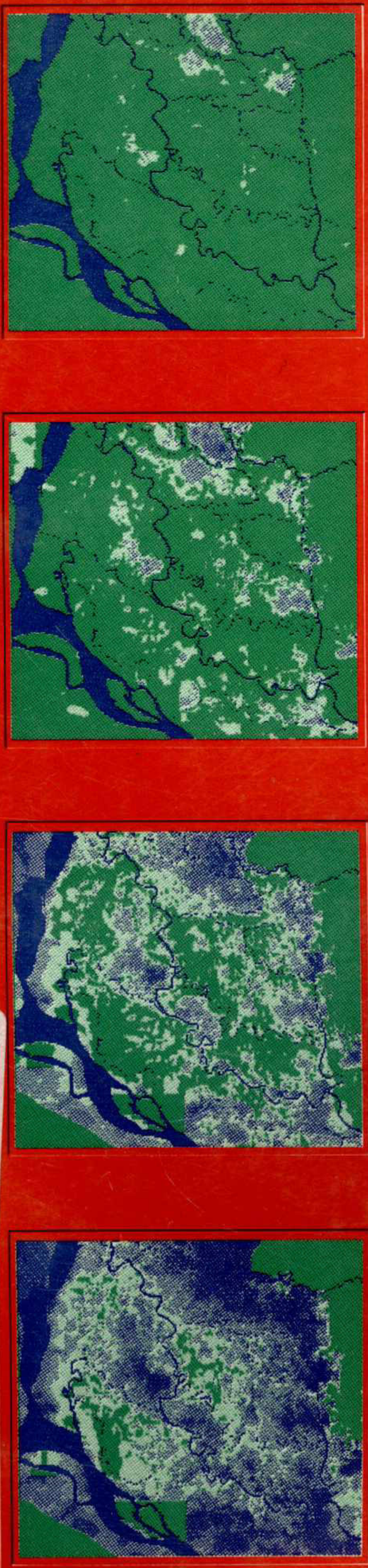


Government of the
People's Republic of Bangladesh
Flood Plan Coordination Organisation

FAP25

Flood Modelling and Management

Flood Management Model

Final Report - Volume I
Main Report

Danish Hydraulic Institute

in association with
Euroconsult
BCEOM

Donors
Denmark, France, the Netherlands

FAP 25: Flood Modelling and Management

Flood Management Model

Final Report

Volume I: Main Report

October 1994

FMM DOCUMENTS

FAP25-FMM has produced the following documents

Reports

- Inception Report
- Interim Report - I
- Interim Report - II
- Final Report
  Vol I: Main Report
  Vol II: Applications and Demonstrations

Technical and Training Documents

- MIKE11-GIS Reference and User's Guide
- MIKE11-GIS Training Manual
- MIKE11-GIS Menus
- MIKE11-NAM Dynamic Interface - Reference and User's Guide
- Training Materials for the FPCO Training Course

Proposals

- Transfer and Establishment of FMM at SWMC

Papers

- *Bangladesh Flood Management Model - Toward a Spatial Decision Support System* 2nd International Conference on River Flood Hydraulics, HR Wallingford, UK, 1994.
- *Flood Management Model an Integrated Numerical Flood Modelling-GIS Approach* 9th Congress of APD/IAHR, Singapore, 1994
- *Flood Maps and Improved Flood Management* Paper presented at the Bangladesh Institution of Engineers, Dhaka, 1994.
- *Profiling a Flood Management System for Bangladesh: The strategy of the generic model - GIS connection* Journal of Hydraulic Research, Issue on Hydroinformatics, 1994.
- *GIS in Flood Mapping for Improved Flood Management* Hydroinformatics Conference, IHE Delft 1994.

EXECUTIVE SUMMARY

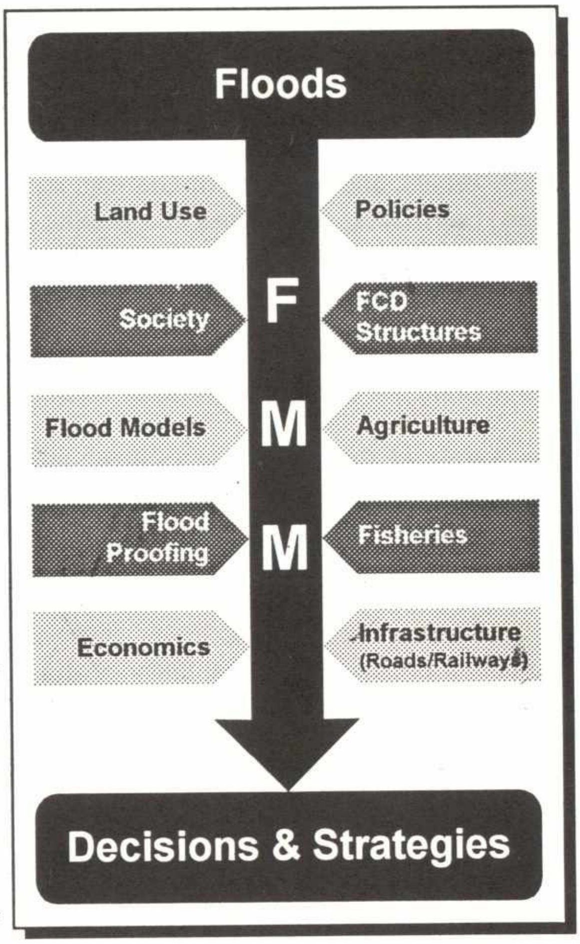
In Bangladesh, floods and flood management are a part of life. For centuries, people have been managing and controlling the passage of flood waters for protection and irrigation of crops. Minor floods are in fact beneficial, but major floods can be devastating to society, industry and the country's economy. Total flood protection is unrealistic and probably unwise. Nevertheless, schemes which reduce flood damage, ranging from flood preparedness to embankments, are necessary for the further development of Bangladesh.

In order to study and predict flooding in Bangladesh, mathematical flood models have been developed and applied at the Surface Water Modelling Centre and other FAP projects. However, these models do not produce flood maps, an ideal medium for examining impacts and providing valuable information for evaluating flood mitigation schemes.

This study presents a methodology aimed at generating flood depth and flood impact maps. The result is a modelling system for flood management (FMM), which integrates flood models and a GIS (Geographic Information System), and when combined with agriculture, fisheries, society, infrastructure and other data, opens up new avenues for multi-sectoral flood management practices.

Concept of FMM

Flood management is about making decisions based on policies reflecting the needs of communities and the environment. It is complex and often without solutions which fully satisfy all concerned parties. The many components: land use; environment; infrastructure; flood control structures; irrigation needs; agriculture; economics; society; fisheries; flood preparedness and flood forecasting, render decision making and policy formulation extremely difficult.



Modelling floods in Bangladesh has been the primary role of MIKE11 flood models. The models output flood levels along the rivers and over the floodplains, and more importantly, simulate the impacts of interventions on flood levels.

However, flood models do not produce the flood maps needed for identifying and prioritising flood management zones, nor do they produce maps of impacts on flood levels which greatly assist in assessing alternative solutions and carrying out multi-sectoral flood impact analyses.

To produce these maps, and to perform multi-sectoral impact analyses, GIS technology is needed. Flood depths and levels are represented as layers of data in the GIS which can be geographically related and analysed with data from other flood management components. The maps and results of multi-sectoral analyses are easily assimilated using a combination of graphic and statistical formats.

FMM is an integrated MIKE11-GIS modelling system which has the potential to assist in clarifying and disseminating information through enhanced mapping of impacts on flood levels, communities, agriculture, fisheries and the environment. The maps would also help provide project design specifications; monitor and assess the performance of flood control and drainage structures; and help distribute flood forecasts in a readily acceptable form to the general public.

Objectives and Achievements

The objectives were to produce generic FMM computer software, manuals and guidelines; apply in order to demonstrate FMM at national, regional and compartment levels; build local FMM expertise; hold workshops and informal presentations to increase FMM awareness; and make recommendations on institutionalisation.

The objectives have been achieved. Software, manuals and guidelines designed for future general application are complete. Three pilot FMMs at national, regional and compartment levels have been developed, demonstrated and are available for further use. Workshops and demonstrations have increased the awareness of potential beneficiaries, and recommendations on future developments, applications, institutionalisation and training programmes have been made. Local expertise has been developed through on-the-job training and training courses.

Software, Manuals and Guidelines

FMM software fully integrates the MIKE11 flood modelling system with a GIS. The inputs are flood model details, and a variety of GIS data such as: ground elevations in the form of a DEM; rivers; roads; beels/lakes; settlements; and satellite images. The outputs are: processed topographic data for flood models; a variety of flood maps; flood level impact maps; graphs; and flood inundation and impact statistics.

The software has been documented in detail, including guidelines for application, in a reference and user's guide. A training manual has also been prepared for teaching and learning to use FMM.

The Terms of Reference also required minor additions to MIKE11. These have been covered, especially the need for a dynamic interface between flood model and rainfall/runoff computations, and the operation of multiple gates in a single flood control and drainage structure.

The software, documentation and expertise developed have great potential for enhancing many aspects of flood management. In particular: environmental impact assessments; planning and design of flood mitigation projects (structural and non-structural); flood forecasting and warning; and design and operation of flood control and drainage structures.

There is great potential for further FMM development, especially for multi-sectoral analysis. It is recommended that further development be carried out on a project by project basis.

Pilot FMMs

FMM was applied and demonstrated at three levels: national, regional and compartment.

National FMM: A coarse FMM covering the major national and regional rivers.

Regional FMM: A detailed FMM for the western part of the North Central Region.

Compartment FMM: A detailed FMM for the Tangail Compartment Pilot Project (FAP20).

National Level FMM

The national level FMM was developed and tested based on the Surface Water Modelling Centre's General (flood) Model, and GIS data supplied by FAP19. It shows the capability of producing flood maps for the greater part of the country, and statistical information for regions and local government administrations.

The National FMM is limited in its applicability for flood mapping. The General Model, which was designed to supply boundary data for regional models, produces flood levels along the major rivers, with only a rough representation over the floodplain. Therefore, flood mapping is likely to be inaccurate over the floodplains, and should not be used for detailed consideration.

This is not to say that no useful output can be obtained. In the case of a flood peak, when river and floodplain levels are probably very similar, an FMM flood map may be indicative of the real situation.

It is recommended that no further FMM work should be considered until affordable computers are sufficiently powerful so that a more detailed model, which can address the current deficiencies in floodplain representation, can be developed.

Regional Level FMM

The regional level FMM was based on the Surface Water Modelling Centre's North Central Regional (flood) Model and GIS data from FAP19. A brief programme of hydrometric data collection and embankment surveys during 1993 was carried out to supplement the existing data.

The North Central Regional Model was restructured in the western half to further improve the representation of the floodplains. The resulting model, while more complex, provides the basis for differentiating between river and floodplain water levels.

Flood depth maps were produced based on the 1988 and 1993 floods which represent a high and 'average' flood respectively. The effects of flood interventions at a sub-regional level were demonstrated by modelling a system of hypothetical compartments, and at a regional level by modelling a single major embankment. The exercises included most structural elements required to be modelled, such as embankments, gates, weirs, drainage channels and river overspills.

The changes in flood depth between with and without project conditions were mapped to visualise the impact on flood levels. The effects of an embankment breach was also simulated and illustrated using flood depth and impact maps. Flood mapping using statistical envelopes of 25 historical floods was carried out to illustrate the potential for using FMM for flood zoning based on frequency and depth of flooding.

Regional level FMM application was shown to be practical and usable, and is recommended for planning and pre-feasibility studies, and for flood forecasting. Computer and resource limitations place an upper limit on the amount of detail that can be practically included. Users and clients must therefore be aware of the implications in interpreting the resulting flood maps. Detailed FMM application at a sub-regional level is also encouraged for feasibility studies and design.

Compartment Level FMM

The compartment level FMM was based on the FAP20 Tangail Compartment (flood) Model, GIS data from FAP19, and GIS data produced by FAP25. The model was upgraded using FMM tools to include recent survey information from FAP18. The north-western part was further detailed to include internal structures to control water levels on a chawk level.

The resulting model was used for testing flood control and drainage structure operations for the 1987, 1991 and 1993 floods. General gate operation guidelines, and target water levels within each sub-compartment were used to show the feasibility of controlled structure operation. However, the issue of simple guidelines for field operators needs to be addressed.

Flood maps were produced for selected flood events showing the depth and extent of the flooding in sub-compartments. A flood map for July 24, 1993 was compared with radar imagery of the same date acquired by FAP19. The flood extents on both maps were compared, showing good agreement. Based on this encouraging result the use of radar imagery should be further pursued to assist in the verification of FMM flood maps.

Impacts on existing flood levels resulting from flood control and drainage structures were illustrated with maps showing the change in flood level and flood zoning. Indicative crop damage maps were produced taking into account the combined effects of flood duration, depth and damage criteria based on crop growth stages. While rigorous analyses of this type require specialist input, the maps demonstrate the potential of FMM for multi-sectoral investigations.

At the compartment level, FMM provides significant enhancement for understanding flood behaviour. It will be of particular help in public participation exercises, which seek to convey the effects of complex flood control processes. Also, the modelling of complex flood control and drainage structures is more easily handled with the improvements to MIKE11. Compartment FMMs are potentially very useful and their continued development is strongly recommended. This level of FMM is most suited for development of damage mapping.

Flood Forecasting

The Terms of Reference required establishing a close linkage to FAP10 (Flood Forecasting and Warning Project). The next phase of FAP10 had not started at the completion of FMM. Therefore, any close collaboration was not possible, although close relations with Bangladesh Water Development Board's Flood Forecasting and Warning Centre were pursued.

The usefulness of FMM for flood forecasting was demonstrated at the regional level. Using real-time outputs of the Surface Water Modelling Centre's flood forecasting version of the national flood model as inputs to the north-central regional model, the potential for mapping predicted inundations was demonstrated.

Technology Transfer

Technology transfer has been achieved through formal workshops, training, study tours, on-the-job training and demonstrations. Six local engineers were fully trained to use FMM tools, two of whom are also trained in modifying, adapting and extending the software for future applications.

Eleven senior to junior level government engineers were trained in the overall concept and knowledge of FMM. Awareness of FMM has been created among government and non-government agencies, FAP consultants, and potential users through three workshops, during which participants provided feedback to the FMM development process.

The training manual produced for the FMM software contains a training programme, hands-on computer tutorials, and teaching aids, and will form the basis for future training activities.

Institutionalisation and Sustainability

One of the most important, and to some extent, unresolved issue is the institutionalisation of FMM, and the technology transfer to that institution. The logical and most widely supported organisation is the Surface Water Modelling Centre. It is the most suited custodian, especially as it houses the flood models on which FMM depends.

Selected staff from the Centre would need to undergo intensive training, and FAP25 local staff should accompany FMM. Transferring local FMM experts, especially those who have developed and maintained the software, will be important. Without a sustainable environment for FMM and local expertise, the products of this study may not be fully and properly utilised in future applications.

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ACRONYMS AND ABBREVIATIONS

ARC/INFO	GIS software package developed by ESRI
BARC	Bangladesh Agricultural Research Council
BMD	Bangladesh Meterological Department
BUET	Bangladesh University of Engineering and Technology
BWDB	Bangladesh Water Development Board
CAT	Coordination Advisory Team
CPP	Compartmentalization Pilot Project (FAP20)
DAE	Department of Agricultural Extension
Danida	Danish International Development Assistance
DEM	Digital Elevation Model. Three-dimensional (X,Y,Z coordinate) description of the ground surface topography.
DHI	Danish Hydraulic Institute
DOE	Department of Environment
FAP	Flood Action Plan
FAP19	Geographic Information System Component of FAP
FAP20	Compartmentalization Pilot Project (CPP) Component of FAP
FAP25	Flood Modelling and Management Component of FAP
FCD	Flood Control and Drainage
FF&WC	Flood Forecasting & Warning Centre
FPCO	Flood Plan Coordination Organization
FMM	Flood Management Model
GOB	Government of Bangladesh
IFCDR	Institute of Flood Control and Drainage Research
JICA	Japan International Cooperation Agency
LGED	Local Government Engineering Directorate
MIWDFC	Ministry of Irrigation, Water Development and Flood Control
MIKE11	River Modelling System developed by DHI
MIKE11-GIS	FMM software interfacing MIKE11 and ARC/INFO GIS
NAM	Rainfall runoff software developed by DHI (Danish Abbreviation)
NCRM	North Central Regional Model
NGO	Non-Government Organization
O&M	Operation and Maintenance
POE	Panel of Experts
RAJUK	Rajdhani Unnayan Katripakkha (Capital Development Authority)
RHD	Roads and Highways Department
RRI	River Research Institute
SOB	Survey of Bangladesh
SPARRSO	Space Research and Remote Sensing Organization
SWMC	Surface Water Modelling Centre
SWSMP	Surface Water Simulation Modelling Program
TCM	Tangail Compartment MIKE11 Model
TOR	Terms of Reference for FAP25-FMM
WARPO	Water Resources Planing Organization
WASA	Water and Sewerage Authority

GLOSSARY OF TERMS

Beel Small lake, low-lying depression, a permanent body of water in a floodplain or a body of water created by rains or floods.

Chawk A chawk is the smallest unit of crop land demarcated with physical barriers such as existing road, periphery of settlement area etc.

Compartment An area in which effective water management, particularly through controlled flooding and controlled drainage, is made possible through structural and institutional arrangements. A compartment can be subdivided into sub-compartments.

Compartmentalisation The spreading of the flood water over the flood plains by establishing interlinked compartments, with the objective to provide a more secure environment for agriculture, fisheries and integrated rural and urban development through water management (controlled flooding and drainage).

Khal A natural drainage channel.

Sub-Compartment A sub-unit of a compartment, in which to a certain extent the water management can be controlled by the people living in the area represented in a Water Committee. The sub-compartment is mostly separated from the adjoining ones by embankments or roads provided with (semi) controlled structures.

Radar Image Image taken by satellite using radar technology. Radar has the ability to provide images in all weather and lighting conditions.

CONTENTS

LIST OF COLOUR PLATES

1 INTRODUCTION

1.1 Background

Floods in Bangladesh hamper national economic progress by causing widespread damage to infrastructure and national resources. The resulting international concern led to the formulation of the Flood Action Plan (FAP) which is the first stage in the development of a long term flood management plan for Bangladesh. It is comprised of a phased program of initiatives to assess controlled flooding options, supported by special studies, surveys and pilot projects. The Flood Modelling and Management Project is Component 25 of FAP and one of its supporting studies.

The FAP 25 - Flood Modelling and Management Project commenced in October 1990 and has three components sponsored by the governments of Denmark, France, the Netherlands and United Kingdom:

- Coordination Advisory Team
- Flood Hydrology Study
- Flood Management Model

A Coordination Advisory Team (CAT) was set up to ensure consistency and compatibility in modelling throughout FAP, and to coordinate development of models for FAP at the Surface Water Modelling Centre (SWMC).

The Flood Hydrology Study (FHS), now complete, established the hydrological basis for engineering design criteria along the major rivers, and developed common modelling standards and techniques for FAP studies.

The third component is the development of a modelling system for flood management, denoted FMM, and the demonstration of its applicability. The FMM concept was based on the need for providing detailed information on floodplain inundation. The FMM component commenced in October 1992 and has been completed within the stipulated 2 year period. The CAT has supervised and guided FMM activities.

The Flood Plan Coordination Organisation (FPCO) under the Ministry of Irrigation, Water Development and Flood Control (MIWDFC) is the implementing agency of the FMM component. Danida is the coordinating donor agency on behalf of the contributing donors, Denmark, France and the Netherlands.

FMM is conceived as a decision support tool which integrates the MIKE11 based flood modelling system with a Geographic Information System (GIS). FMM facilitates wider examination of alternative structural and non-structural flood management options than would be possible using standard methods, and forms a basis for real-time inundation forecasting and warning.

1.2 Objectives

Based on the Terms of Reference (TOR) the overall long term objective is to achieve an on-line computer system, linked to a flood forecasting model, which would provide information to assist in the management and control of floods in real-time. The system would indicate flood levels, areas and depths of inundation over the floodplain, and the potential impacts on crops, communities and infrastructure in clear graphical and tabular forms which are easily and rapidly assimilated. The information would be used for disaster preparedness and management as well as for the operation of flood control measures.

The TOR also states that "clearly such a model would be a highly ambitious undertaking at this stage". Therefore, FAP25-FMM was proposed as a "limited objective project" to produce generic (generally applicable) computer software, manuals and guidelines; apply and demonstrate the software at national, regional and compartment levels; build local expertise; hold workshops and informal presentations to increase awareness; and make recommendations on institutionalisation.

The objectives of the FAP25-FMM study are:

- Development of software, including manuals and guidelines, for mapping flood extent, depths and impacts.
- Collaborate with relevant FAP projects and SWMC.
- During the course of the study present concepts and developed technology to potential beneficiaries, obtain feedback, and identify and implement realistic modifications.
- Develop pilot FMMs on a national, regional and compartment level.
- Make recommendations for future development, institutionalisation and training.

1.3 Final Report

1.3.1 Volume I: Main Report

The Main Report is intended to provide a description of the FAP25-FMM project in a non-technical manner, not only for government, donors and other FAP projects, but also for organisations directly or indirectly involved in flood management.

With the highly technical content of this project, the use of some technical terms is unavoidable. Their use has been minimised to assist the non-technical readers in understanding this report. More technical discussions are presented in Volume II and in the FMM software documentation (see following sections).

Chapter 2, FMM Concepts, introduces the concepts of flood management and the possible benefits of FMM. The software used for FMM is simply described.

Chapter 3, FMM Inputs and Outputs, presents the various inputs and outputs to provide guidance on the types of data that are required and the types of output that can be produced.

Chapter 4, Floodplain Modelling, deals with the concept of modelling floodplains, not the technical details. This is a very important aspect for accurate flood mapping.

Chapter 5, FMM Demonstration, summarises the national, regional and compartment level pilot FMM applications. Volume II presents the detailed discussion.

Chapter 6, Technology Transfer, presents the activities related to technology transfer including training and workshops.

Chapter 7, Institutionalisation, raises the FMM institutionalisation issues.

Chapter 8, Conclusions and Recommendations, summarises the FMM study.

1.3.2 Volume II: Applications and Demonstrations

Volume II presents the development and application of the pilot FMMs. The volume is divided into three parts:

- Part A: National level
- Part B: Regional Level
- Part C: Compartment Level

The volume targets a more technically based readership, primarily aiming at future FMM users. However, much of the technical detail has still been omitted by concentrating primarily on the inputs and outputs of the pilot FMMs. The use of colour plates gives the reader a clearer interpretation and understanding of FMM output.

1.3.3 Technical and Training Documents

Three documents, *MIKE11-GIS Reference and User's Guide*, *MIKE11-GIS Training Manual* and *MIKE11-GIS Menus*, accompany the *Final Report*.

MIKE11-GIS Reference and User's Guide is both a non-technical and technical reference and also a user's guide for the main FMM software. It represents almost a complete documentation of FMM capabilities. Its intended audience is for FMM users, although the first several chapters are at a non-technical level.

MIKE11-GIS Training Manual is a series of courses and tutorials for training potential FMM users. It was designed to be used for FMM technology transfer activities.

MIKE11-GIS Menus is a documentation of FMM software menus.

These three documents are intended to accompany the software for future FMM activities.

2 FMM CONCEPTS

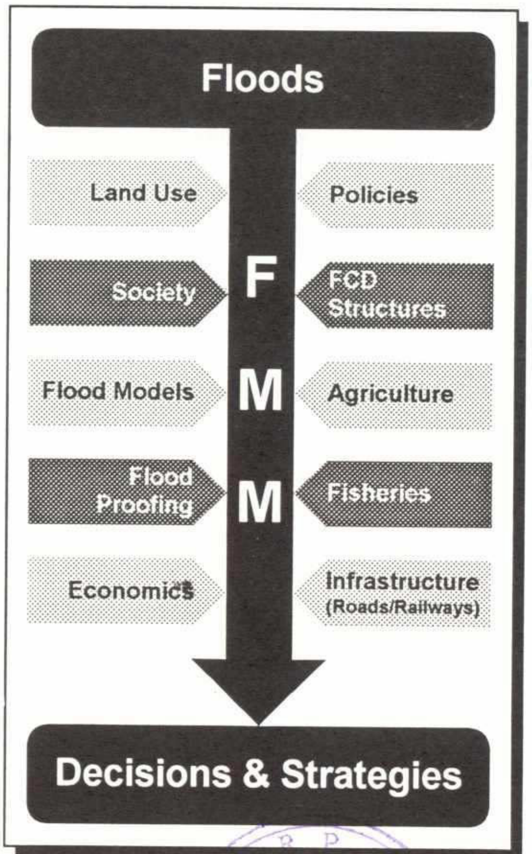
Flood management encompasses many environmental, social and engineering constraints. Decision making, although complex and difficult, can be greatly helped by using mathematical flood models and Geographic Information Systems (GIS). FMM unites these technologies as a first step towards a spatial decision support tool for flood management.

