996. *Decision Support for Management*. Prentice-Hall, A Simon & Schuster Company, Upper Saddle River, New Jersey, USA.
- Srinivasan, R. and Engel, B.A., 1994. A Spatial Decision Support System for Assessing Agricultural Nonpoint Sources Pollution. *Water Resources Bulletin*, Vol. 30, No. 3, pp. 441-452.
- Srikanthan, R., Elliott, J. and Adams, G., 2000. *A review of Real-Time Flood Forecasting Methods*. Technical Report, Cooperative Research Centre for Catchment Hydrology, Australia.

- Srinivasan, A., Sundaram, D. and Davis, J., 2000. *Implementing Decision Support Systems: Methods, Techniques, and Tools*. McGraw-Hill, Berkshire, UK.
- Stansbury, J., Woldt, W. and Bogardi, I., 1991. Decision Support System for Water Transfer Evaluation. *Water Resources Research*, Vol. 27, No. 4, pp. 443-451.
- Stow, C.D., 2002. High-Resolution Studies of Rainfall on Norfolk Island. Part IV: Observations of Fractional Time Raining. *Journal of Hydrology*, Vol. 263, No.1-4. pp. 156-176.
- Stow, C.D. and Dirks, K.N., 1998. High-Resolution Studies of Rainfall on Norfolk Island. Part 1: The Spatial Variability of Rainfall. *Journal of Hydrology*, Vol. 208. No. 3-4, pp. 163-186.
- Sun, X., Mein, R.G., Keenan, T.D. and Elliott, J.F., 2000. Flood Estimation Using Radar and Rain Gauge Data. *Journal of Hydrology*, Vol. 239, No. 1-4, pp. 4-18.
- Szymkiewicz, R., 2002. An Alternative IUH for the Hydrological Lumped Models. *Journal of Hydrology*, Vol. 259, No.1-4, pp. 246-253.
- Taher, S.A. and Labadie, J.W., 1996 Optimal Design of Water-Distribution Networks with GIS. *Journal of Water Resources Planning and Management*, ASCE, Vol. 122, No. 4, pp. 301-311.
- Taylor, K., Walker, G. and Abel, D., 1999. A Framework for Model Integration in Spatial Decision Support Systems. *International Journal of Geographical Information Science*, Vol. 13, No. 6, pp. 533-555.
- Terblanche, D.E., Pegram, G.G.S. and Mittermaier, M.P., 2001. The Development of Weather Radar as A Research and Operational Tool for Hydrology in South Africa. *Journal of Hydrology*, Vol. 241, pp. 3-25.
- Thierauf, R.J., 1982. *Decision Support Systems for Effective Planning and Control: A Case Study Approach*. Prentice-Hall, Englewood Cliffs, New Jersey, USA.
- Urbanski, J. A., 1999. The Use of Fuzzy Sets in the Evaluation of the Environment of Coastal Waters. *International Journal of Geographical Information Science*, Vol. 13, No. 7, pp. 723-730.
- U.S. Army, 1987. *GRASS Reference Manual*, USA CERL, Champaign, Illinois, USA.
- U.S. Army Corp of Engineers (USACE), 1982a. *HEC-2: Water Surface Profiles, User's Manual*. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1982b. *HEC-5: Simulation of Flood Control and Conservation Systems, Program User's Manual*. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1990a. *HEC Data Storage System User's Guide and Utility Program Manual*. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1990b. *HEC-1: Flood Hydrograph Package, User's Manual*. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1991. *HECLIB, Vol. 2: HECDSS Subroutines. Programmer's Manual*. Hydrological Engineering Centre, Davis, California, USA.

- U.S. Army Corp of Engineers (USACE), 1997. HEC-RAS River Analysis System: Application Guide, Version 2.0. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1998a. HEC-RAS River Analysis System: User's Manual, Version 2.2. Hydrological Engineering Centre, Davis, California, USA.
- U.S. Army Corp of Engineers (USACE), 1998b. HEC-RAS River Analysis System: Hydraulic Reference Manual, Version 2.2. Hydrological Engineering Centre, Davis, California, USA.
- Van der Perk, M., Ertsen, A.C.D. and Bleuten, W., 1992. Modelling Van Slibsedimentatie Van Zware Metalenbelasting in Een Uiterwaard Langs de Waal. (in Dutch with English summary). H00, 25: 233-237.
- van Walsum, P.E.V. and Drent, J., 1987. Decision Support System for Water Management in Regions with Intense Agriculture, In "System Analysis in Water Quality Management", published by Pergamon Press, New York, USA.
- Vassilakis, K.M., Vorgia, L., and Micheloyannis, S., 2002. Decision Support System for Classification of Epilepsies in Childhood. *Journal of Child Neurology*, Vol. 17, No. 5, pp. 357-364.
- Walsh, N.R, 1993. Toward Spatial Decision Support System in Water Resources. *Journal of Water Resources Planning and Management*, ASCE, Vol. 119, No. 2, pp. 158-169.
- Wang, J., Perera, B. J. C., and Takyi, A. K., 1998. A Decision Support System for Flood Control in the Maribyrnong River- Conceptual Framework. *Proceedings of First International Conference on New Information Technologies for Decision Making in Civil Engineering*, 1998, Montreal, Canada, pp. 979-988.
- Wang, J. and Perera, B. J. C., 2000. Real-time Forecasting of Flood Hydrographs in a Decision Support System. *Proceedings of the Xth World Water Congress - Melbourne 2000*.
- Wang, J. and Perera, B. J. C., 2005. Spatial Analysis of Flood Levels in a Decision Support System, *Proceedings of The 29th Hydrology and Water Resources Symposium - Water Capital, Canberra, ACT, 20-23 February 2005*.
- Wang, Q.J., 1991. The Genetic Algorithm and its Application to Calibrating Conceptual Rainfall-Runoff Models. *Water Resources Research*, Vol. 27, No. 9, pp. 2467-2471.
- Water Resources Council Victoria, 1978. *Flood Plain Management in Victoria - A Report on the Principles used in Defining Flood Plains, together with Guidelines for Permissible Works and Structures*. Melbourne, Australia.
- Watkins Jr., D.W. and McKinney, D.C., 1995. Recent Developments Associated with Decision Support Systems in Water Resources, *Reviews of Geophysics*. Vol. 33 Supplement 1995. American Geophysical Union. 2000 Florida Avenue, Washington, D.C., USA (<http://www.agu.org/journals/rg/rg9504S/contents.html>)
- Westphal, K.S., Vogel, R.M., Kirshen, P., Chapra, S.C., 2003. Decision Support System for Adaptive Water Supply Management. *Journal of Water Resources Planning and Management*, ASCE, Vol. 129, No. 3, pp. 165-177.

- Westrick, K.J. and Mass, C.F., 2001. An Evaluation of a High Resolution Hydrometeorological Modeling System for Prediction of a Cool-Season Flood Event in a Coastal Mountainous Watershed. *Journal of Hydrometrology*, No. 2, pp. 161–180.
- Westrick, K.J., Storck, P. and Mass, C.F., 2002. Description and Evaluation of a Hydrometeorological Forecast System for Mountainous Watersheds. *Weather and Forecasting*, Vol. 17, No. 2, pp. 250-262.
- Williams, J.R., Nicks, A.D. and Arnold, J.G., 1985. Simulator for Water Resources in Rural Basis, *Journal of Hydraulic Engineering*, ASCE, Vol. 111, No. 6, pp. 970-986.
- Wong, K.M., Strecker, E.W. and Stenstorm, M.K., 1997. GIS to Estimate Storm-water Pollutant Mass Loadings. *Journal of Environmental Engineering*, ASCE, Vol. 123, No. 8, pp.737-745.
- Yates, D.N., Warner, T.T. and Leavesley, G.H., 2000. Prediction of A Flash Flood in Complex Terrain. Part II: A Comparison of Flood Discharge Simulations Using Rainfall Input from Radar, A Dynamic Model, and An Automated Algorithmic System. *Journal of Applied Meteorology*, Vol. 39. pp. 815- 825.
- Yen, C.D., 1986. Design of A Decision Support System using Expert System Techniques. University Microfilms International, Ann Arbor, Michigan, USA.
- Zheng, P.Q. and Baetz, B.W., 1999. GIS-Based Analysis of Development Options from a Hydrology Perspective. *Journal of Urban Planning & Development*, ASCE, Vol.125, No. 4, pp.164-180.
- Zhang, S., Cordery, I. And Sharma, A., 2002. Application of an Improved Linear Storage Routing Model for the Estimation of Large Floods. *Journal of Hydrology*, Vol. 258, No.1-4, pp. 58-68.
- Zhao, R.J., 1992. The Xinanjiang Model Applied in China. *Journal of Hydrology*, Vol. 135, pp. 371-381.
- Zhao, R.-J., Zhuang, Y.-L., Fang, L.-R., Liu, X.-R. and Zhang, Q.-S., 1980. The Xinanjiang Model Hydrological Forecasting. *Proceedings of Oxford Symposium, IASH 129*, pp. 351-356.