2.1 Introduction

Flood management is about making decisions based on policies reflecting the needs of communities and the environment. It is complex and often without solutions which fully satisfy all concerned parties. The many components: land use; environment; infrastructure; flood control structures; irrigation needs; agriculture; economics; society; fisheries; flood preparedness and flood forecasting, render decision making and policy formulation extremely difficult.

Modelling floods in Bangladesh has been the primary role of MIKE11 flood models. The models output flood levels along the rivers and over the floodplains, and more importantly, simulate the impacts of interventions on flood levels.

However, flood models do not produce the flood maps needed for identifying and prioritising flood management zones, nor do they produce maps of impacts on flood levels which greatly assist in assessing alternative solutions and carrying out multi-sectoral flood impact analyses.



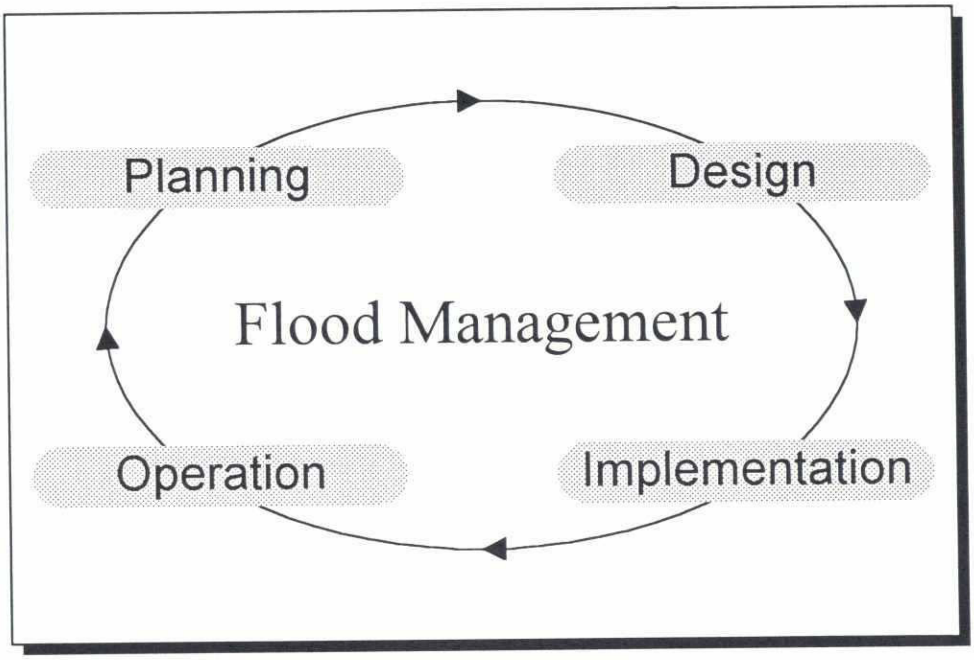
To produce these maps, and to perform multi-sectoral impact analyses, GIS technology is needed. Flood depths and levels are represented as layers of data in the GIS which can be geographically related and analysed with data from other flood management components. The maps and results of multi-sectoral analyses are easily assimilated using a combination of graphic and statistical formats.

FMM is an integrated MIKE11-GIS modelling system which has the potential to assist in clarifying and disseminating information through enhanced mapping of impacts on flood levels, communities, agriculture, fisheries and the environment. The maps would also help provide project design specifications; monitor and assess the performance of flood control and drainage structures; and help distribute flood forecasts in a readily acceptable form to the general public.

2.2 Use of FMM in Flood Management

2.2.1 Flood Management Cycle

Flood management follows a cyclic pattern linking ideas, proposals, consultations, adopting proposals, preparing guidelines, design, construction/implementation, and operating and maintaining finished schemes. This is the flood management planning, design, implementation and operation cycle, in which FMM plays a useful role.



Flood management is a never ending cycle of planning, design, implementation and operation.

At the planning level FMM helps assess proposed flood mitigation options and prepare environmental impact assessments.

For design, FMM functions as a tool for determining civil works design criteria, designing FCD structure operation rules, and providing inputs to flood preparedness programmes.

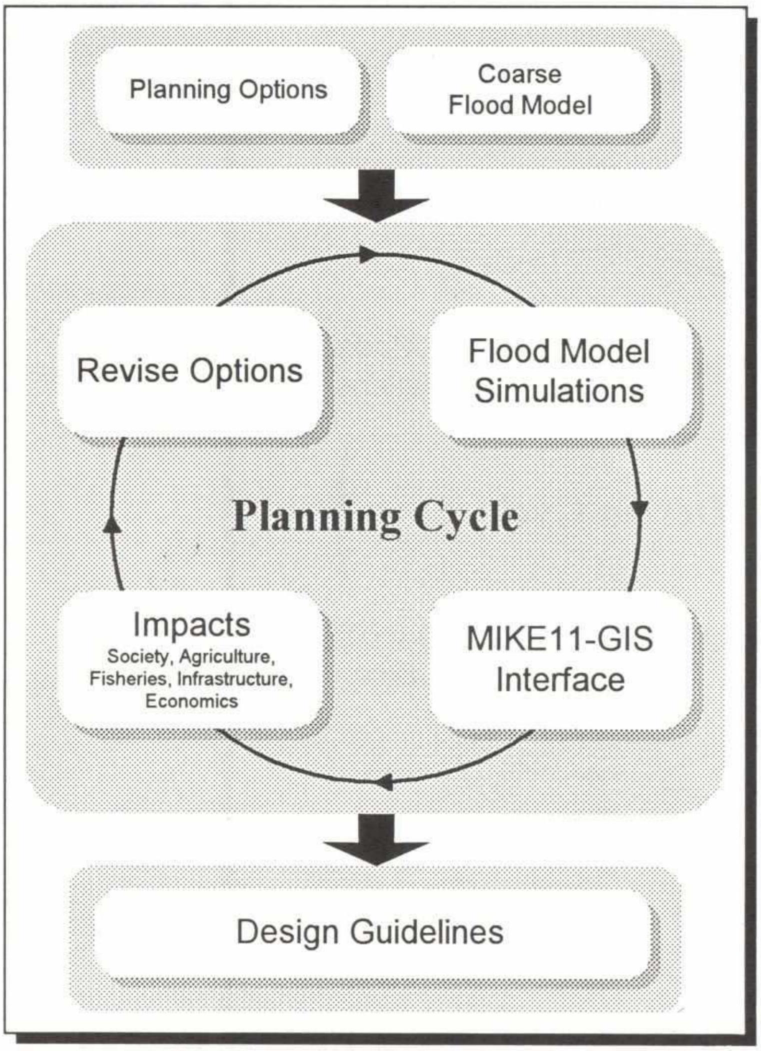
At the implementation stage, FMM may be useful for a range of needs from scheduling flood prone construction works to a flood preparedness training aid.

Real-time FMM operation linked with flood forecasting would help guide FCD structure operators and assists emergency relief operations. FMM would also help present the consequences on flooding due to repair and maintenance of FCD structures.

2.2.2 Planning

Flood management planning projects may range from flood preparedness programmes to major civil works. To help plan projects, FMM can be usefully applied as a decision support tool for planning.

Planning options must be identified, a calibrated coarse (preliminary) flood model must be developed, and other preparations made. The planning cycle then commences: flood model simulations; MIKE11-GIS interface analysis and graphic output; impact assessments; revising options. Finally, guidelines are prepared to receive feedback, and to outline design, implementation and operation recommendations.

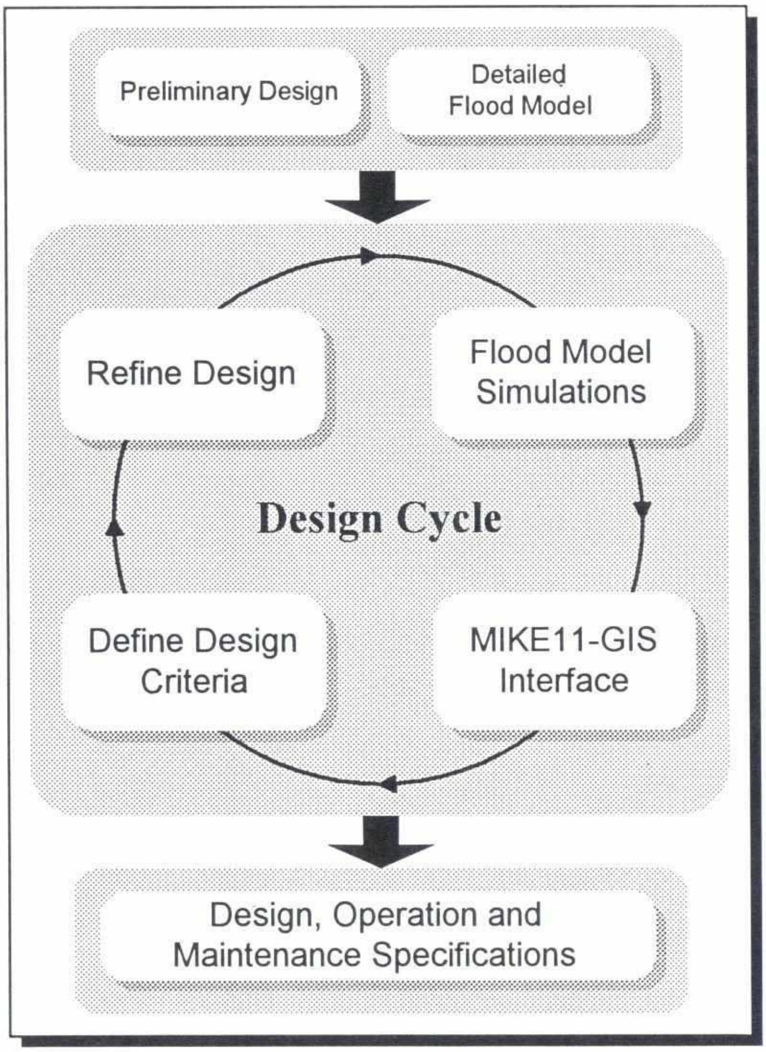


The MIKE11-GIS interface is a useful flood management planning tool. Output from flood model simulations can be displayed as flood maps showing depths, inundation duration and differences in flood levels. These maps in turn can be used for impact assessments on socio-economics, agriculture, fisheries and infrastructure. Flood maps are also excellent media for communicating options during consultations and for receiving feedback.

2.2.3 Design

Preparations for the design stage require a preliminary design based on planning recommendations, and detailed flood model development and calibration to define existing flood conditions.

The design cycle needs more accurate flood model simulations, uses the MIKE11-GIS interface to display and define design flood levels and to ensure impacts are within planning guidelines, and finally refines the design. When not all planning criteria are attainable they may need to be reviewed. The iterations of modelling and design refinement culminate in final design, operation and maintenance specifications.



The MIKE11-GIS interface is also a useful design tool. Output from flood model simulations can be displayed as flood maps showing design depths and to verify that impacts are within planning guidelines.

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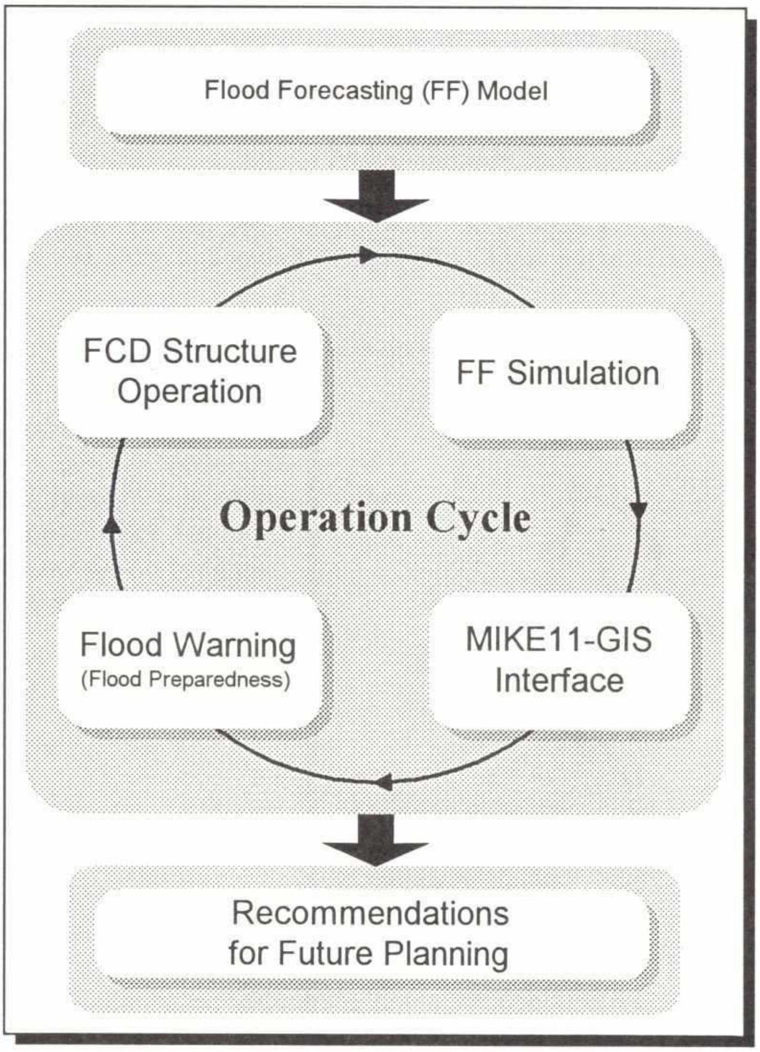
2.2.4 Operation

FMM combined with flood forecasting would aid dissemination of flood warnings for FCD structure operations and flood preparedness programmes. Real-time flood predictions presented as flood inundation maps allow rapid interpretation and dissemination of potential danger areas to field operators and emergency relief organisations.



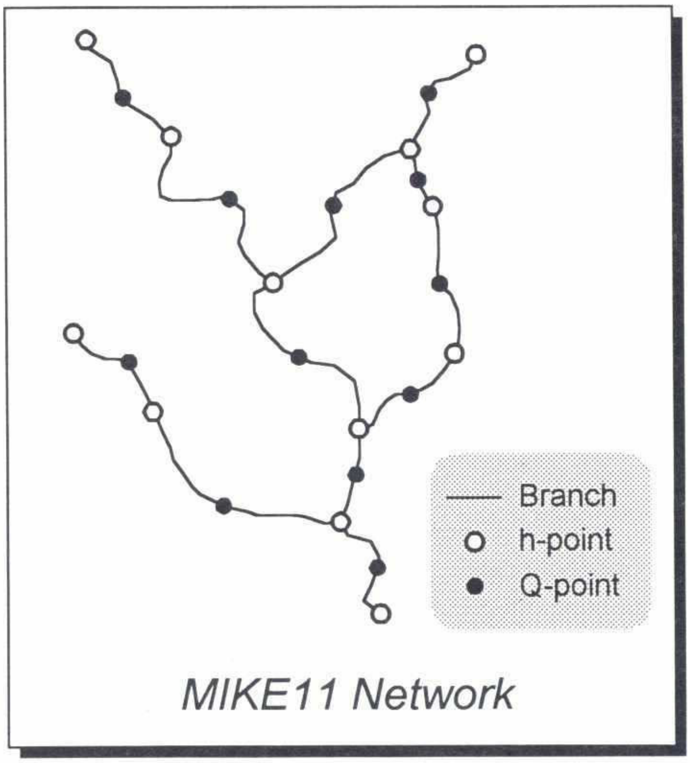
Linked with a flood forecasting (FF) model, the MIKE11-GIS interface is a helpful real-time flood management operation tool. Output from the FF model can be displayed as flood inundation maps combined with GIS coverages to warn communities of potential flood dangers and for guiding FCD structure operators.

2.3 MIKE11

The MIKE11 software package models flows and water levels in rivers and estuaries. It is used as a tool to simulate flooding behaviour of rivers and floodplains. Models numerically represent the river and floodplain topography and are calibrated to recorded flood levels and discharges. Once a base model is established, flood impacts from artificial or natural causes can be quantified as changes in flood level and discharge.

MIKE11 is based on an efficient numerical solution of the complete non-linear equations for 1-D flows. A network configuration represents the rivers and floodplains as a system of connected branches. At discrete points along the branches flood levels (at h-points) and discharges (at Q-points) are calculated as a function of time.

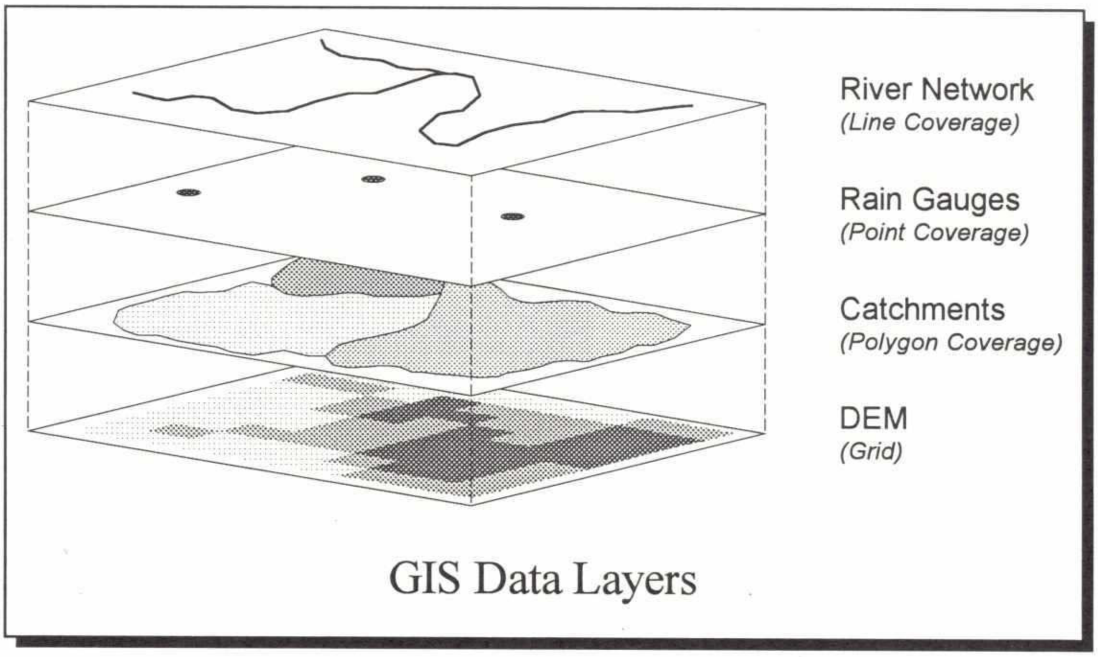
The menu based user interface is used for data capture and display, and carrying out simulations. For details refer to the *MIKE11 Reference Manual* and *MIKE11 User's Guide*.



A MIKE11 network is an inter-connected system of branches representing rivers and floodplains. Along the branches are located h-points and Q-points. Flood levels are calculated at h-points and discharges at Q-points.

2.4 Geographic Information System (GIS)

The concept of GIS is best visualised as layers of data, where each layer has a theme. A layer may be a river network, rain gauge locations, a DEM or a water level surface.



GIS data is managed as layers of data, each having a different theme.

The most powerful feature of GIS is its capacity to display, query and analyse layers of data in relation to each other.

Data are related through a common coordinate system and can be displayed graphically on the computer screen to give the appearance of a map (for example, a map of roads, settlements, rivers and tube well locations could be displayed as four layers of data overlaid on one another).

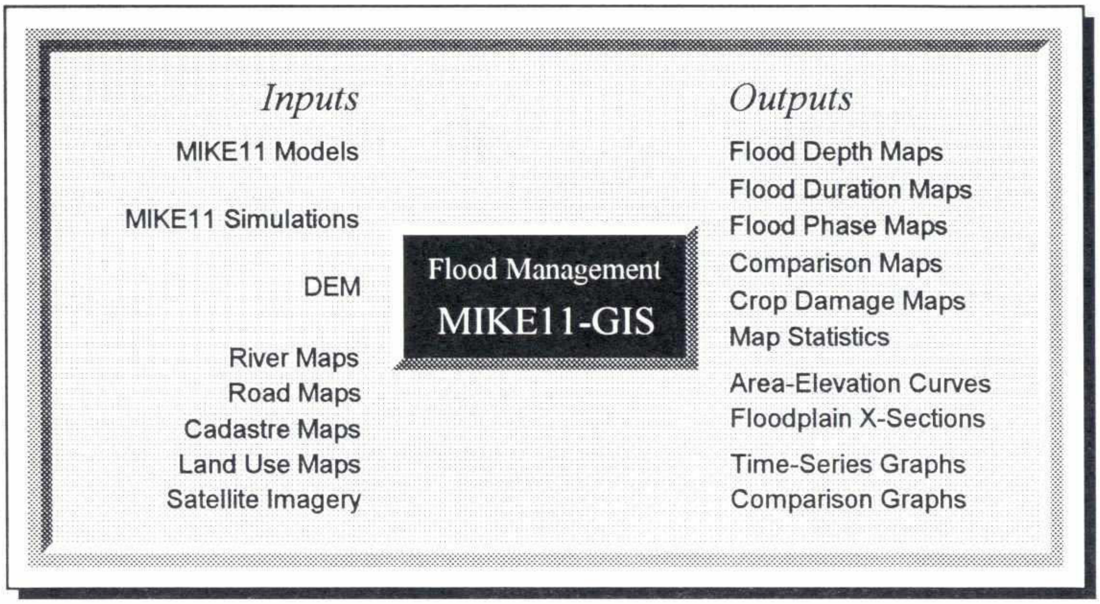
The data can also be queried and analysed in many ways (depending on the capabilities of the GIS software). For example, a simple exercise would be to highlight all tube wells which are within a 4 km distance of a settlement. These tube wells can be subjected to further queries, such as show which of them are within 2 km of a road, and so on. Through GIS, it is easy to make simple to complex analyses based on the spatial relationship(s) between data.

Data, and output from queries and analyses, can also be presented in tabular and statistical formats.

FMM uses the ARC/INFO GIS, developed and maintained by Environmental Systems Research Institute (ESRI). It is one of the world's most established and well-known GIS.

2.5 MIKE11-GIS Interface

The MIKE11-GIS interface merges the technologies of MIKE11 flood modelling and GIS as a spatial decision support tool for river and floodplain management.



MIKE11-GIS requires input from MIKE11 flood models, a DEM and optionally GIS data such as river, road, land use maps, satellite images, etc. It outputs floodplain topographic data (flooded area curves and cross-section profiles), flood maps and other graphic displays.

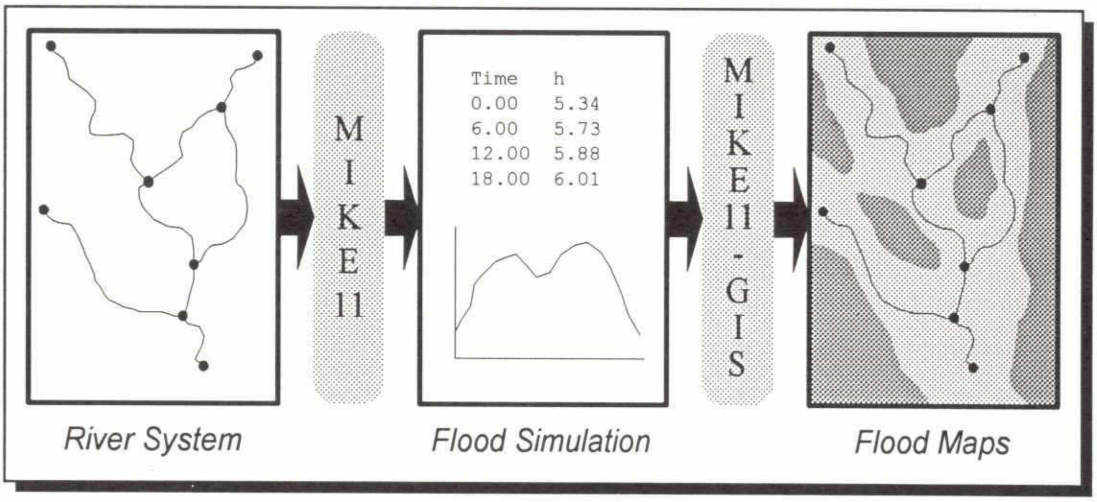
MIKE11-GIS requires information on flood model networks and simulations. A DEM (three-dimensional model of ground surface elevations) is the other essential input. Other useful inputs are maps of rivers, infrastructure, cadastre, land use, agricultural use, satellite imagery or other project specific data needs.

MIKE11-GIS's main outputs are flood maps and comparative flood maps. The flood maps show in graphic detail inundation depths, flood durations and flood phases, and can be used for flood damage assessments on infrastructure, agriculture, fisheries and other sectors. Flood map accuracy is very dependent on the accuracies of the flood models and the DEM.

Comparative flood maps show the differences between two flood maps illustrating the impacts or changes resulting from proposed works, structure failure, embankment breaching and other interventions.

Statistical information on flood or comparison maps can also be output, providing a tabular summary of the map.

MIKE11-GIS also outputs floodplain topographic data (cross-section profiles and flooded area versus elevation curves) from a DEM to improve a flood model's schematisation.



Information on river and floodplain topography, rainfall, discharges and water levels are fed into MIKE11. MIKE11 calculates water levels and discharges over time throughout the river system and exports these to MIKE11-GIS. MIKE11-GIS produces flood maps showing depths, duration of inundation, impacts, etc.

3 FMM INPUTS AND OUTPUTS

The main inputs to FMM are flood models and results, GIS coverages and DEMs, while the main outputs are floodplain topographic data for flood models, and maps showing flood depths and impacts on flood levels. Applying forethought and careful preparation of the inputs, and understanding the type of outputs will greatly help in successfully completing an FMM application.

3.1 Introduction

The main data inputs to FMM are flood models, GIS coverages, one or more DEMs, and, if available, imagery from satellites or aerial photography.

Coverages (see Section 3.2.2) are displayed on the computer screen to show graphically features over the floodplain. Examples are rivers, roads, villages and beels. Thought should be given before the study commences to the types of coverages which would be useful. Coverages are also used to incorporate into the DEM the features they represent.

The quality of the DEM is fundamental to the quality of FMM output. A well prepared DEM is necessary for visualising the floodplain topography on the computer screen, and most importantly, for accurate flood mapping.

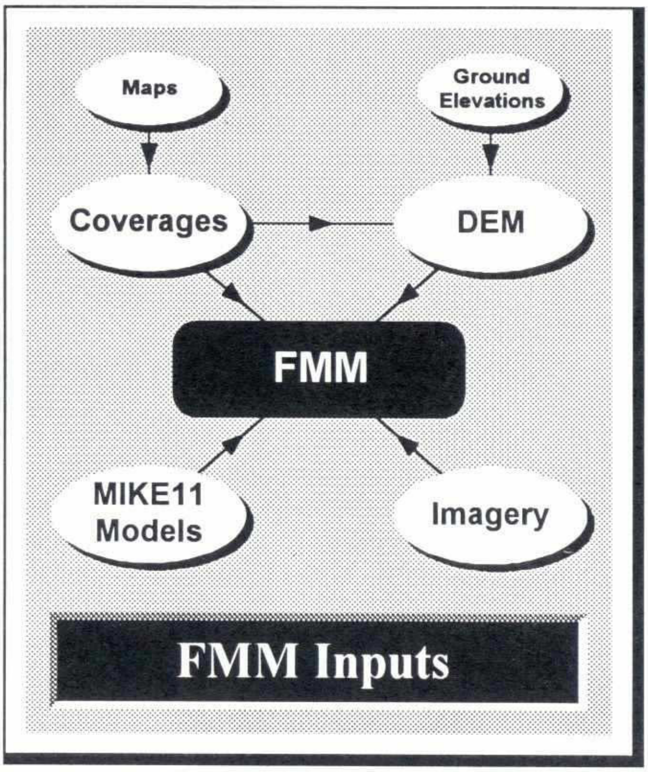
If imagery from satellites or aerial photography is available, it may also be displayed on the computer screen to help visualise the rivers and floodplains.

From a DEM, FMM outputs floodplain topographic data in two forms: cross-section profiles and flooded area versus elevation curves. Floodplain cross-section profiles can also be merged with MIKE11 river profiles. Flooded area versus elevation curves are computed to quantify the storage capacity of sections of the floodplain.

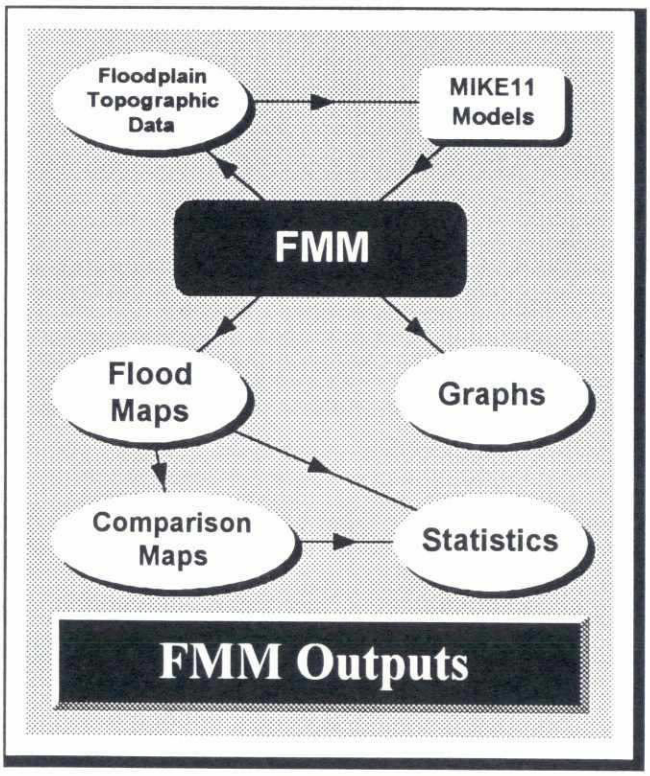
The main FMM outputs are flood maps, an ideal medium for visualising and understanding flooding, and for analysing flood impacts on other sectors because of interventions. The types of flood maps are: flood depth maps, duration depth maps and depth classification maps. Comparison maps, which compare two flood maps of the same type, show the impact from flood interventions or the change in flooding over time. Flood maps and comparison maps can be used by other sectors for flood damage mapping.

Statistics can be output to summarise any flood or comparison map. The areas of inundation for different depth classifications is one example of statistical output. Statistics can be produced for the whole map or for different zones.

Time-series and other conventional graphs can also be output to supplement the flood and comparison maps.



FMM requires inputs of coverages (roads, rivers, settlements), a DEM, flood models and, if available, satellite and photo imagery.



FMM outputs topographic data for use in flood models and post-processes flood model simulation results into flood maps, comparison maps and graphs. Statistics are produced from the flood and comparison maps.

3.2 FMM Inputs

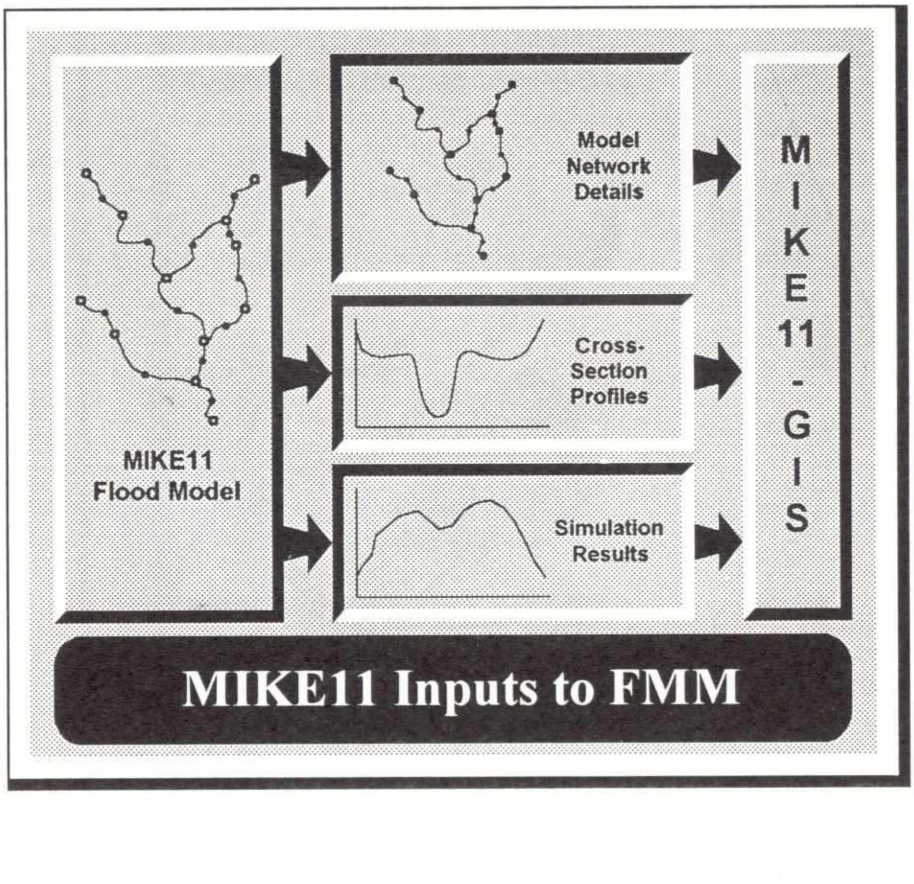
3.2.1 Flood Models

Flood models are a necessary input for flood mapping, the main function and output of FMM. To produce the flood maps, details of a model's network and flood simulation results are required.

Also, using FMM, flood models are further developed and enhanced by making use of the floodplain topographic data in a DEM. Therefore, both flood model development and FMM application may occur in unison.

MIKE11 exports to MIKE11-GIS information on flood model network, cross-section databases and results from flood simulations.

MIKE11 cross-section databases are exported to MIKE11-GIS to display cross-section profiles, and for merging river cross-sections with DEM floodplain profiles. Imported flood model simulation results are used for flood mapping, graphing and statistical output.



MIKE11 exports to MIKE11-GIS details of model networks, cross-section databases and flood simulation output.

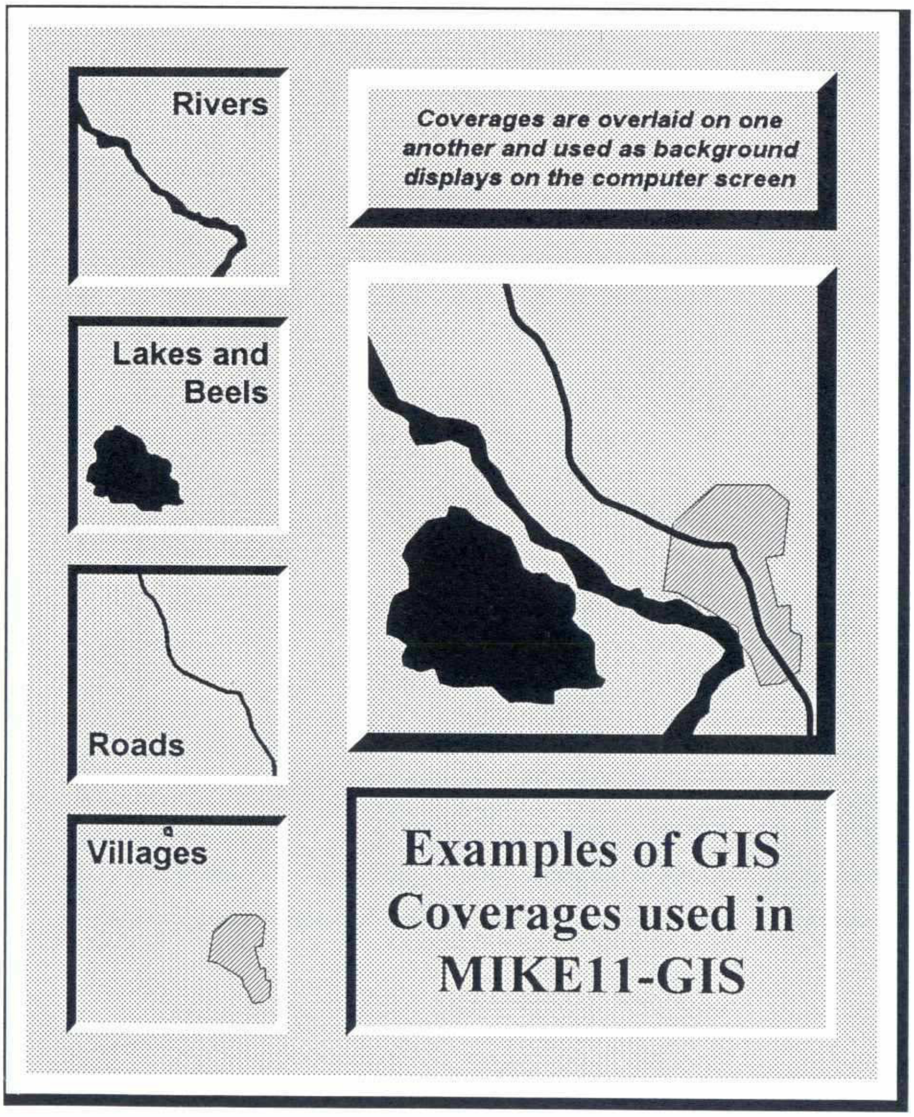
3.2.2 Coverages

Coverages were described in Chapter 2 as layers of geo-referenced data which represent themes. Typical themes used for MIKE11-GIS are rivers, lakes or beels, roads, railways, townships and villages.

They are displayed on the computer screen to help visualise the floodplain. Coverages may also be used as aids in the building of a DEM as discussed in the section, **DEM**, below.

Before applying MIKE11-GIS some thought should be given to acquiring or digitising coverages of appropriate themes for the study. A GIS specialist will be needed for advice and preparation.

Plate 1 shows several coverages used for the Tangail Compartment FMM.



A variety of coverages are used to display on-screen features over the floodplain. This helps the user visualise the study area. Coverages are also used for making a DEM (see next section).

Settlement, River, Beel and Road Coverage Examples

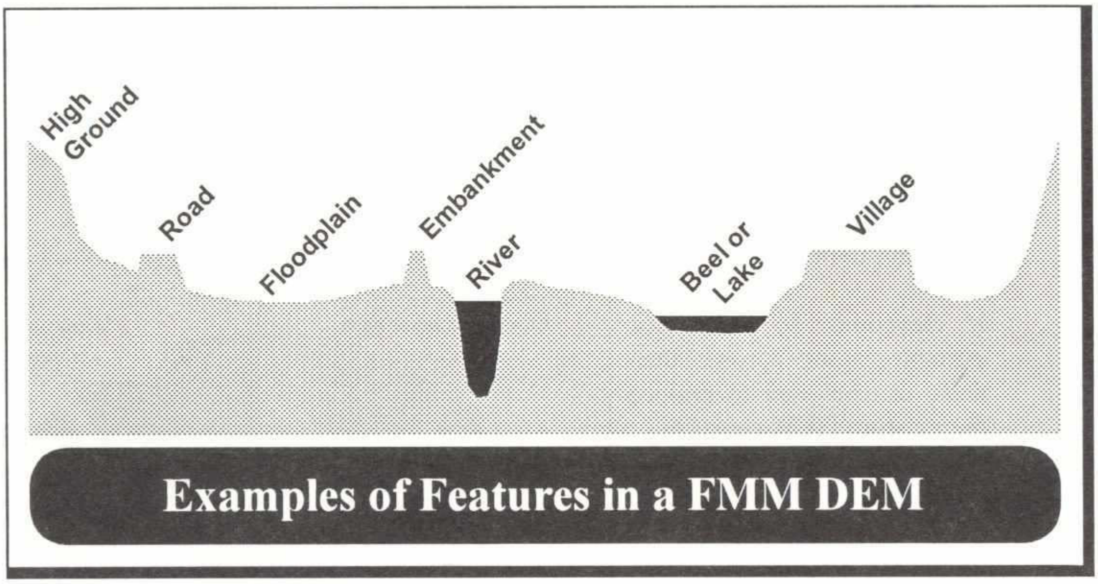
Settlement
River
Beel
Road

3.2.3 DEM

A DEM, in the context used here, is a ground elevation model. It consists of elevation points of the ground surface (defined by X,Y,Z coordinates).

The elevations in a DEM used by MIKE11-GIS are derived from three basic types of topography: floodplains; high ground; and features which depress or raise the floodplain (eg. rivers, khals, beels, roads, embankments and settlements). The floodplain is characterised by very flat topography, while high ground is typically steep.

A DEM developed for another study may not be suitable for an FMM study, because DEMs usually lack sufficient data over the floodplain. The discussion below aims to provide guidance on the typical inputs and procedure for preparing an FMM DEM.



An FMM DEM may contain a variety of features besides the floodplain and high ground. Typical features are roads, embankments, lakes and settlements.

The two main types of inputs to an FMM DEM are:

1. Ground surface elevations.

2. GIS coverages depicting floodplain features such as rivers and roads (for features which are never flooded or permanently wet elevations are not essential).

Ground elevations are obtained from field surveys, photogrammetry and other survey sources. Elevations on high, flood-free ground need not be accurate, while floodplain elevations must be accurate. For flood mapping it is essential that the DEM accurately models the floodplain undulations. The spacing between surveyed elevation points should be sufficient to pick up variations in ground slope, with a closer spacing required in areas of significant variation such as river levees.

GIS coverages of rivers, roads, settlements, lakes, etc can be used to build these features into a DEM even though no knowledge of elevations may exist. If these features are either flood-free or permanently wet, they can be assigned an elevation above the peak flood level or below the minimum flood level respectively.

Regions of permanent water in rivers, lakes and beels often have no bed (ground) elevation information. Also, river cross-section profiles used for the flood model are usually not frequent enough for their elevations to be included in a DEM. However, it is highly desirable for rivers and lakes to be built into a DEM, if only for visualising their location (if a river is not in a DEM then the flood map will not show deep water along its course).

If coverages of the rivers and lakes are available or digitised then these can be used to lower the DEM elevations to below dry season water levels. The rivers and lakes will then appear as deep water on the flood maps.

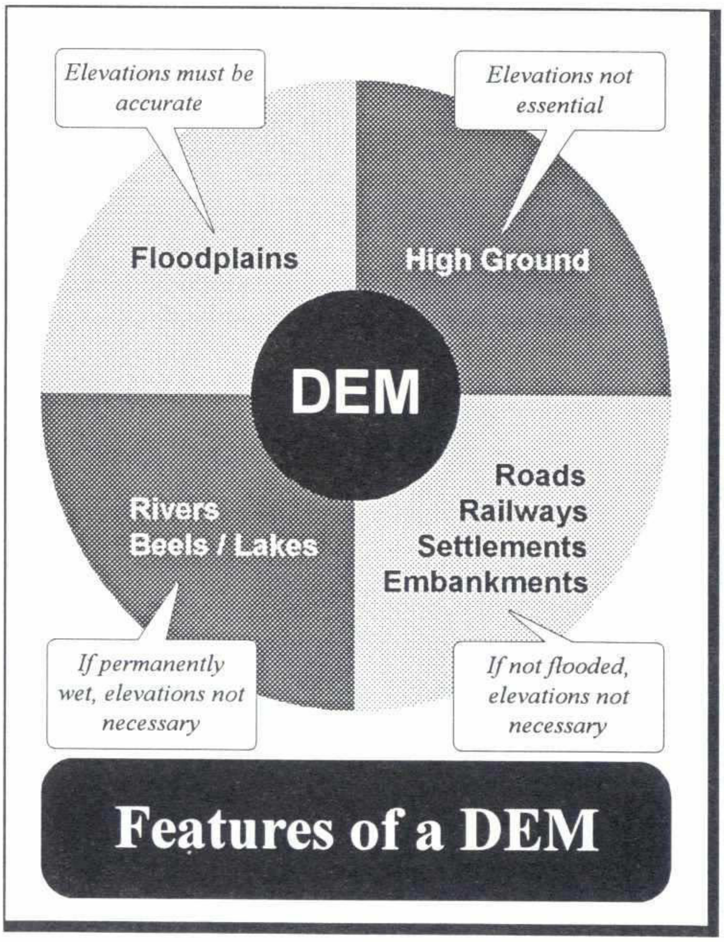
Similarly to rivers and lakes, features or parts of features, such as embankments, roads and villages, which never flood can be represented in a DEM by raising the DEM elevations. A coverage of each feature is necessary to modify the DEM.

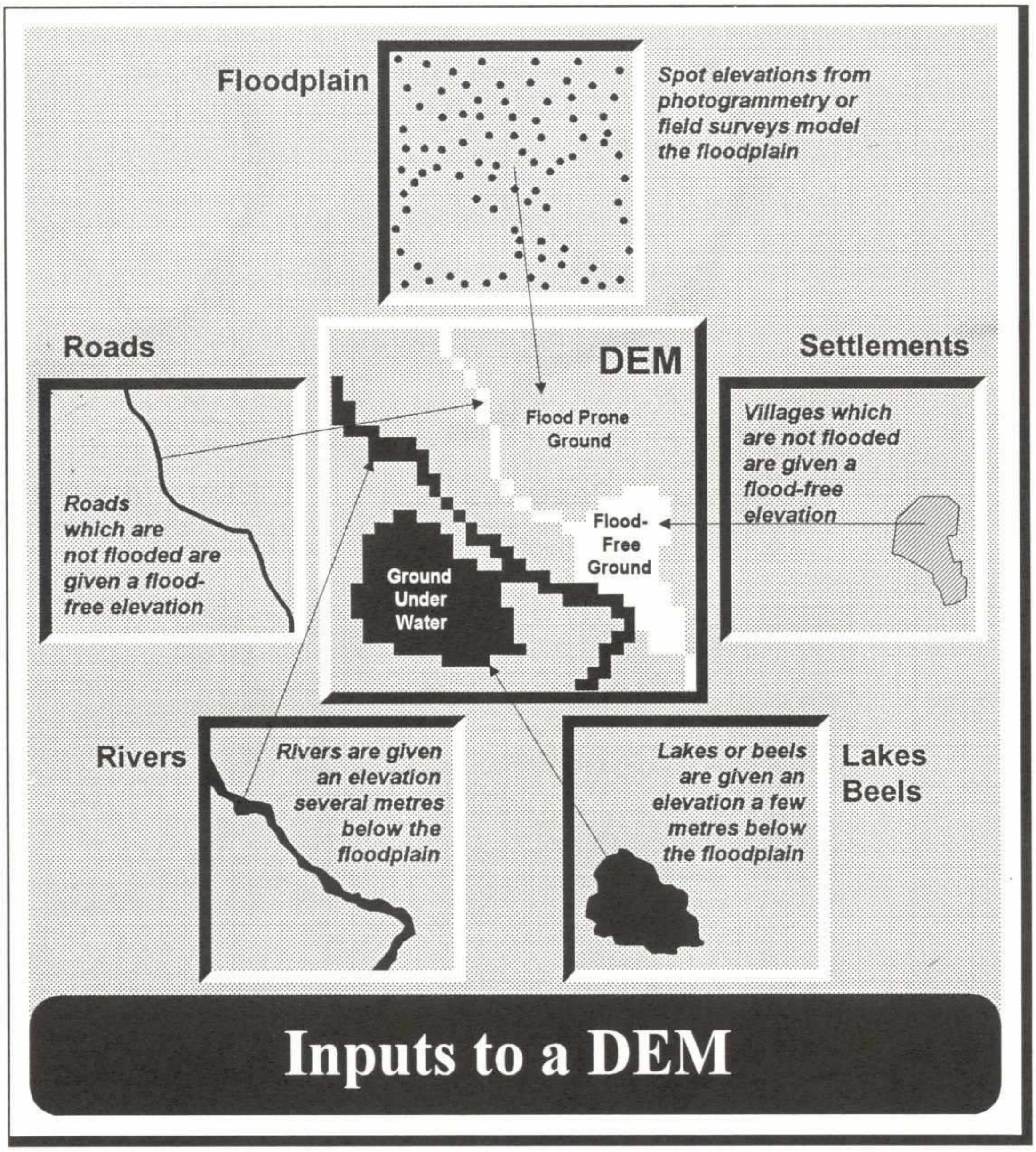
If elevations do exist, for example, along a road, then these can be used to replace the existing DEM elevations.

Building an FMM DEM is a very important step. The technical details are not further elaborated because the topic is too vast, however, the basic steps are illustrated on a following figure. A GIS specialist will be needed to help produce a DEM.

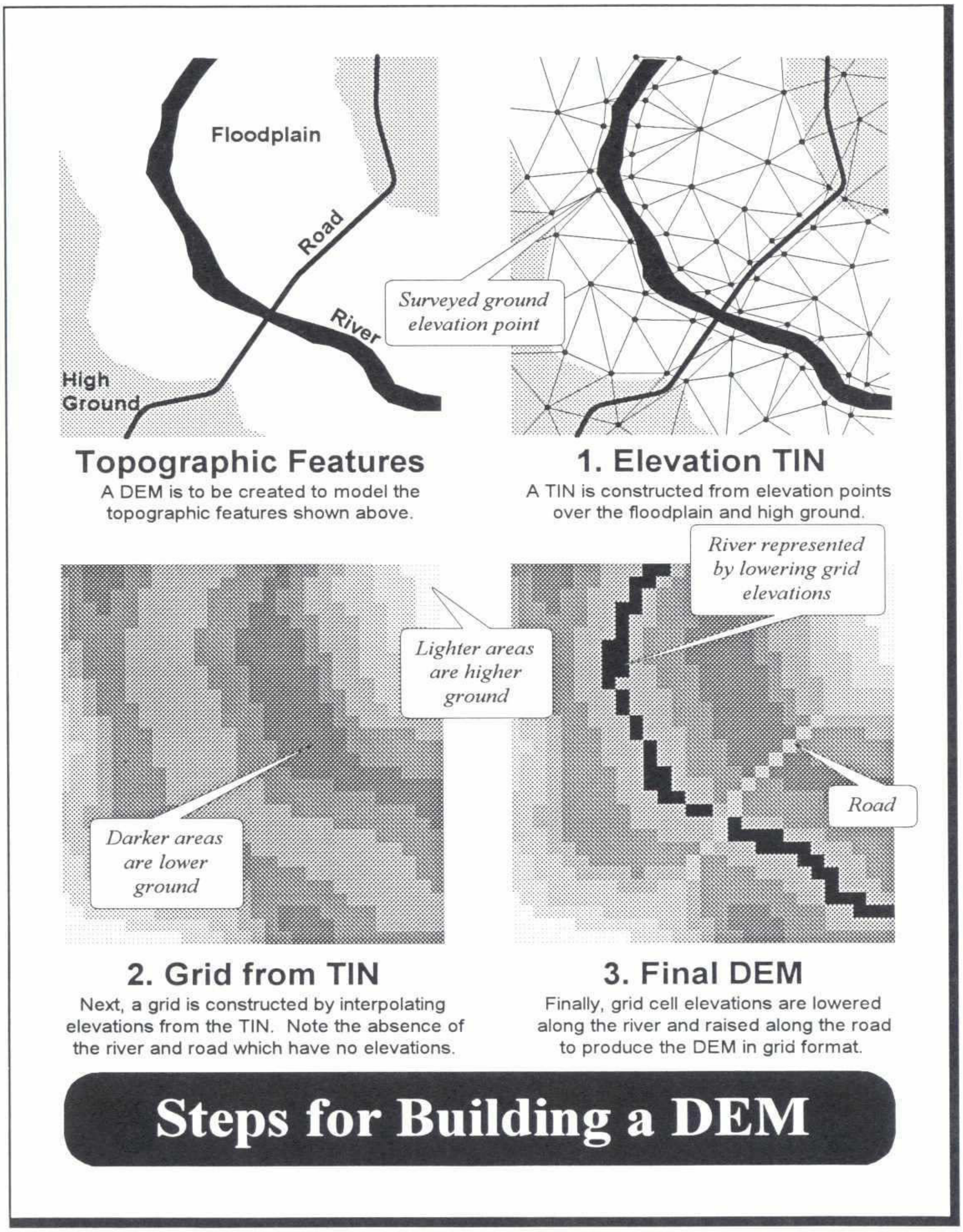
Plate 2 illustrates a detailed DEM of the Tangail Compartment area. The annotation on the plate helps describe the DEM.

A DEM contains a variety of features which may or may not need ground elevations.



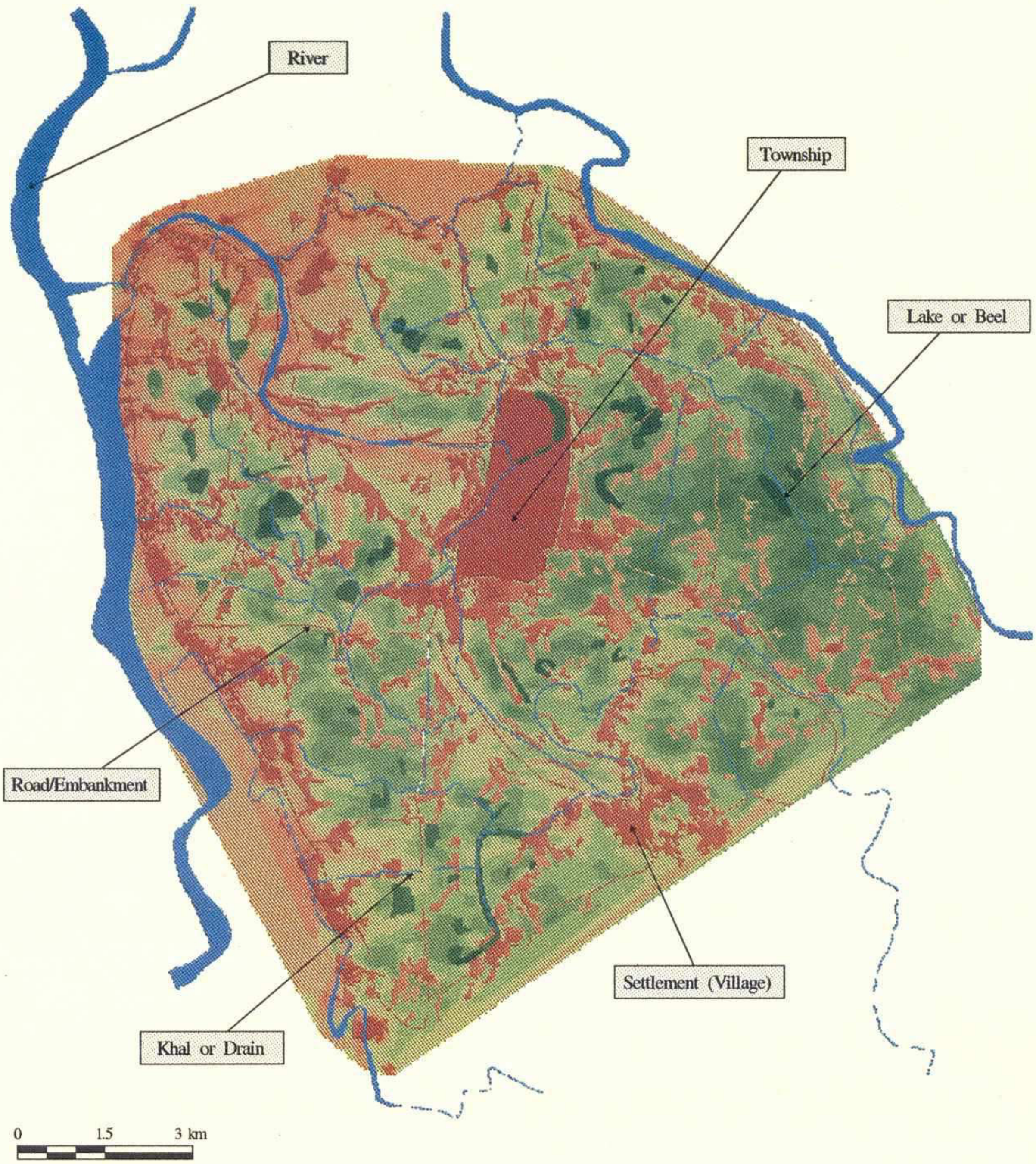


Elevations over the floodplain along with coverages of features such as roads, rivers, lakes and settlements are used to make a DEM suitable for flood mapping.



The steps for creating an FMM DEM are illustrated in the above example. A TIN (Triangulated Irregular Network) is used for Step 1 to model the ground surface based on irregularly located spot elevations (the triangle is the simplest geometrical shape which defines a three-dimensional plane surface). A grid (or raster surface) is a mesh of regular squares (cells) - each cell being the same size, and having a single elevation.

DEM Example



Elevation (m) – PWD Datum

Below 7.0	9.0 – 9.5	11.0 – 11.5	Above 14.0
7.0 – 8.0	9.5 – 10.0	11.5 – 12.0	River/Khal
8.0 – 8.5	10.0 – 10.5	12.0 – 13.0	
8.5 – 9.0	10.5 – 11.0	13.0 – 14.0	

3.2.4 Fine or Coarse DEM?

For flood mapping and display on the computer screen a DEM must be in a grid format. A grid (or raster surface) is a matrix of square cells, every cell being the same size and each having a single ground elevation.

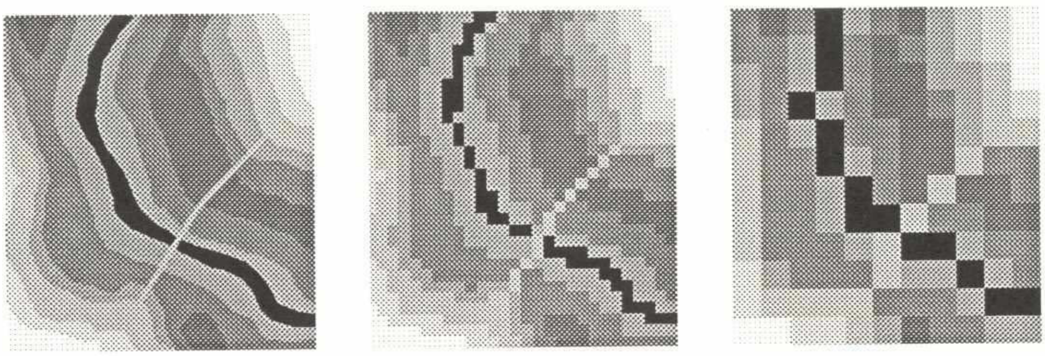
Coarse grids (large cell size) appear very "blocky" and give poor resolution of features such as rivers, lakes, embankments and roads. However, they consume only a small amount of disk space and are very fast for analysis and display.

Fine grids give a high resolution image, but require much more disk space and are slower to display. For example, reducing the grid cell size by one third increases disk space and analysis computation times by a factor of nine.

Initially the DEM cell size should be selected according to the resolution of the source data and software/hardware limitations. This, usually coarse, DEM is used for producing floodplain topographic data (see next section) and preliminary flood mapping.

However, usually a fine DEM should be used for reporting and presentations. *If a fine DEM is not used for reporting and presentation, acceptance by those unfamiliar with GIS may not be easy.* This is an important consideration, even though using a fine DEM may be excessive when compared to the resolution of the source data.

Another important consideration is the scale of the DEM. For example, if the grid cell size is 1 km, then incorporating features such as roads and embankments which are only 5 to 20 m wide, is not appropriate.



Fine DEM
The grid cell size is of similar size to a pixel on the computer screen, giving a high resolution image.

Coarse DEM
The larger grid cell size gives a "blocky" effect, however, the DEM requires much less disk space and generating flood maps is much faster.

Very Coarse DEM
This grid cell size is too large making visual interpretation very difficult.

The fineness or coarseness of a DEM must be selected to suit the need. Start with a coarse DEM for initial work, but use a fine DEM for final flood mapping, reporting and presentations.

Therefore, for DEMs which cover a large area such as the National DEM for Bangladesh, only the major rivers can realistically be represented.

However, for relatively small area DEMs, such as the Tangail Compartment DEM, details of rivers, villages, beels and roads can be incorporated (see Plate 2).

The DEMs created during this study ranged in cell size from 1000 metres (national level) to 10 metres (chawk level mapping in the Tangail Compartment). For the regional level FMM, cell sizes of 300 m for the whole region, and 100 m for sub-regional flood mapping were used.

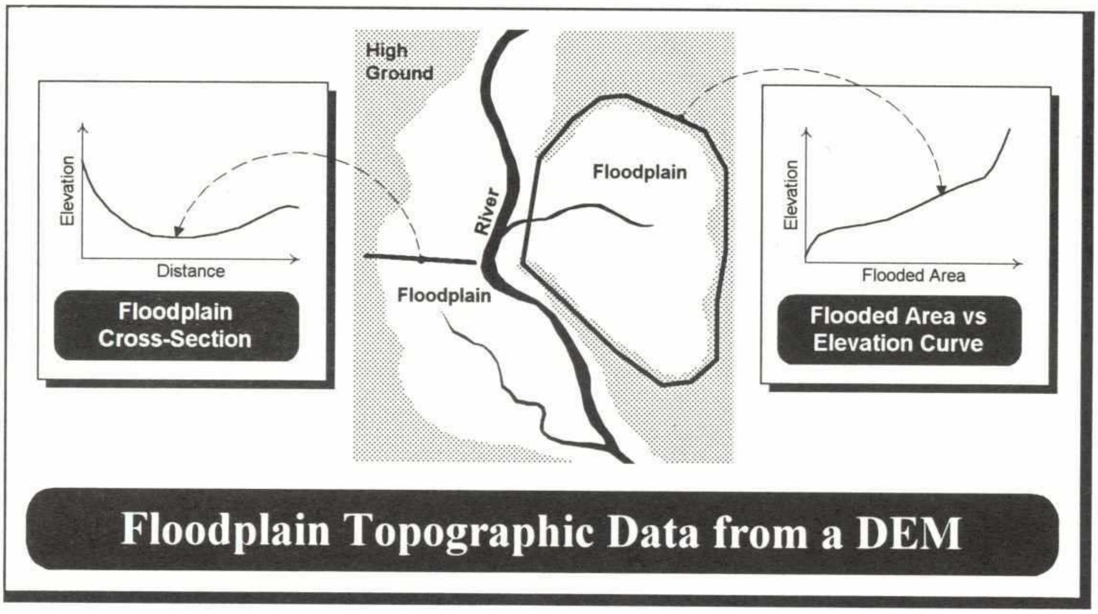
3.3 FMM Outputs

3.3.1 Flood Model Topographic Data

Preparing floodplain topographic data for flood models has been one of the most difficult and time-consuming tasks. Because of this, the accuracy of the data and the quality of the model over the floodplain can be poor, resulting in inaccurate and misleading interpretation of flooding behaviour.

A DEM contains a wealth of floodplain topographic data. MIKE11-GIS extracts and outputs floodplain topographic data from a DEM to MIKE11. Two types of MIKE11 data are produced: cross-section profiles and flooded area versus elevation curves. Both types can be directly placed into a MIKE11 cross-section database.

An additional facility merges MIKE11 river cross-sections with floodplain cross-sections from the DEM.



MIKE11-GIS outputs data from a DEM for input into MIKE11 models. The types of data are floodplain cross-section profiles and flooded area versus elevation curves.

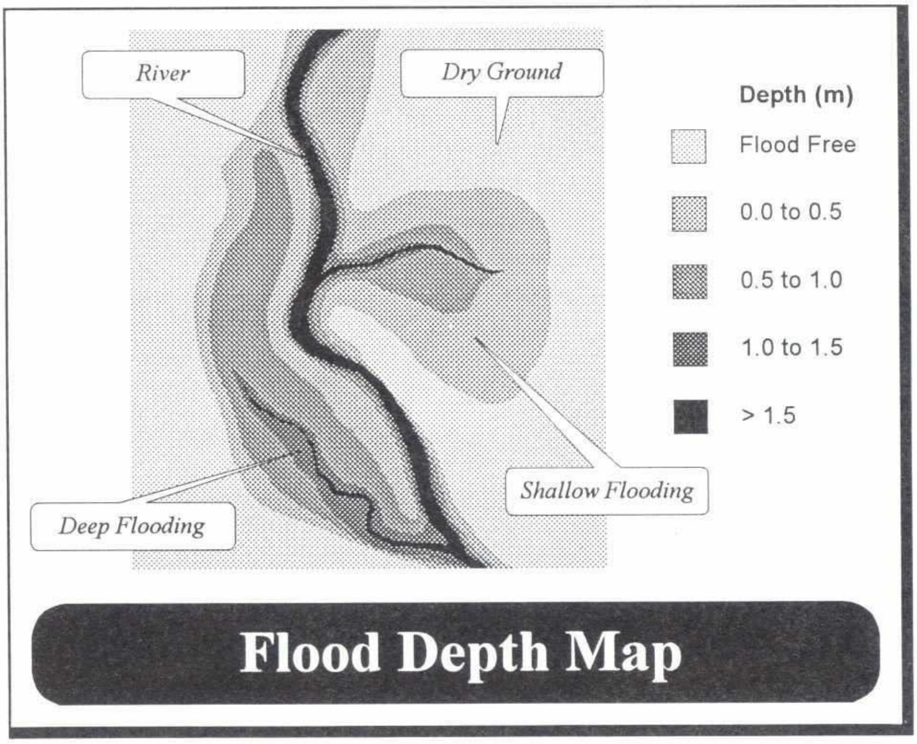
3.3.2 Flood Depth Maps

Flood depth maps show the variation in flood depth over the floodplain, along with the flood-free areas. They give a clear picture of the depth and extent of flood inundation.

The maps are produced using the results from a flood model simulation, and can be at an instant in time, or based on the maximum flood levels over the entire simulation.

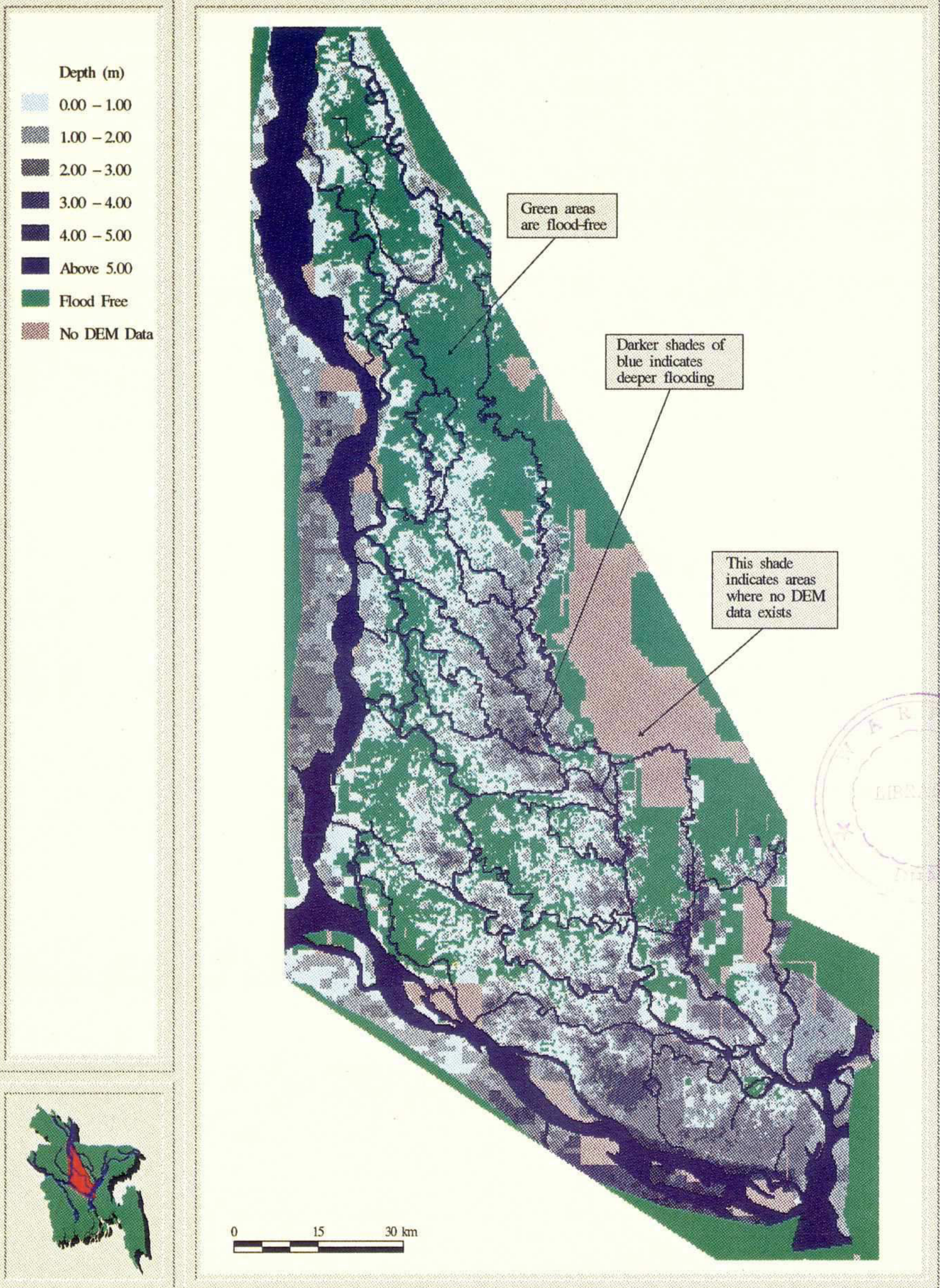
Plate 3 illustrates a flood depth map with annotation providing explanations.

The flood depth maps illustrated in this report show the rivers shaded with the darkest of the blue shades used for depicting flood depths. For example, the rivers in Plate 3 are shaded using the "Above 5.00" metres depth shade, even though this may not be a correct representation of the flood depths in the rivers. The flood depths in the rivers cannot be shown because the river bed levels are not included in the DEMs for reasons discussed in Section 3.2.3.



Flood depth maps show the variation in depth of flooding over the floodplain, giving a clear and concise image.

Flood Depth Map Example



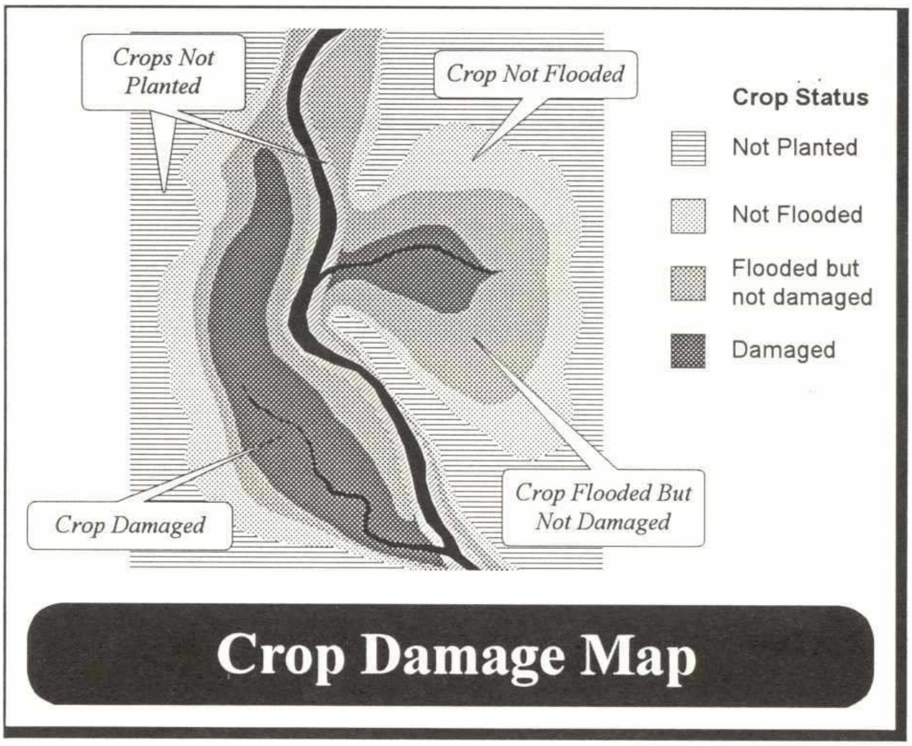
3.3.3 Duration Depth and Crop Damage Maps

Duration depth maps are similar to flood depth maps, but take into account the critical duration of flooding (typically three days) which a crop can withstand without being damaged. From the duration depth map, crop damage maps are produced.

The normal procedure is to work with periods (10 to 15 days, or monthly) which correspond with the crop's growth stages. The critical depths (the depth of water which will damage a crop if it is inundated for longer than the critical duration) must be supplied for each period.

A crop damage map for a period is produced by comparing the depths on the duration depth map with the critical depth. If a duration depth exceeds the critical depth the crop is damaged. Other criteria such as once the crop is damaged it remains damaged must also be applied.

Plate 4 shows an example of a duration depth map and a crop damage map.



Duration depth maps are used for producing crop damage maps. The maps take into account the duration under which a crop can tolerate submergence, and also the crop's growth stages.

3.3.4 Depth Classification Maps

Depth classification maps are also similar to flood depth maps, but instead of using a constant depth increment for showing different depths, depths are grouped into different classes.

An example is the Bangladesh flood phase classification, which groups flood depths into five classes, F0 to F4.

Bangladesh Flood Phase Classes		
Class	**Flood Phase**	**Depth Range**
F0	Non-flood	< 0.3 m including flood-free ground
F1	Shallow Flood	0.3 m to 0.9 m
F2	Medium Flood	0.9 m to 1.8 m
F3	Deep Flood	1.8 m to 3.6 m
F4	Very Deep Flood	> 3.6 m

Depth classification maps can be based on flood depth maps or duration depth maps. Plate 5 shows a depth classification map based on the flood phase categories for the Tangail Compartment using the peak flood levels from the 1993 flood. Flood phase maps shown in this report do not make allowances for non-agricultural land, therefore, settlements, permanent water bodies and other non-agricultural features are included in one of the classes.

3.3.5 Comparison Maps

Comparison maps show the change between two flood maps. The two types of comparison maps are:

- The impact of a flood intervention.
- The change in flooding over time.

For the first type, two flood maps of the same theme and/or time are needed, one based on a MIKE11 simulation of the pre-intervention conditions, and the other on the post-intervention conditions. By comparing the two flood maps, the impact or change in flooding can be readily observed.

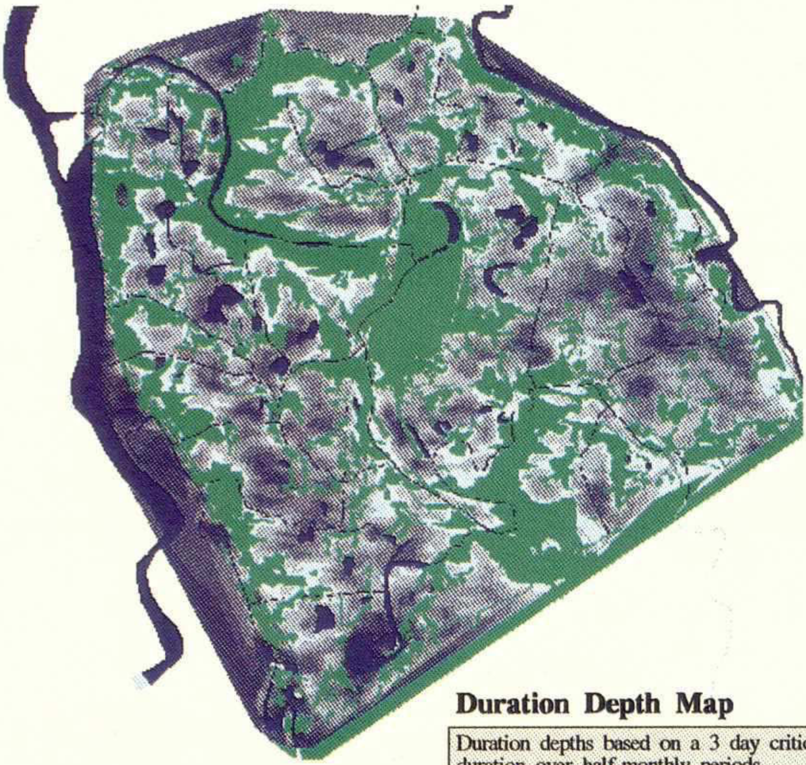
The second type requires two flood maps at two different times from the same MIKE11 simulation. The map shows the change in flooding between the two times.

Plate 6 shows a comparison map with annotation to explain the output.

Duration Depth and Crop Damage Map Examples

Duration Depth (m)

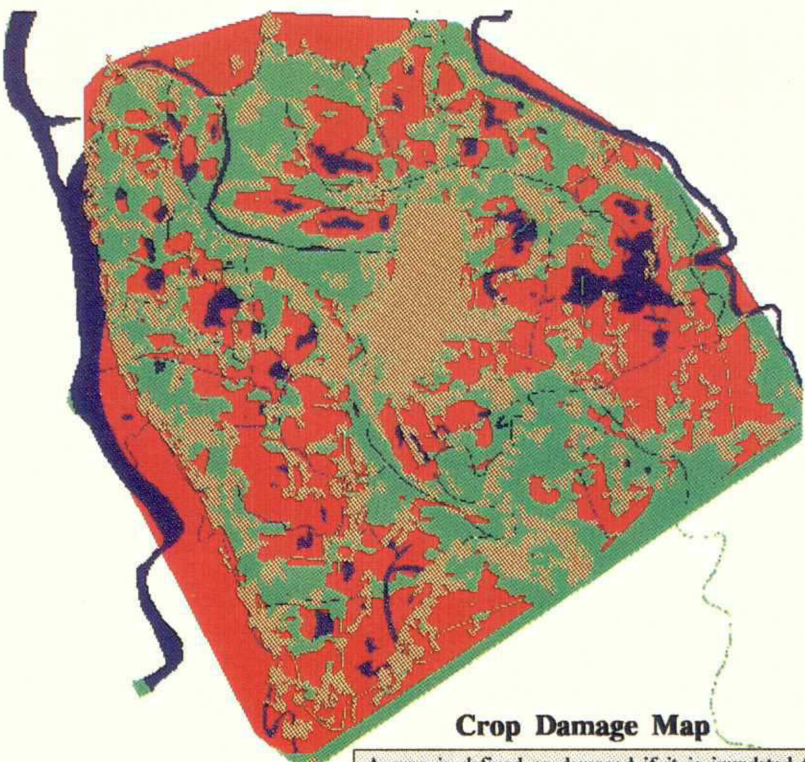
- 0.00 – 0.30
- 0.30 – 0.60
- 0.60 – 0.90
- 0.90 – 1.20
- 1.20 – 1.50
- 1.50 – 1.80
- 1.80 – 2.10
- Above 2.10
- Flood Free



Duration Depth Map

Duration depths based on a 3 day critical duration over half-monthly periods.

- No Damage
- Crop Damaged
- Crop not Planted
- Settlement/ Township



Crop Damage Map

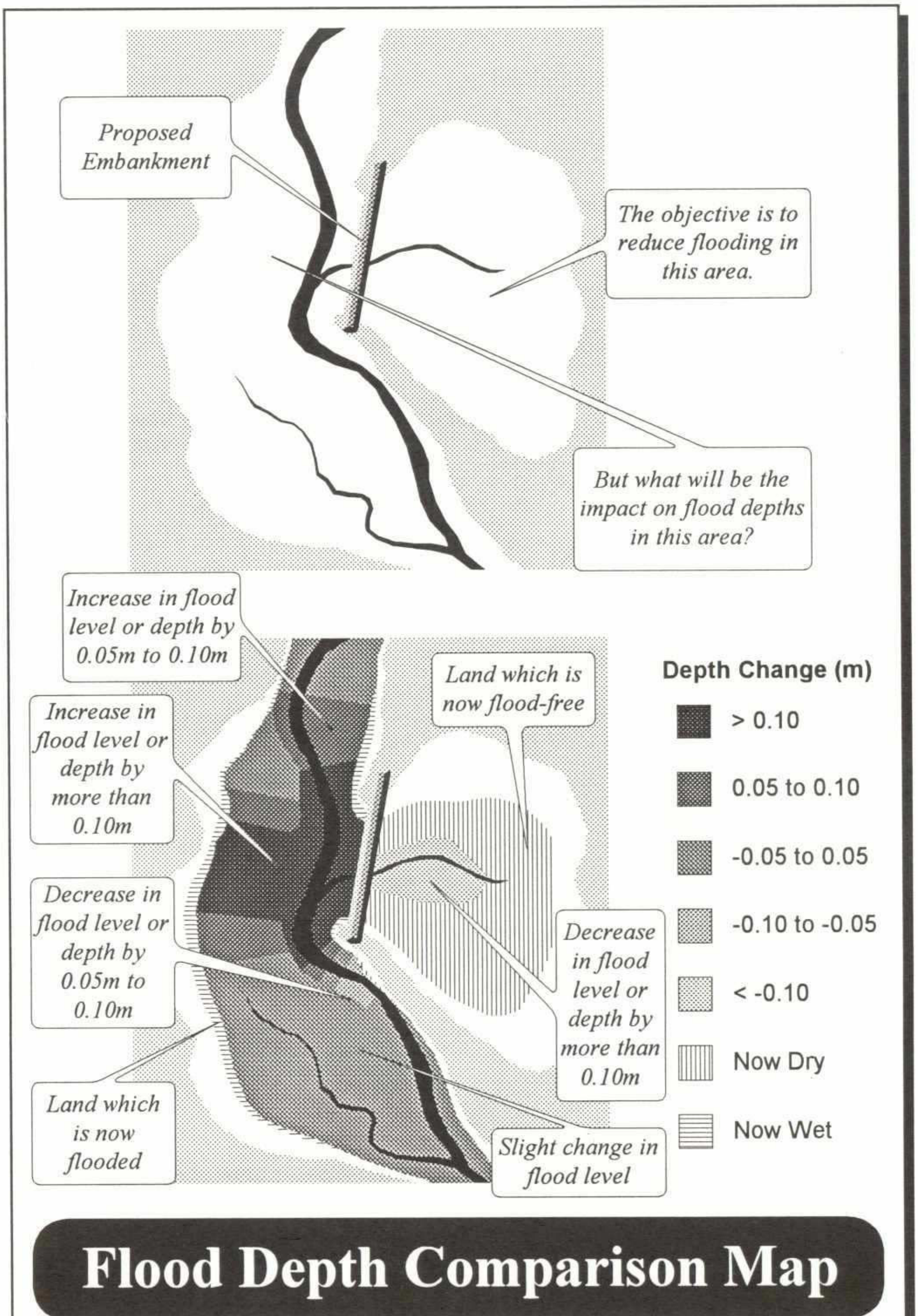
A crop is defined as damaged if it is inundated for more than 3 consecutive days at a depth greater than its critical depth. The critical depth is defined for half- monthly periods based on the crop's growth rate and resistance to flooding.

0 2 4 km

Depth Classification Map Example - Flood Phases

Flood Phase

- F0 (< 0.3 m)
- F1 (0.3 – 0.9 m)
- F2 (0.9 – 1.8 m)
- F3 (1.8 – 3.6 m)
- F4 (> 3.6 m)



Comparison maps are a powerful medium for showing the extent of the impact from a flood intervention.

3.3.6 Statistics

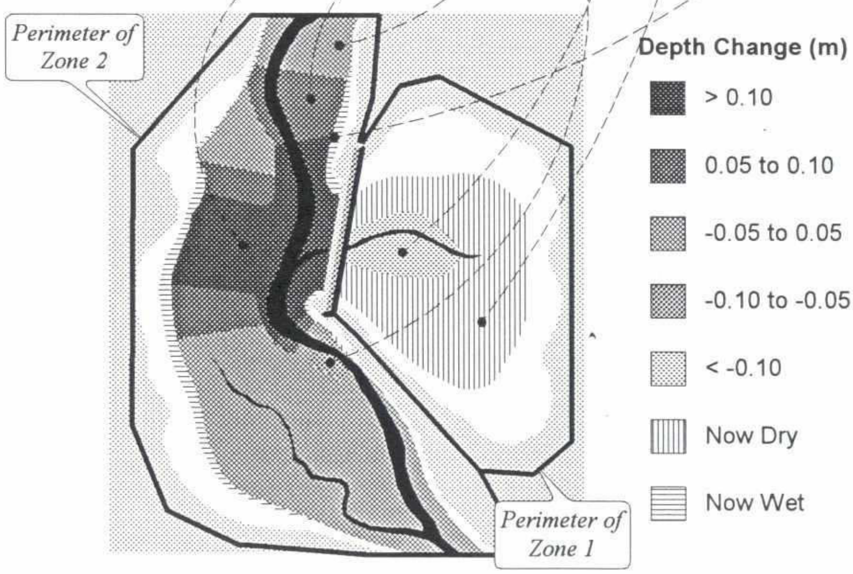
Statistics can be produced for flood and comparison maps. A table of values is generated showing, for example, the areas of inundation at different depths. Maps can be divided into zones and statistics created for each zone.

A file is produced and can be imported into a spreadsheet or wordprocessor for further analysis, chart display and incorporation in reports.

Statistics are calculated from flood or comparison maps to provide a summary. The inundation or impact for different zones are presented in a table which can be exported to spreadsheets for charting and further analysis.

Flood Depth Comparison Statistics

	Area (km2)							
	Total	>0.10	0.05 0.10	0.05 -.05	-.05 -.10	<-.10	Now Dry	Now Wet
Zone 1	63	0 0%	0 0%	0 0%	0 0%	5 8%	23 37%	0 0%
Zone 2	109	16 15%	9 8%	37 34%	1 1%	0 0%	0 0%	4 4%



Statistics
(from a Flood Depth Comparison Map)

Map Type	Statistical Output	
Flood Depth Duration Depth Depth Classification	**Values:**	Area of inundation and percentage of total zone area.
	Rows:	One row for each zone.
	Columns:	One column for each depth / duration depth increment or depth classification. "Dry" column for flood-free areas. Total area column.
Flood Depth Comparison Duration Depth Comparison Depth Classification Comparison	**Values:**	Area of inundation and percentage of total zone area.
	Rows:	One row for each zone.
	Columns:	One column for each depth / duration depth difference increment or the change in depth classification. "Now Dry" column for areas previously flooded but now flood-free. "Now Wet" column for areas previously flood-free, but now flooded. Total area column.

The above table lists the type of output from the different types of maps.

		Decrease			**Increase**				
Zone	**Flood Free**	**Less than -1.1m**	**-.1m to -1.1m**	**None or Slight**	**0.1m to 0.3m**	**0.3m to 0.5m**	**More than 0.5m**	**Now Dry**	**Now Wet**
	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2	km^2
A	0.0	20.4	1.4	0.1	0.1	0.1	0.1	34.1	0.0
B1	145.0	10.1	3.6	0.2	0.0	0.0	0.0	15.0	0.0
B2	7.2	4.7	44.6	0.5	0.3	0.1	0.1	40.8	0.0
B3	0.0	100.7	10.3	0.4	0.1	0.0	0.0	9.5	0.0
C1	0.2	35.4	2.9	0.2	0.4	0.1	0.0	15.3	0.0
C2	0.0	70.6	4.9	0.2	0.3	0.0	0.0	81.9	0.0
Outer	N/A	9.1	55.4	N/A	1138.4	168.7	45.2	4.7	49.6

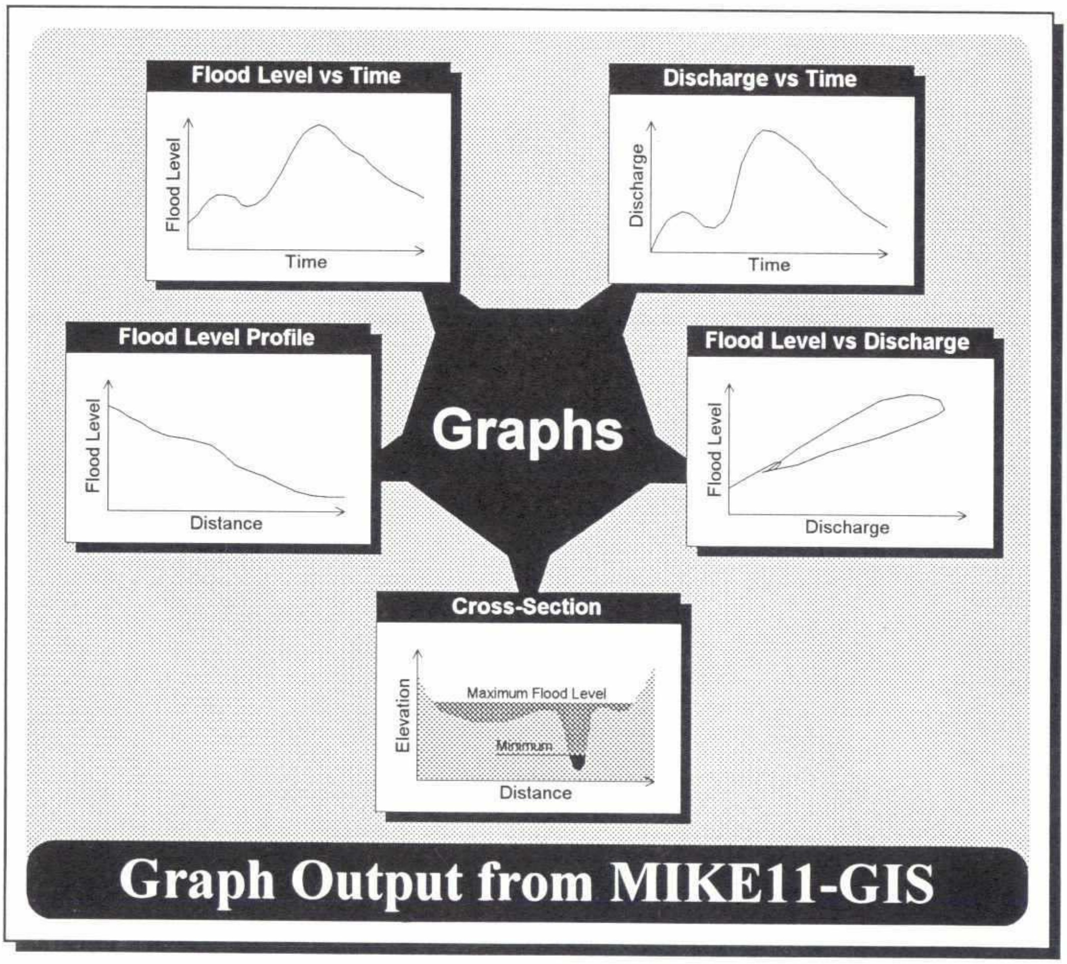
The change in flood level statistics due to the compartment intervention illustrated in Plate 6 are shown above. The compartments, A, B1, B2, B3, C1 and C2, are shown on the plate, and outer is the region outside of the compartments.

3.3.7 Graphs

MIKE11-GIS also displays several types of graphs. They provide additional support to the flood maps for viewing MIKE11 simulation results.

The types of graphs are:

1. Flood Level versus Time.
2. Discharge versus Time.
3. Flood Level versus Discharge (Stage-Discharge curve).
4. Flood Level Longitudinal Profiles.
5. Cross-section Profiles.



MIKE11-GIS outputs graphs in several formats to supplement the flood and comparison maps.

Several MIKE11 simulations or several locations in the MIKE11 model can be shown on the same graph, thereby making comparative assessments easy.

Comparison Map Example - Impact on Flood Levels

Depth (m)
- 0.00 – 1.00
- 1.00 – 2.00
- 2.00 – 3.00
- 3.00 – 4.00
- 4.00 – 5.00
- Above 5.00
- Flood Free
- No DEM Data

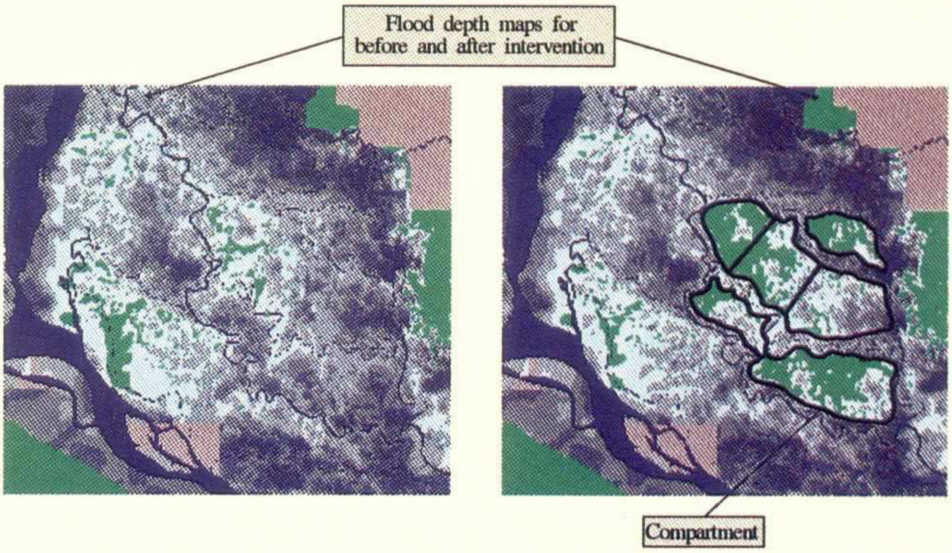
Flood Level Change
- None/Slight

Increase (m)
- Above 0.50
- 0.40 to 0.50
- 0.30 to 0.40
- 0.20 to 0.30
- 0.10 to 0.20

Decrease (m)
- – 0.10 to – 0.60
- – 0.60 to – 1.10
- – 1.10 to – 1.60
- Below – 1.60

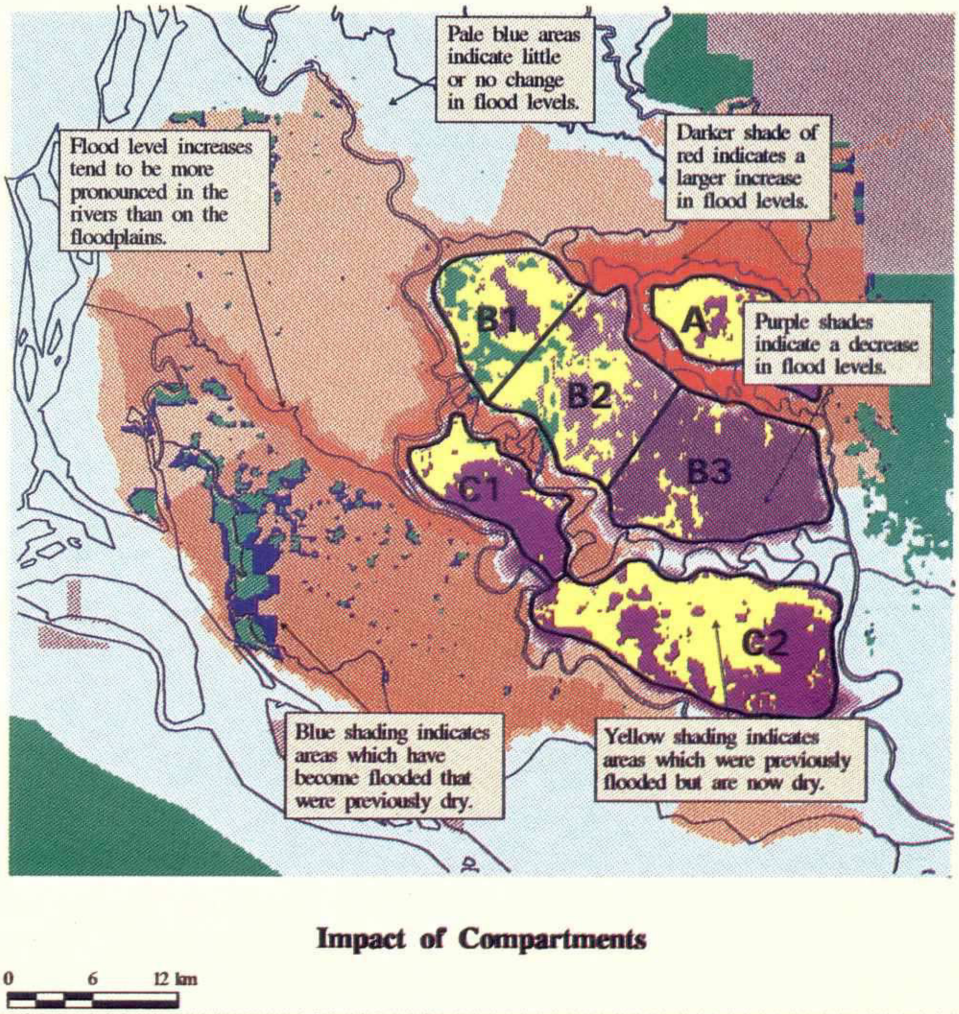
- Now Dry
- Now Wet
- Flood Free
- No DEM Data

- River
- Compartment



Without Compartments
(Before Intervention)

With Compartments
(After Intervention)



Impact of Compartments

4 Floodplain Modelling

This chapter reviews the basic methods for modelling floodplains, and illustrates the necessity of adopting methods which will achieve an adequate level of detail for flood mapping, and for correctly modelling and mapping the impacts on flood levels due to an intervention.

4.1 Introduction

Floodplains are hosts to intensive agriculture, industrial sites, urban and rural communities, and environmentally sensitive areas. During periods of flooding, most damage and disruption will occur on the floodplains - not in the rivers. Therefore, correctly modelling floodplains and their interaction with rivers is very important.

Different modelling methods can be applied according to the floodplain's hydraulic characteristics and the study objectives and resources. Simpler methods lump the left and right bank floodplains with the river. The limitation, however, is that the floodplain flood level is always the same as the river level, and some interventions, such as an embankment dividing the river and floodplain, cannot be studied.

Alternatively, there is the more detailed approach of modelling the river and adjacent floodplains as separate flow paths. However, inadequate data, increased model complexity and greater human and computer resource needs sometimes prevent more detailed methods being applied.

A combination of methods, simple and detailed, should be used for economic and efficient model development. However, a detailed approach is recommended in areas where significant differences between river and floodplain flood levels occur, especially if these differences *result* from an intervention. A detailed approach is particularly relevant for:

- Flood mapping.
- Modelling floodplain inundation and drainage.
- Modelling the impacts on flood levels due to an intervention.
- Flood damage assessments where both flood depth and duration are important factors (for example, crop damage).

4.2 Floodplain Inundation and Drainage

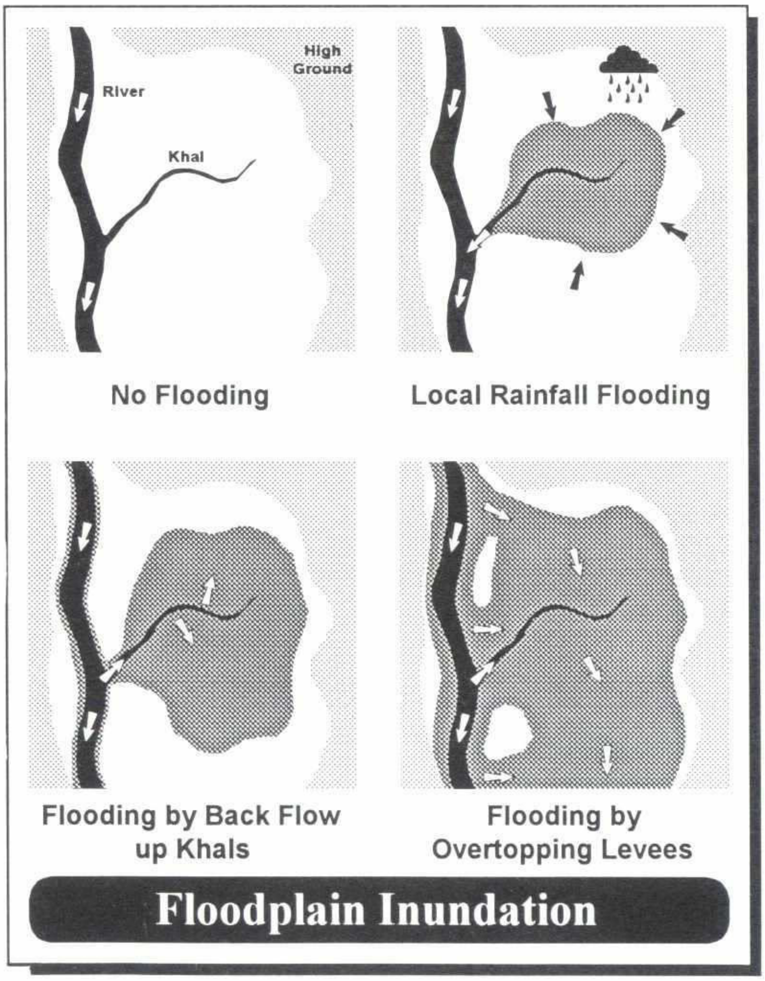
Floodplain modelling requires an understanding of the modes of floodplain inundation and drainage. The modes must be defined and reflected in the flood model if the model is to accurately simulate the flooding and drainage of floodplains.

4.2.1 Inundation

Floodplain inundation is caused by a combination of river based flooding and localised rainfall/runoff. Furthermore, river based flooding inundates the floodplain by either backing up khals and drainage channels, or by overtopping levees and embankments.

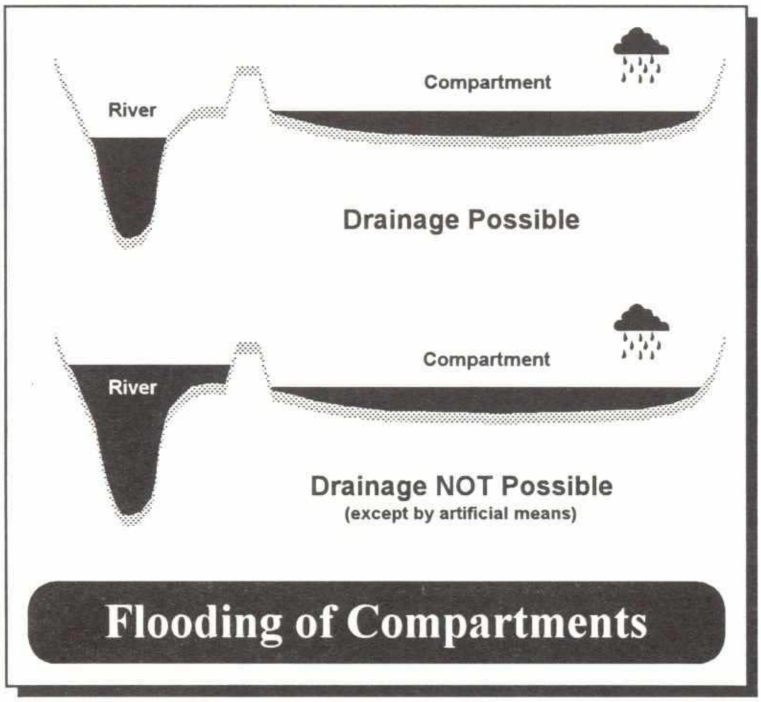
The relative importance of the different flooding modes varies depending on the stage, height and timing of the flood, and the topography of the river and floodplain.

Local rainfall flooding occurs in areas where local rainfall/runoff can not easily be removed because of inadequate drainage and/or high river levels. It is particularly relevant for compartments (areas protected from river flooding) as it is the only type of flooding which can occur.



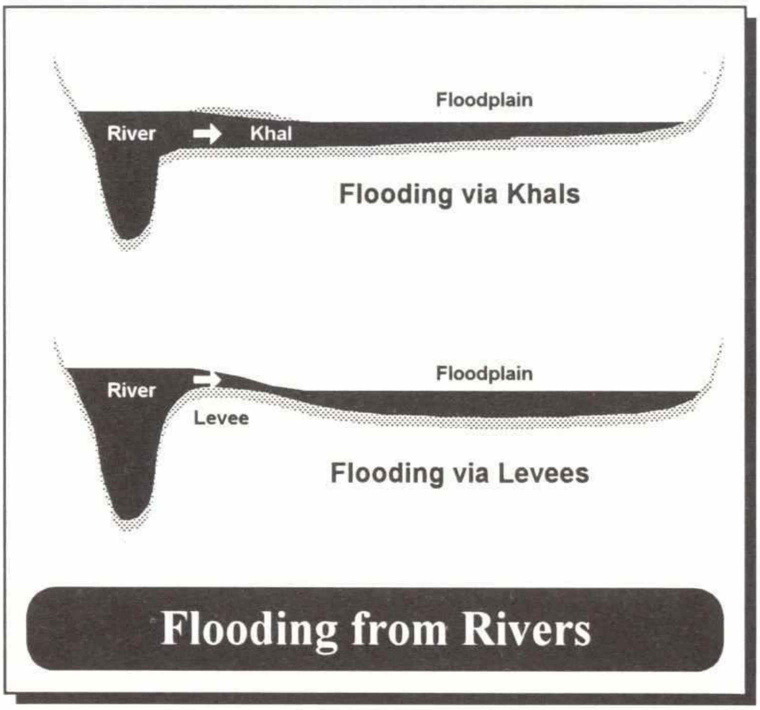
Inundation of floodplains can be caused by local rainfall/runoff; rivers backing up khals and drainage channels; and overtopping of river levees and embankments.

For small to average floods, there is usually no significant overtopping of river levees, therefore, inundation by back flows through khals or backwater effects along khals because of high river levels will prevail. For larger floods, levee and embankment overtopping inundation will dominate, however, prior to overtopping flooding via khals will also occur.



Flooding of Compartments

Local rainfall flooding of compartments is very dependent on the outfall river level which determines whether natural drainage is possible.



Flooding from Rivers

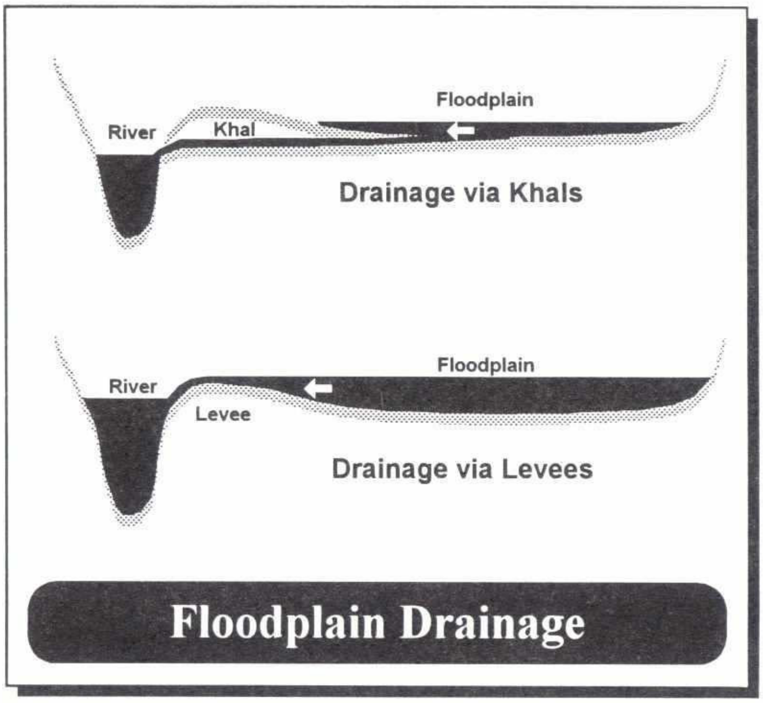
Flooding from rivers may be either caused by back flow through khals and drainage channels, or by overtopping of levees and embankments.

Flooding may also result from a combination of local rainfall/runoff and backwater effects because of high river levels.

4.2.2 Drainage

Floodplain drainage occurs after heavy localised rainfall or during the falling stage(s) of a flood. In either case, the floodplain water level has to be higher than the river level for natural drainage to be possible. Flood waters will either percolate into the ground, drain via khals and drainage channels, or flow back over the levees.

Infiltration is usually negligible during the course of a flood (it is more critical over longer, drier periods), and is therefore not considered any further. Drainage back over levees and embankments occurs during the receding stage of larger floods. As flood waters recede further drainage will eventually stop and remaining flood waters will drain via khals and drainage channels.



Drainage of floodplains occurs via khals and drains, and for larger floods, also back over levees and embankments.

4.3 Methods

Floodplains are generally modelled by a 1-D scheme such as MIKE11 in four different ways:

FP1 They are ignored. This may be satisfactory where the floodplain has negligible influence; for setting up a pilot model; preliminary investigations; or in areas well removed from a study interest area.

FP2 River cross-section profile plus additional flooded area curve (AE curve) to model the floodplain storage. Limitations: floodplain conveyance is not modelled, and the river and floodplain water levels are the same.

FP3 Cross-section profiles include both river and floodplain(s). The roughness coefficient can be varied across the river bed and floodplain. Limitation: river and floodplain water levels are the same.

FP4 The river and floodplains are modelled separately (quasi 2-D modelling). This is the most detailed and accurate method but requires greater resources.

FP1, FP2 and FP3 will be inadequate when river and floodplain water levels differ significantly, however, in many situations they may be satisfactory. FP1 is the simplest, most economical and can be adequate for preliminary investigations, while FP2 and FP3 require information on the floodplain topography.

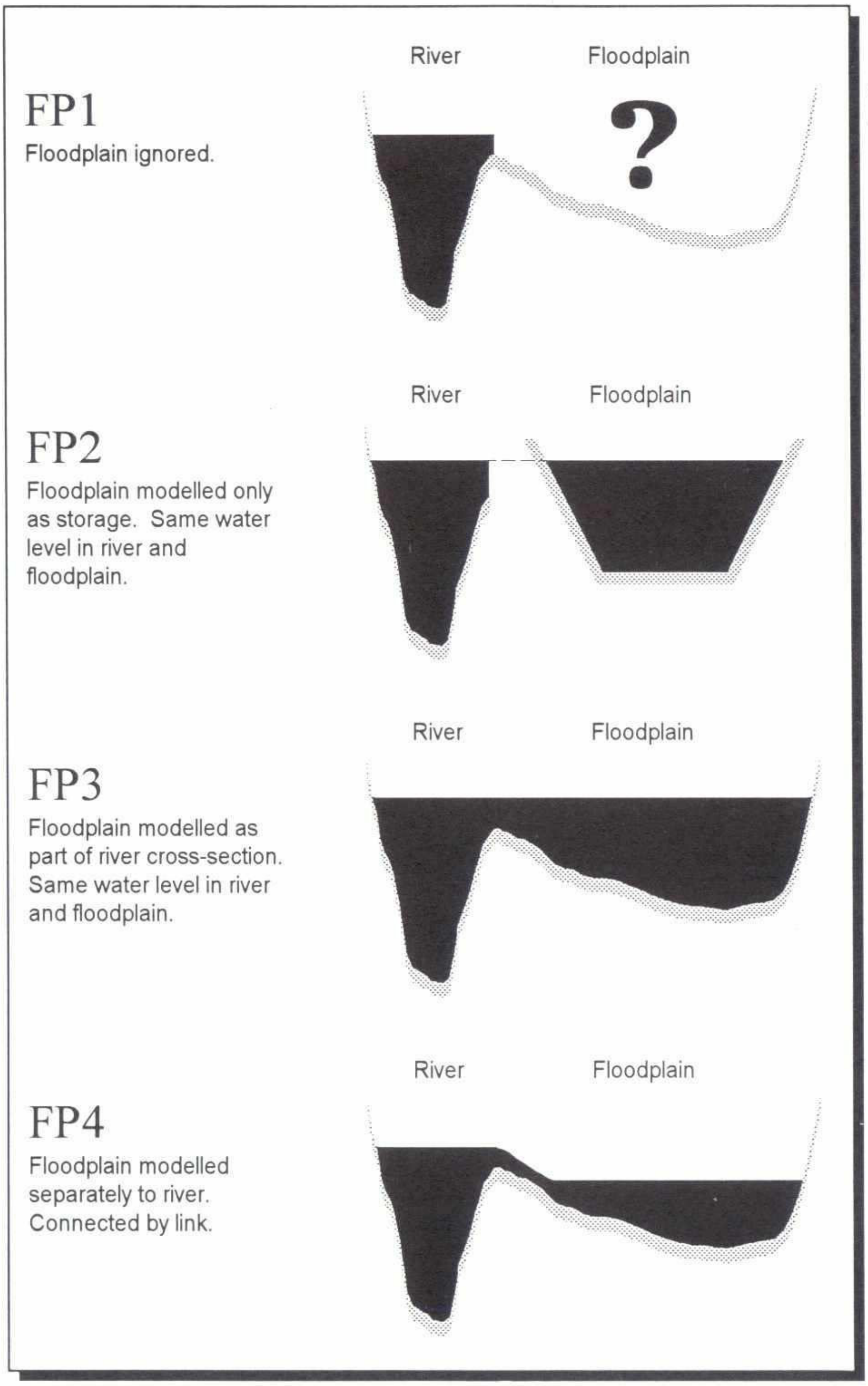
FP4 is the most accurate, complex and suitable where river and floodplain flood levels differ. The extra complexity to separately model the river and floodplain increases model development time and may require greater computer resources.

Deciding which method to use is a function of available resources, study objectives, data and the interaction between river and floodplain. All four methods may be used throughout a model - it is not wise to adopt a single method. For example, for floodplains remote to an area of interest, FP1 may be suitable, however, in the area of interest, FP4 may be necessary.

Undoubtedly, data and experience are the crucial elements in modelling floodplains. Hydrometric data should be obtained both on the rivers and the floodplains to calibrate and verify the model. These data will also guide the modeller on the best method to use.

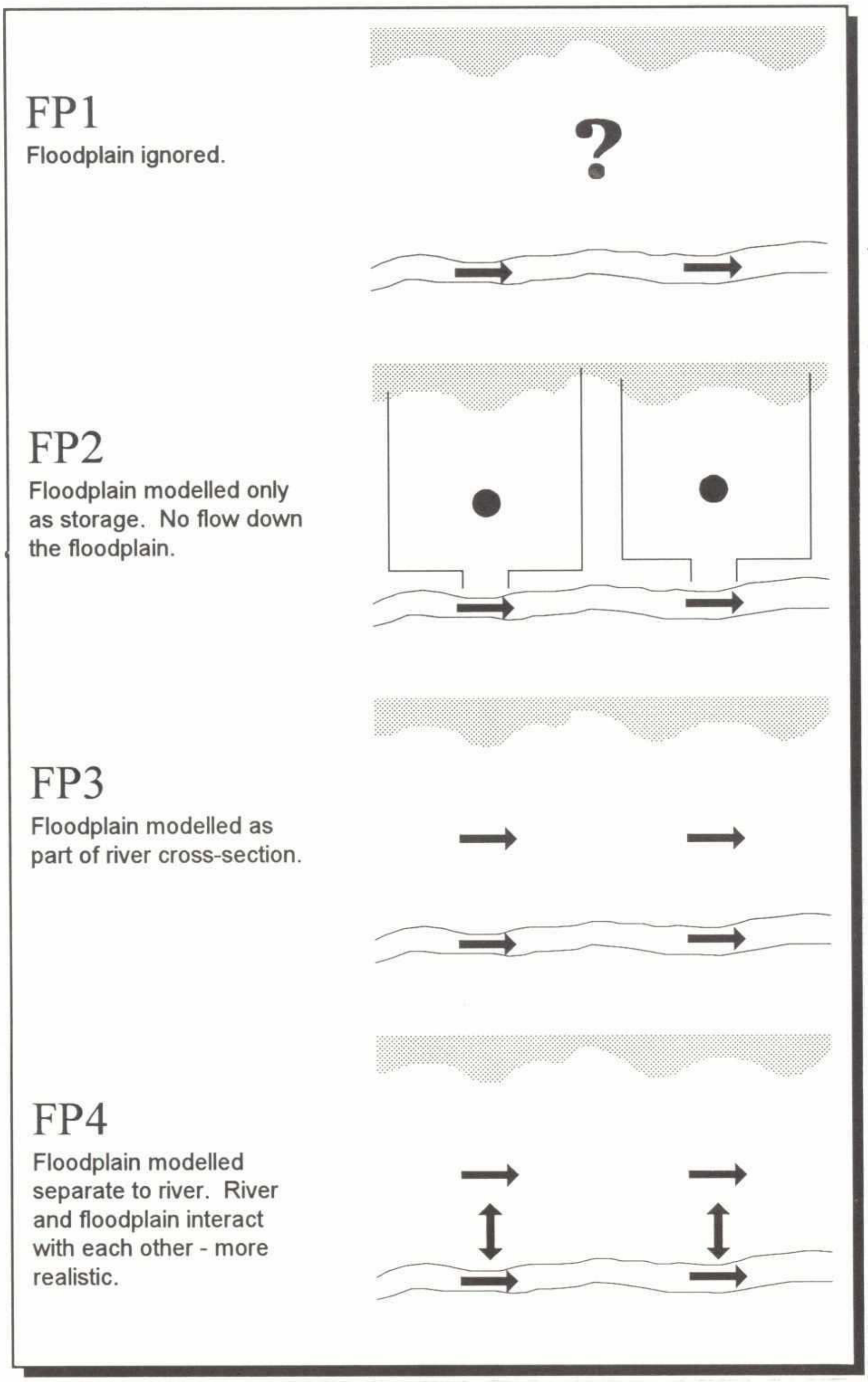
Topographic Data	FP1	FP2	FP3	FP4
River Cross-Sections	Yes	Yes	Yes	Yes
Floodplain Cross-Sections	No	No	Yes	Yes
DEM or Contour Maps	No	Yes	Optional	Yes

The different types of topograpic data required for Methods FP1 to FP4 are indicated in the table.



The four basic methods for modelling floodplains each have advantages and dis-advantages. A mixture of methods should be adopted according to resources and constraints; size and type of floodplain and project objectives.

The advantages and dis-advantages of the four basic methods for modelling floodplains may also be viewed by the flow interaction between river and floodplain.

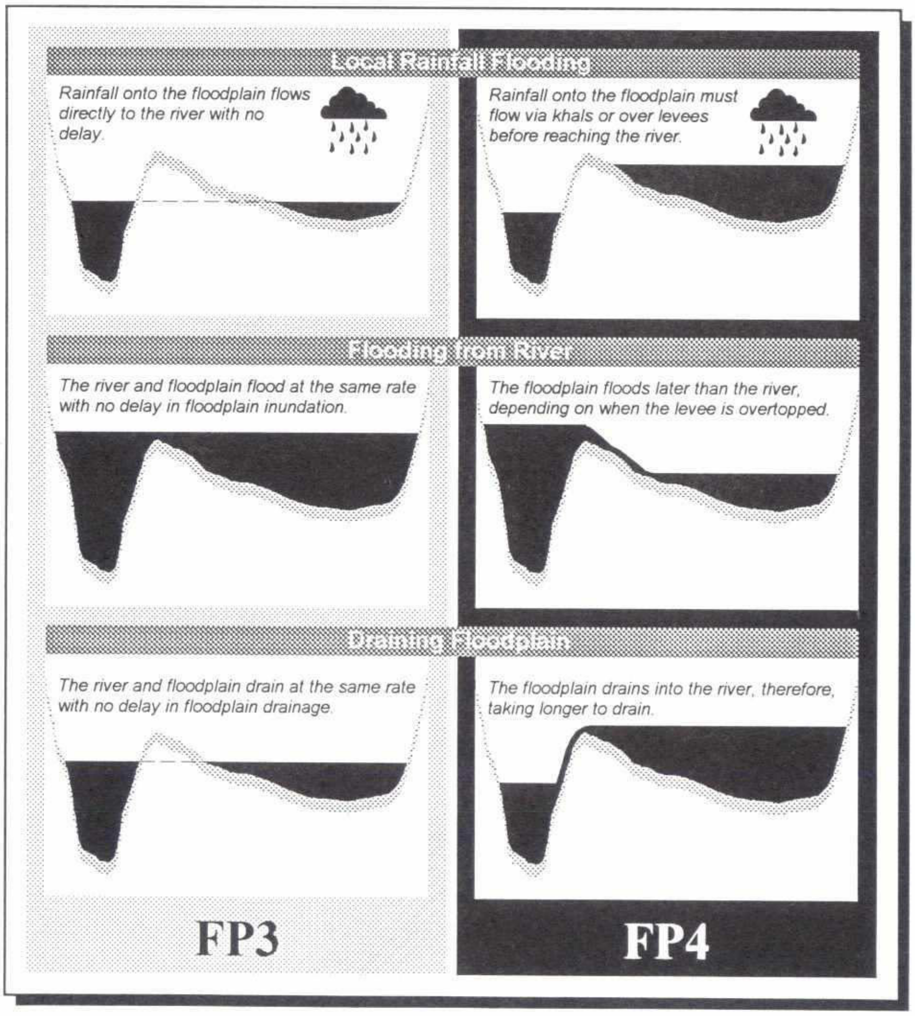


4.3.1 Modelling Inundation and Drainage

Modelling the different inundation and drainage modes is very important for designing FCD schemes which plan not only to prevent or control flooding, but to also drain flood waters. Of particular note is the time duration to drain flood waters for assessing agricultural impacts and other flood damages.

Methods FP1, FP2 and FP3 are not applicable for modelling the inundation and drainage modes unless the river level and floodplain levels are similar, ie. the floodplain fills and drains at the same rate as the river. This is because the river and floodplain are represented as one cross-section with one water level. For example, local rainfall will drain directly to the river without delay, irrespective of any natural or artificial controls.

FP4 models the river and floodplain separately and therefore is suited to modelling floodplain inundation and drainage. The dynamic interaction between river and floodplain is modelled using links which connect the river and floodplain.



Methods FP1, FP2, FP3 and FP4 yield different results when modelling floodplains. Being aware of the differences is an important part of flood modelling and management. Illustrated are examples comparing FP3 and FP4.

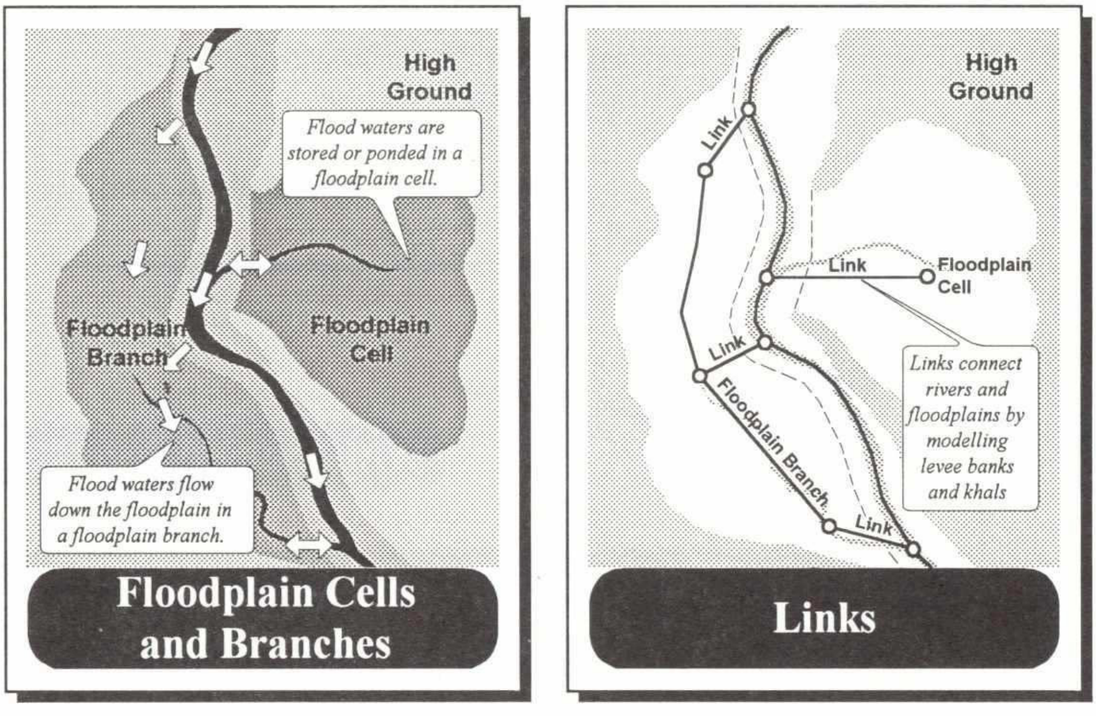
4.4 Floodplain Representation

The FP4 or quasi 2-D approach requires that floodplains are represented separately from the rivers. Unfortunately, floodplains, unlike rivers, do not always follow a defined course and are therefore more difficult to schematise. Floodplains also behave in a variety of ways, from simple storage basins to major conveyors of flood waters. Behaviour also varies depending on the height of the flood.

Floodplain cells receive, store and drain flood waters, but do not model conveyance (except via links). They must have one or more links with the river(s) to model the exchange of water between river and floodplain. Floodplain branches, like river branches, model flood storage and conveyance. A branch will have links at its upstream and downstream ends, and also along its length.

Links model the flow between river and floodplain. They play an important role in modelling floodplain inundation and drainage.

A link may be an embankment, a natural levee or a khal. Links can be lumped together to reduce the model size, ie. several khals and a river levee may be represented as one link. FCD structures may also be incorporated into a link.

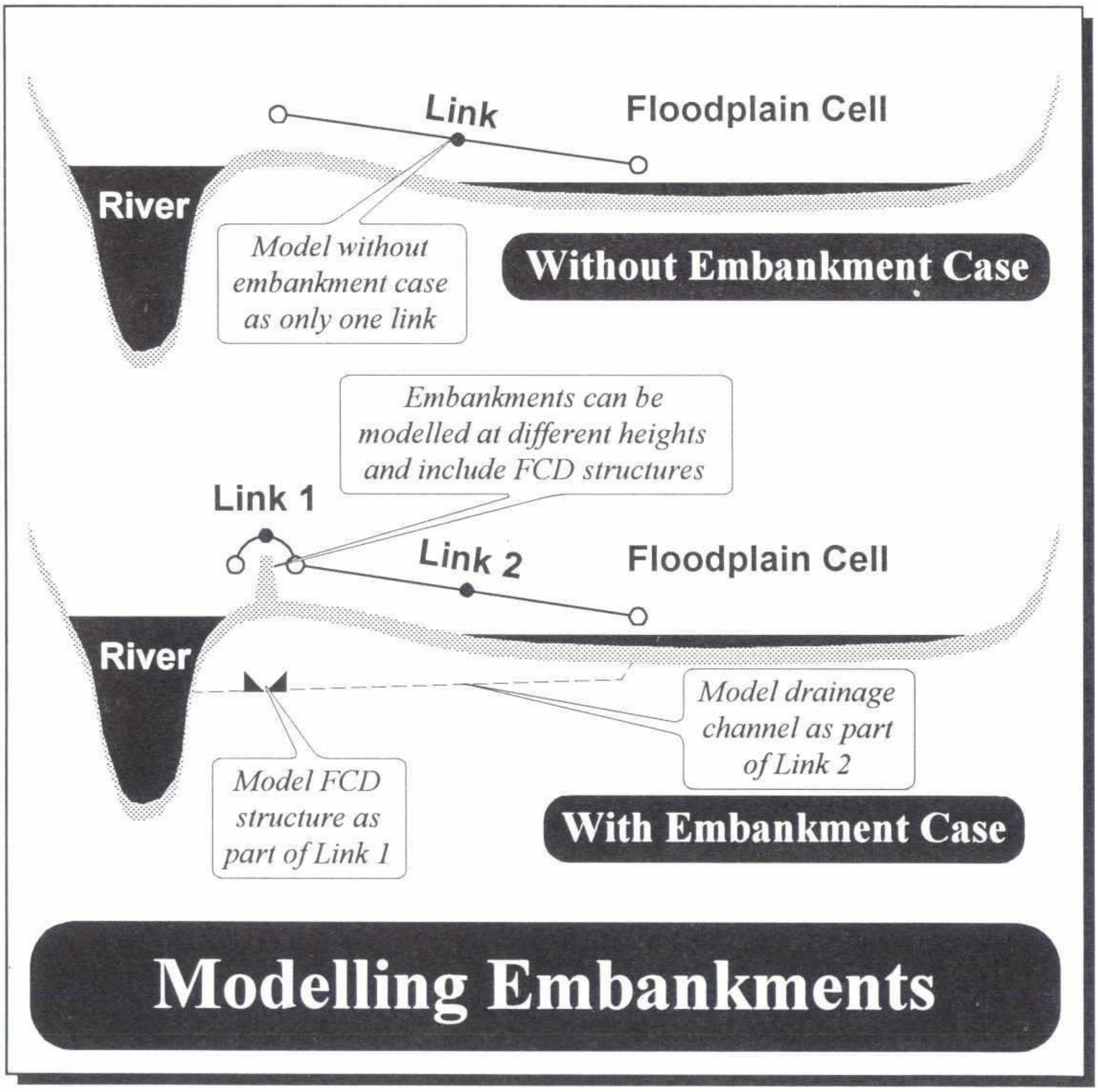


Floodplains are schematised as either a floodplain cell or a floodplain branch. Floodplain cells are backwaters or storage ponds, while a floodplain branch is a flood flow path. Links connect the rivers and floodplains. They model embankments, river levees, khals and drainage channels. FCD structures can also be included in a link.

4.5 Modelling Embankments and FCD Structures

Embankments and other artificial structures such as roads, which can be overtopped, require additional attention because of their small width. Also, embankments will have one or more FCD structures for control and drainage of flood waters.

The recommended approach is to use a separate link for the embankment (see figure below). Any structures located along the embankment can be modelled as multiple structures attached to the link.



Embankments are modelled as a very short link (Link 1), usually connected with another link (Link 2) onto the floodplain. FCD structures in the embankment can be included in the embankment link. The figure shows the difference for without and with embankment cases.

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4.6 Hydrometric Data Needs

To calibrate a flood model, hydrometric data - flood levels and discharges - are needed.

Where detailed floodplain modelling is required, flood level gauges on the floodplain should be installed in addition to the ones on the rivers. Selecting sites for floodplain flood level gauges can be difficult and should be based on advice from local people or by inspecting aerial photography or satellite imagery taken during a flood. Sites should be kept away from the immediate vicinity of structures, including openings along roads, to avoid localised hydraulic effects. Water bodies which are perched or isolated during flooding should also be avoided.

Flood levels must be taken throughout the course of the flood. At the peak of the flood, river and floodplain levels will often be similar, however, during the rising and falling stages significant differences can occur. This is very important when considering the duration of flood waters on the floodplain.

It is very difficult to measure discharges over the floodplain. This is not necessarily a serious problem, especially if good discharge measurements have been taken at several locations in the rivers. By comparing river discharges it is possible to ascertain whether flood waters have moved on to or off the floodplains. For example, if the discharge in a river appears to decrease significantly, then either there is more water flowing on to the floodplain or there is a problem with the accuracy of the measurements.

It is very unusual to find enough data to satisfy the needs of flood engineers. To minimise this problem, detailed data collection programmes should be carried out during at least one monsoon before the commencement of modelling activities.

An interesting new development in floodplain modelling is the use of radar imagery to verify flood extents. Radar imagery for the Tangail Compartment acquired during a pilot project carried out by FAP19, was compared with flood extent maps produced by MIKE11-GIS. The outcome showed good agreement between the images and flood maps (see Plate 11 in Chapter 5).

Based on the positive outcome of this exercise, radar imagery should, if possible, be incorporated in the model verification process.

5 FMM DEMONSTRATION

5.1 Introduction

Three pilot FMMs were developed and applied at national, regional and compartment levels to demonstrate applications in various flood management activities.

National FMM: A coarse FMM covering the major national and regional rivers.

NCR-FMM: A detailed FMM for the western part of the North Central Region.

TC-FMM: A detailed FMM for the Tangail Compartment Pilot Project (FAP20).

This chapter summarises the development and application of the three FMMs (full details are presented in Volume II).

The objective of the applications is to demonstrate capabilities and usefulness of FMM, rather than to produce definitive and accurate flood management plans. Except in the case of Tangail Compartment, the flood management scenarios tested are hypothetical. However, it is expected that these demonstrations will provide sufficient guidelines for the application of dedicated FMMs.

5.2 National Level FMM

The national level FMM was developed and tested based on the SWMC General Model, and GIS data supplied by FAP19. It shows the capability for producing flood maps for the greater part of the country, and providing statistical information for regions and local government administrations.

However, the National FMM is limited in its applicability for flood mapping. The General Model, which was designed to supply boundary data for regional models, only produces flood levels along the major rivers, with only a rough representation over the floodplain. Therefore, flood mapping in areas where river and floodplain levels differ will be inaccurate, and should not be used for detailed consideration. Also, flooding from localised rainfall cannot be mapped.

This is not to say that no useful output can be obtained. In the case of a flood peak, when river and floodplain levels are probably very similar, an FMM flood map may be indicative of the real situation.

Several flood depth maps were produced at different stages of the 1988 flood. Plate 7 shows the flood depth map on August 29, near the peak of the flood.

A demonstration of the potential usefulness of the National FMM for planning was performed by modelling the impact on flood levels of an embankment along the left bank of the Jamuna River. However, the output cannot be considered definitive because of the coarse nature of the General Model. An interpretation of the output is provided in Volume II.

A close linkage with FAP10 (Flood Forecasting and Warning Project) was to be established to initiate possibilities for deriving off-line relationships between river levels and floodplain inundation to be used in conjunction with real-time flood level forecasting.

The next phase of FAP10 was planned to start during the course of FMM, but is now expected to start after the completion of FMM. Therefore, any close collaboration with FAP10 was impossible, although close relations with BWDB's Flood Forecasting and Warning Centre were pursued.

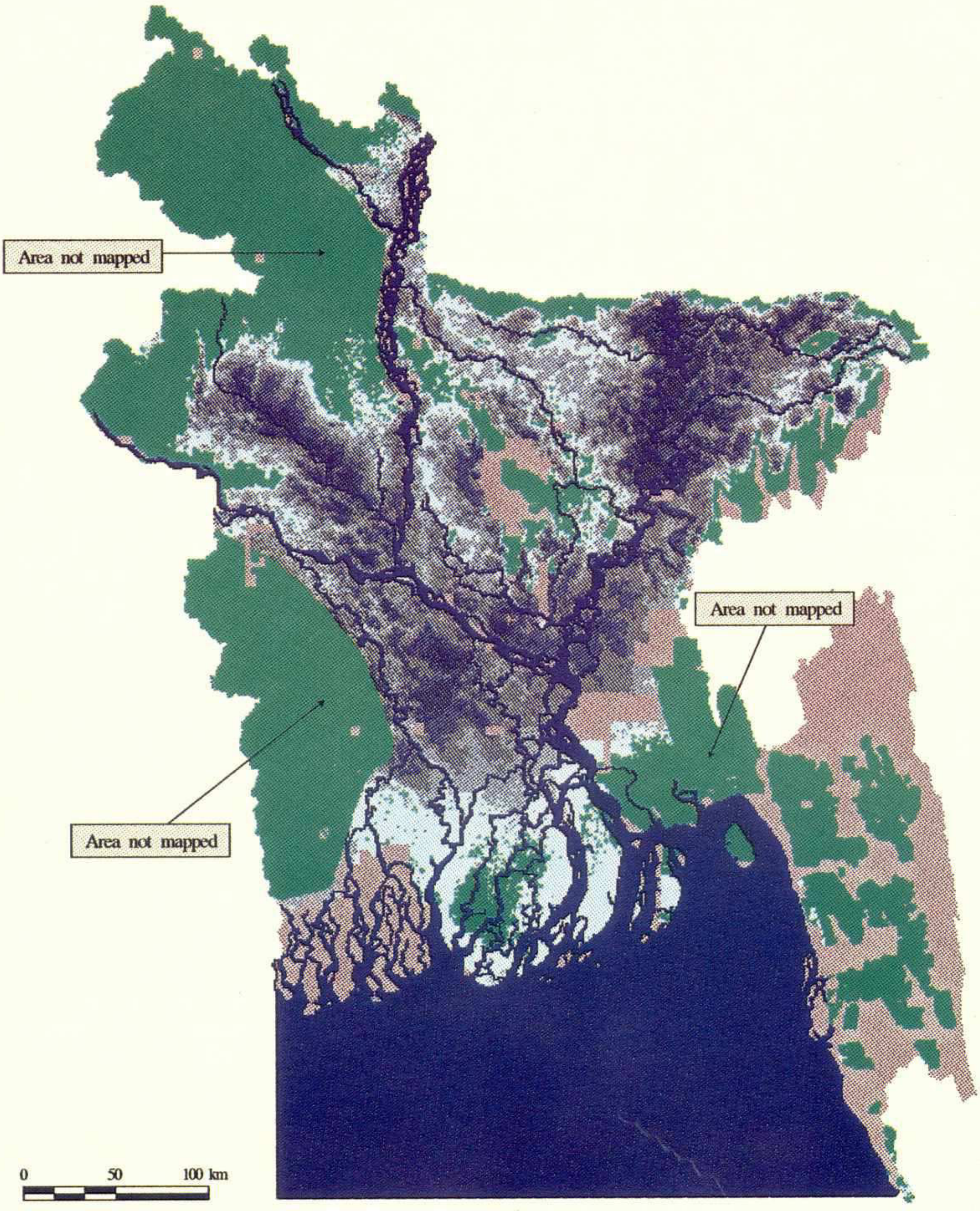
Also, the modelling approach in the next phase of FAP10 has recently been revised by a Danida appraisal mission. The modelling activities will concentrate on flood inundation mapping for selected sub-regional pilot areas rather than at a national level. To help in this regard, a flood forecasting exercise was carried out for the regional level FMM.

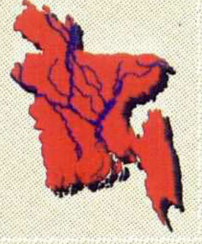
The regional level FMM flood forecasting exercise showed computers are now sufficiently powerful to simulate a flood forecasting model and produce FMM flood maps in real-time, therefore removing the need to derive off-line relationships.

In conclusion, the National FMM is functional and usable, but limited in its accuracy. Since the General Model is too coarse on the floodplains to adequately model changes in floodplain flood levels due to structural interventions, the National FMM cannot be used with confidence as a general planning tool. From the viewpoint of FMM, the General Model should be used solely to provide boundary conditions to regional models.

The recommendation is that no further development should be carried out at the national level in the immediate term. However, with the advent of more powerful computers, a General Model of Bangladesh with much more detail on the regional rivers and floodplains will be viable in the future. A National FMM requires a General Model of this complexity if it is to be useful as a flood management tool.

National Simulated Flood Depths - August 29, 1988





Depth (m)

- 0.00 – 1.00
- 1.00 – 2.00
- 2.00 – 3.00
- 3.00 – 4.00
- 4.00 – 5.00
- Above 5.00
- Flood Free or Not Mapped
- No DEM Data

5.3 Regional Level FMM

The regional level FMM was based on the Surface Water Modelling Centre's North Central Regional Model (NCRM), and GIS data from FAP19. A brief programme of hydrometric data collection and embankment surveys during 1993 was carried out to supplement the existing data.

The existing SWMC NCRM needed restructuring in order to correspond better with the actual situation found in the North Central Region. The original model from SWMC included floodplains, but modelled them as an integral part of the river cross-section (see Methods FP2 and FP3 in Section 4.3). This description would not permit the proper simulation of floodplain inundation in most of the western part of the North Central Region, where water levels on the floodplains can differ from those in the river.

Only the western half of the SWMC regional model was restructured for use in the development of FMM using the DEM supplied by FAP19. The DEM for the eastern part was not available in sufficient detail to permit sensible flood mapping. The major boundary rivers Jamuna, Padma, part of the Ganges and part of the Upper and Lower Meghna were included in the revised model to enable flood mapping of the active floodplains of these rivers.

Much of the initial effort for the regional applications was devoted to additional data collection in support of the restructuring process. A supplementary programme of hydrometric data collection and embankment survey was carried out prior to and during the monsoon of 1993. This information was used to support the initial calibration of the restructured model. Boundary conditions for the FAP25 NCRM for the years 1988 and 1993 were supplied by the General Model.

Using the NCR-FMM, flood depth maps were produced for the North Central Region based on the years 1988 and 1993. These two years were chosen as they were considered to represent high flood and "normal" flood conditions respectively. These flood depth maps are included as Plate 8 and show the extent of flooding for each year near the peak of the flood.

To demonstrate the effects of various structural options, the concept of compartmentalisation was used. This concept includes most structural elements required to be modelled, such as embankments, gates, weirs, drainage channels and overspill structures. Application demonstrations were set up on a sub-area of the NCR located in the south west of the region. This area was selected because the layout of the rivers and floodplains was particularly suited to the concept of compartmentalisation.

Flood depth maps based on the "without project" situation were made for two historical years (1988 and 1993). Changes were then made to the MIKE11 model setup to simulate the effect of compartments located between the Kaliganga, Dhaleswari and Bangshi South Rivers, inflow to the compartments being controlled by gates located in the surrounding embankments. Flood maps were then made for the "with project" case. The specific changes in flood level were mapped to visually compare the two situations. Plate 9 shows the "without project", (upper left), and "with project", (upper right), flood depth maps, with the impact on flood levels map below.

As an extension of the compartmentalisation theme, the effects of a breach in a compartment embankment was simulated and the resulting flood depths and impact on flood levels mapped (see Volume II).

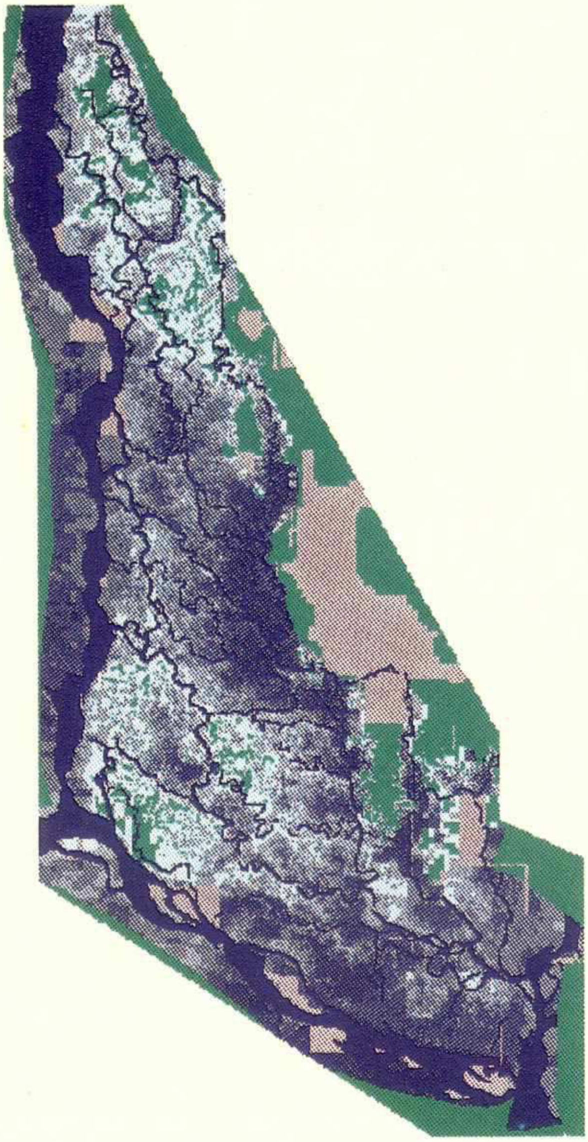
To further illustrate the interpretation of flood maps, a simulation was made of the effects of a major embankment along the left bank of the Jamuna and Dhaleswari. The resulting impacts shown (see Volume II) are discussed and explained, showing how a thorough understanding of the hydraulic processes are required for correct interpretation.

The delay in start-up of the next phase of FAP10 has prevented close collaboration on the flood forecasting potential of a regional FMM. Nevertheless, using the real-time outputs of the General Model flood forecasting model as inputs to the regional model, the potential for mapping predicted inundations was demonstrated (see Volume II).

Flood mapping using statistical envelopes of 25 historical floods was carried out to illustrate the potential for using FMM for flood zoning based on frequency and depth of flooding (see Volume II).

Regional level FMM application was shown to be practical and the results applicable at a level associated with planning and pre-feasibility studies. The present hardware limitations exercise an upper limit on the amount of detail that can be sensibly included in the regional model and the user must be aware of the implications of this in interpreting the resulting flood maps.

NCR Simulated Flood Depths - 1988 and 1993



September 3, 1988 | September 7, 1993

0 20 40 km

Depth (m)

0.00 – 1.00	4.00 – 5.00	Flood Free
1.00 – 2.00	Above 5.00	No DEM Data
2.00 – 3.00		
3.00 – 4.00		

Compartmentalisation Impact on Flood Levels - 1988

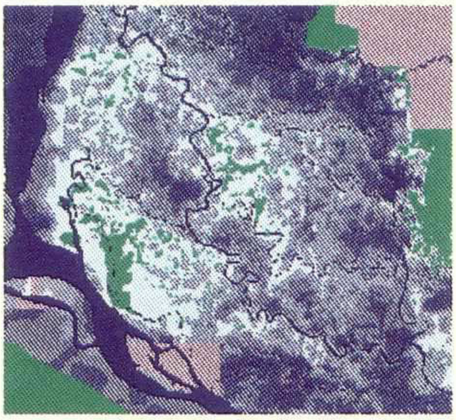
Depth (m)
- 0.00 – 1.00
- 1.00 – 2.00
- 2.00 – 3.00
- 3.00 – 4.00
- 4.00 – 5.00
- Above 5.00
- Flood Free
- No DEM Data

Flood Level Change
- None/Slight

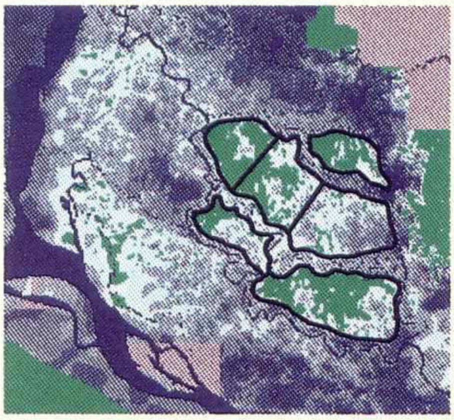
Increase (m)
- Above 0.50
- 0.40 to 0.50
- 0.30 to 0.40
- 0.20 to 0.30
- 0.10 to 0.20

Decrease (m)
- – 0.10 to – 0.60
- – 0.60 to – 1.10
- – 1.10 to – 1.60
- Below – 1.60

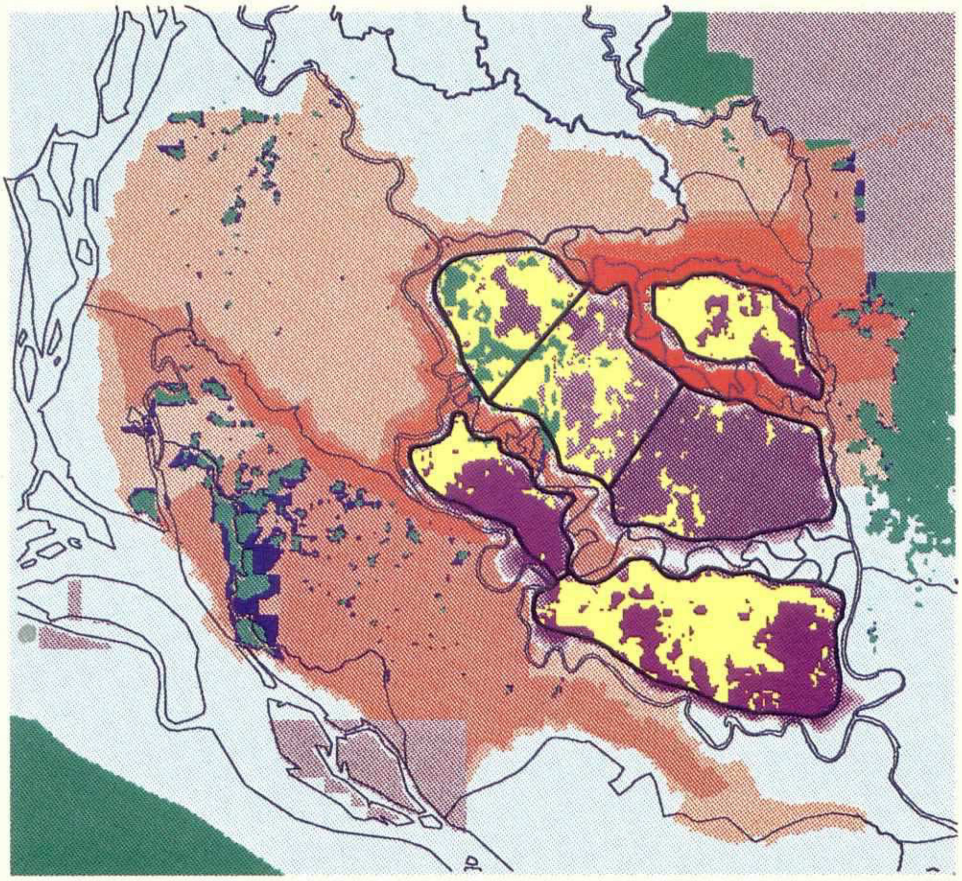
- Now Dry
- Now Wet
- Flood Free
- No DEM Data
- River
- Compartment



Without Compartments
Maximum Flood Depths



With Compartments
Maximum Flood Depths



0 6 12 km

Maximum Change in Flood Level
(Red shades show an increase in flood level
Purple shades show a decrease in flood level)

5.4 Compartment Level FMM

The compartment level FMM was based on the FAP20 Tangail Compartment Model (TCM), GIS data from FAP19, and GIS data produced by FAP25. The model was revised using FMM tools to include recent survey information from FAP18, and additional channels were included and existing cross-sections adjusted based on recent surveys. The north-western part was further detailed to include internal structures to control water levels on a chawk level.

The floodplains contribute little to the movement of water through the compartment, but act as off-stream storage via the khal system. The revised TCM has reflected this by modelling the floodplains as additional storage areas (see Method FP2 in Section 4.3). FMM software was used for extracting flooded area versus elevation data from the DEM built from the FAP18 survey data. The new area elevation curves have improved the accuracy of the model.

General FCD structure operation guidelines and target water levels within compartments were supplied by FAP20 and incorporated into the TCM. The 1987, 1991 and 1993 flood events were used for flood and impact mapping. Plate 10 illustrates flood depth maps in June and September of the 1991 flood, clearly showing the depth and extent of the flooding in each sub-compartment.

A flood extent map produced for July 24, 1993 was compared with radar imagery acquired by FAP19 for the Tangail Compartment for the same date. Plate 11 presents the flood extent map and the radar image.

Comparisons between the with and without project situation were made using maps showing impacts on flood levels and flood phase (see Volume II).

The north-western part of the TCM was detailed to include internal structures to control water levels at chawk level. For the internal outlet structures and the peripheral inlet structures the same general operation rules were applied as for compartment structure operation.

The performance of the structure operation rules to control water levels within pre-defined target ranges was mapped to show areas where further improvement is required. Plate 12 shows the areas maintained within the target range as blue, those where the water level exceeds the target range in red, and below in yellow (green areas are not flooded). From the middle of June to the end of August, 1993, water levels in most of the western chawks are successfully maintained within the target range. However, the dominant red areas in the eastern chawks indicate the structure operation rules for these areas may require revision.

The demonstration of FMM at compartment level presents the opportunity to illustrate its possible use for agricultural damage mapping. This type of mapping introduces the effects of flood duration and depth, together with crop damage criteria. While rigorous analyses of this type require specialist input, the compartment application demonstrates the potential of FMM for this purpose. Plate 13 illustrates indicative crop damage maps for without and with project conditions for two half-monthly periods in July and August during the 1987 flood. The plate shows a significant reduction in crop damage as a result of the project's interventions.

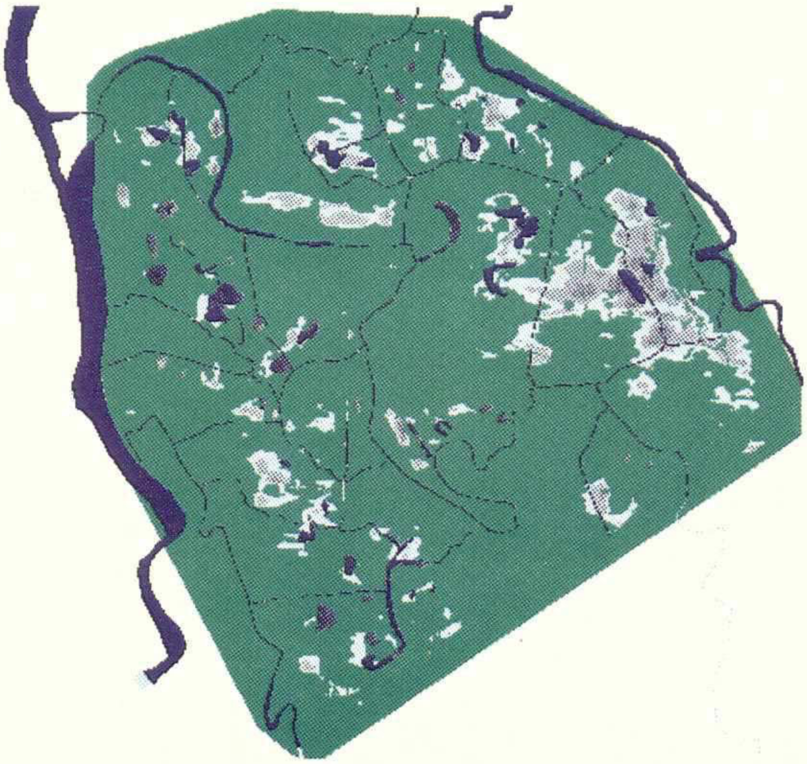
A dedicated FMM for the Tangail Compartment has been developed and its applications demonstrated. It is clear that FMM at this level of detail provides significant enhancement in the understanding and visualisation of flood characteristics. It will be of particular help in public participation exercises, which seek to convey complex processes in the simplest and most easily understood way.

Sub-compartment (chawk level) scale modelling allows much detail to be represented, since data collection is generally over a limited area and may be done in detail without the commitment of the large resources that would be needed at, say, regional level.

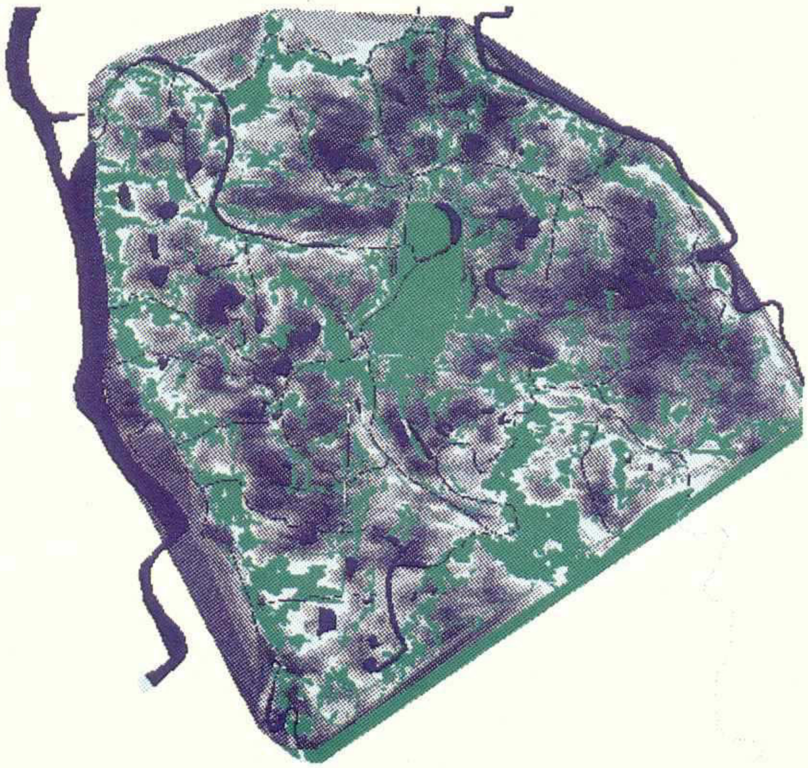
TC Simulated Flood Depths - 1991

Depth (m)

- 0.00 – 0.30
- 0.30 – 0.60
- 0.60 – 0.90
- 0.90 – 1.20
- 1.20 – 1.50
- 1.50 – 1.80
- 1.80 – 2.10
- Above 2.10
- Flood Free



June 14, 1991

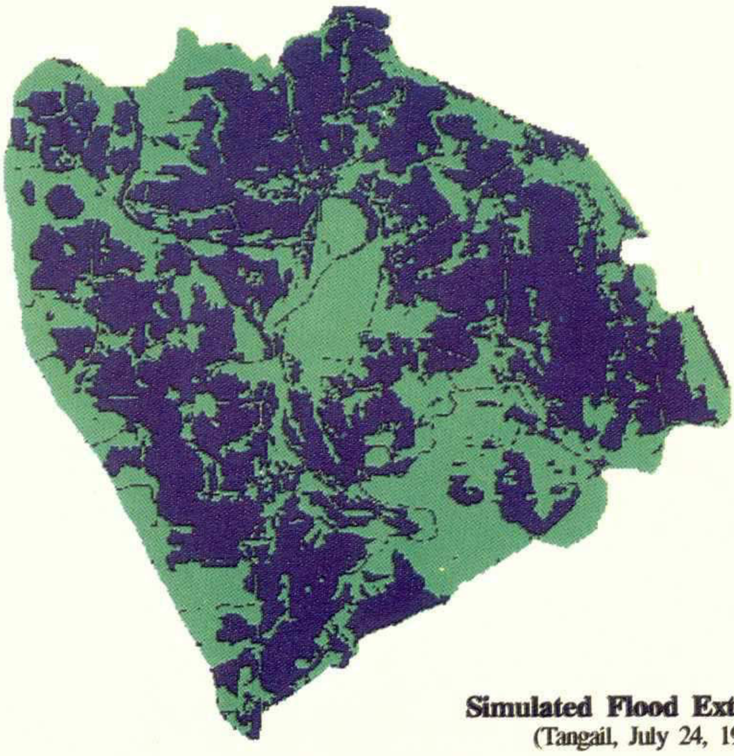


September 13, 1991

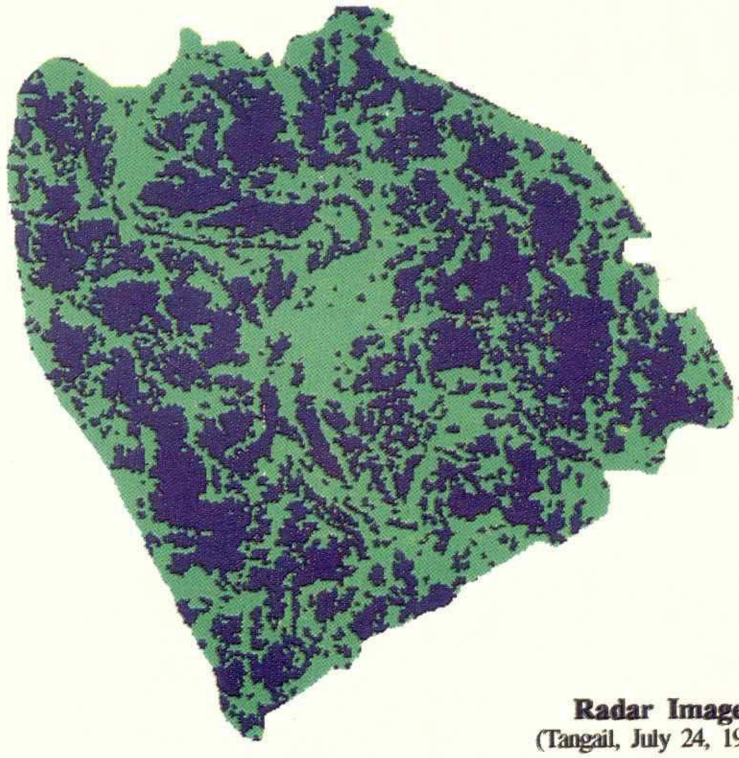
TC Radar Imagery for Flood Extent Verification

Flood Free

Flooded



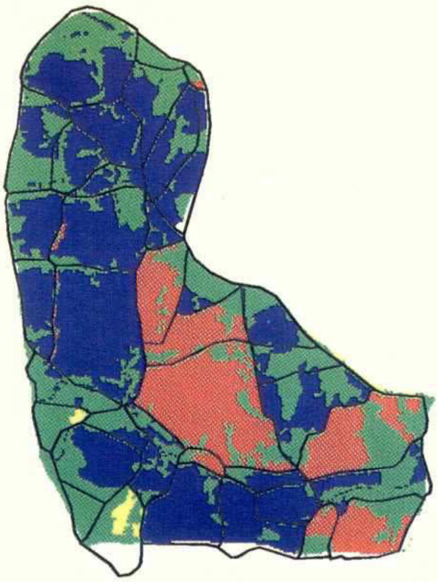
Simulated Flood Extent Map
(Tangail, July 24, 1993)



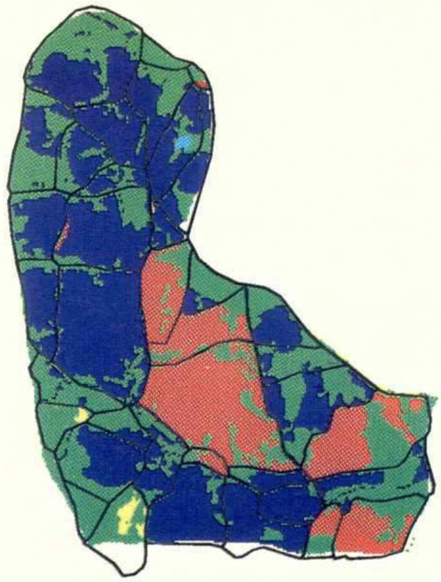
Radar Image
(Tangail, July 24, 1993)

0 1.5 3 km

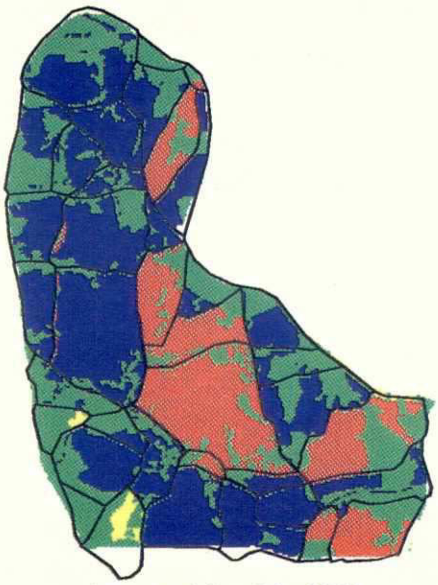
TC Structure Operation Performance - Chawk Level



July 16 - 31, 1993



August 01 - 15, 1993



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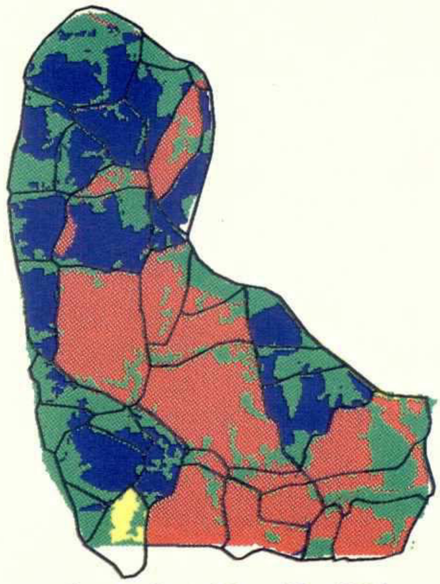
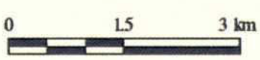


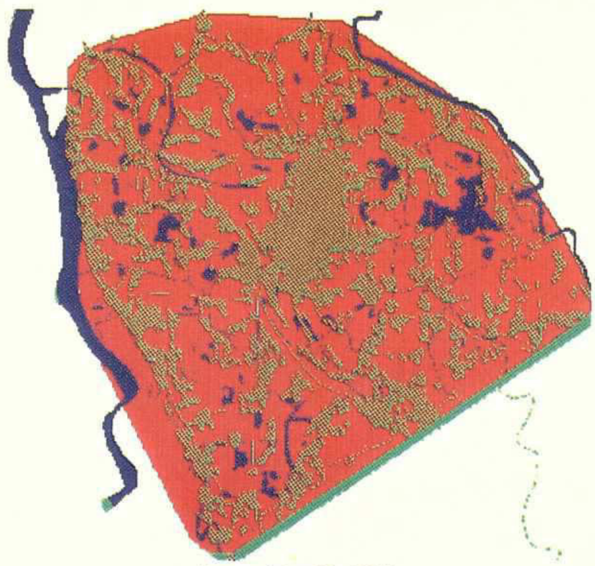
September 01 - 15, 1993



- Flood Free
- Water level below target range
- Water level maintained within target range
- Water level exceeds target range
- — Chawk Boundary

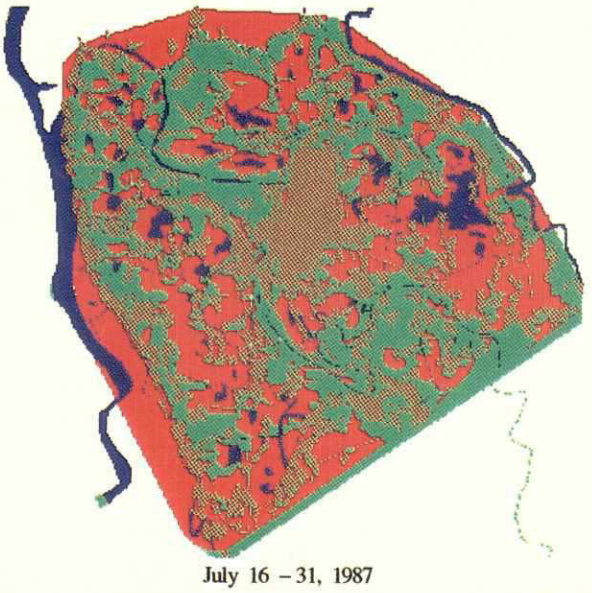
Tangail Compartment - Crop Damage - 1987

July 16 – 31, 1987

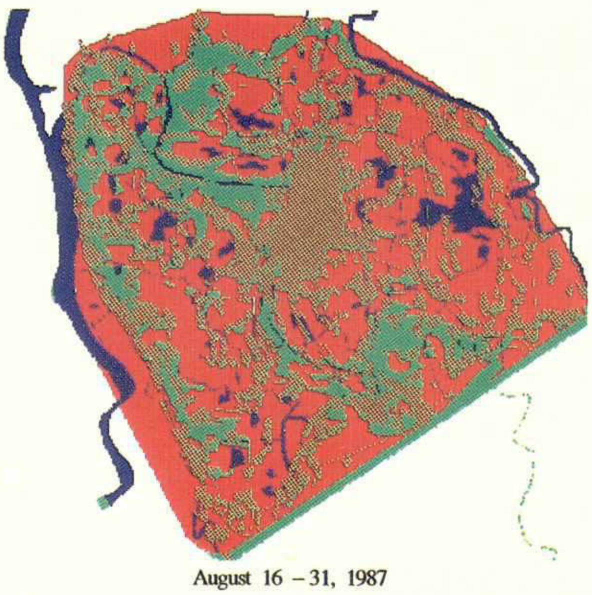


August 16 – 31, 1987

Without Project



July 16 – 31, 1987



August 16 – 31, 1987

With Project

0 3 6 km

- No Damage
- Crop Damaged
- Crop not Planted
- Settlement/Township

Note: A crop is defined as damaged if it is inundated for more than 3 consecutive days at a depth greater than its critical depth. The critical depth is defined for half-monthly periods based on the crop's growth rate and resistance to flooding.

The crops are based on a HYV T.Aus rice crop planted throughout the compartment. Critical depths and other criteria are from TANGAIL CPP INTERIM REPORT (Annex 2: Agriculture).

6 TECHNOLOGY TRANSFER

6.1 Introduction

The future success of FMM is largely dependent on building confidence in its performance and a sound level of local expertise. A major objective of the FMM study was therefore the education and training of local professionals.

While the main scope of the project was to develop the FMM concept and tools and to demonstrate FMM applications, the educational aspect of the technology transfer process was also given suitable emphasis throughout project. This is of critical importance if future users are to understand and utilise the capabilities and limitations of FMM.

This chapter briefly describes the various technology transfer activities carried out.

6.2 Workshops

The TOR provided for organising three workshops during the study. The first workshop was conducted at the end of the inception phase to present the FMM concepts to a wide target group and to assess user needs in flood management (see *FAP25 - Flood Management Model Interim Report I*). The second workshop was conducted at the end of the development phase to present the general developments to government authorities and other potential users with a view to identifying necessary modifications. The third and final workshop is being organised to demonstrate the FMM.

From the above target groups a specific list of key persons and officers of governmental and non-governmental agencies, local and international consultants was prepared for inviting participants to the workshops.

The first workshop to present the FMM concept and assess user needs was held on February 9 and 10, 1993. The activities of the two-day workshop were to:

- develop an understanding of the present modelling capabilities and identify the needs and targets of FMM in relation to flood management decisions in Bangladesh.
- present the FMM concepts and logic, review the draft inception report and obtain feedback.
- provide an opportunity for dialogue among decision makers, potential FMM users, and individuals affiliated to government, non-government and research institutions.

A total of 61 participants from various organisations such as MIWD&FC, SPARRSO, BMD, LGED, RHD, DOE, BARC, DAE, IFCDR, RRI, WARPO, SWMC, BWDB, FPCO, POE/FPCO, CAT, FAP consultants, NGO representatives, donor representatives and FAP25 officials participated.

The second workshop was conducted on November 14, 1993. The main objectives were:

- to present the FMM features developed so far to relevant GOB authorities, FPCO panel of experts, CAT members, consultants, NGOs, university professors and other potential users.

- to obtain feedback for improvement and inclusion of new features (if any).

The workshop was attended by a total of 72 participants from government and non-government organisations, consultants, university professors, FPCO panel of experts, CAT members and donor representatives.

A majority of the participants were engineers working in planning and design and a few had some experience in hydraulic modelling. A large proportion of the participants had attended the first workshop.

The third and final workshop will be conducted on October 20, 1994. The FMM demonstrations and applications carried out by the project will be presented to participants who have attended the first and second workshops.

The proceedings of this and the previous two workshops will be documented after the workshop.

6.3 FPCO Training Course

Following the recommendations of the first workshop, FPCO requested Danida to support an 8 weeks training course on flood modelling and management. This course was conducted by FAP25 with additional resources provided by Danida. The participants included six senior staff of FPCO, two engineers from the Flood Forecasting and Warning Centre of BWDB and three GOB engineers from SWMC.

The training course on Flood Modelling and Management consisted of 4 modules:

Module I: Flood Modelling - 2 weeks:

Module II: Geographic Information System (GIS) - 2 weeks:

Module III: Flood Management Model (FMM) - 2 weeks:

Module IV: Applications of FMM - 2 weeks:

The project staff conducted the training course. Practical exercises were given and extensive hands-on-practice using computers was emphasised. Each course module was concluded with final discussions involving both the theoretical and practical aspects of flood management in Bangladesh. Participants were asked to comment on the course content as well as to evaluate the course. Feedback received from the participants was used to develop further FMM software.

The junior GOB trainees are now sufficiently exposed to the advanced modelling tools and will be able to judge the capabilities and limitations of various approaches in their future activities. It is believed that this training has played a key role in technology transfer.

6.4 On-the-job Training

While due recognition must be given to the effectiveness of the formal training to the local staff of FAP25 during the FPCO training course, the most important component was "on-the-job" training. This was in recognition that many of the practical aspects of modelling for flood management cannot really be imparted in a formal training session.

While two local staff members were directly involved in developing the FMM software, others were regularly exposed to the FMM development process. Regular interactions between "FMM developers" and "FMM in-house users" took place during both the development and application phases. Local staff were taught to interpret the model output carefully and use engineering judgement before accepting the computer results. The importance of input data quality on the output as well as the limitations of the model was always emphasised.

Regular progress review meetings were held throughout the project to monitor and guide the project activities. These meetings, which were attended by all professional staff (local and expatriate), served not only as a forum for reviewing progress in an administrative sense, but also for free discussion and resolution of technical issues and the exchange of ideas among staff members.

To ensure technology transfer, the expatriate experts (long-term and short-term) always worked together with local experts. To complete a project task, inputs of both were required. Confidence building through achievement was another essential aspect of on-the-job training.

In addition to the technical activities of the project, local staff were trained in giving presentations (workshops, demonstration), training, discussion with external agencies (consultants, review missions, etc.), preparation of papers, etc. Day-to-day maintenance of computer hardware, keeping an up-to-date knowledge of computer software were some other examples of on-the-job training. The local staff were also taught to keep a systematic "log" of model simulations, software problems (bugs), etc. On-the-job training has played a key role in the concept of integrated technology transfer in this project.

6.5 Advanced Training and Study Tour

A group of senior, mid-level and junior staff members of FPCO were sent to DHI head office in Denmark and the Asian Institute of Technology (AIT) in Thailand for a total period 13 days. In DHI, the trainees were given exposure to advanced flood modelling techniques. Examples of model application around the world were shown. They discussed various aspects of modelling with senior staff members of DHI. They were taken to study the real-time weather forecasting activities of the Danish Meteorological Institute. The participants were shown the advanced measurement techniques in the Great Belt link project. They also visited the Institute for Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark, and through a visit to VKI Water Quality Institute were introduced to the environment modelling capabilities of MIKE11 and environmental impact assessment methods.

During their two days visit to AIT the participants reviewed flood studies conducted in other countries. They were exposed to various facilities of AIT including the hydraulic laboratory, Continuing Education Centre, GIS and remote sensing facilities. A seminar was given by FPCO on Bangladesh Flood Action Plan, which was attended, among others, by AIT international faculty and students, Thai Government officials and experts from the Mekong Secretariat. The discussions following the seminar provided an opportunity for interchanging ideas on flood mitigation activities and related environmental impacts. The FPCO staff benefited from the wide ranging interaction with the international group of experts. In turn, the AIT community learnt, first hand, about the practical problems associated with the floods of Bangladesh and the Flood Action Plan. It is hoped that this interaction will stimulate future research on floods and flood management in Bangladesh.

6.6 Demonstrations

The FMM tools developed at FAP25 were demonstrated from time to time to GOB officials, SWMC staff, FAP consultants, CAT members, FPCO panel of experts, faculty and students from BUET, donor representatives, review missions of various projects, and other visitors to the project office. Standard demonstrations were prepared by the project to highlight the various activities. Application examples were also demonstrated to obtain feedback.

Further demonstrations are planned to be carried out for organisations such as BWDB and WARPO during the transfer and training period of FMM (see Section 7.5).

Papers based on the FMM project were presented at local and international conferences by the local and expatriate staff of the project.

6.7 Future Training

FMM being a new concept and tool, requires that future users are properly trained. While users will develop full modelling skills only after working on an application project, a formal training course is extremely useful for understanding the basic concepts.

The *MIKE11-GIS Training Manual* was prepared by the project as the basic document for training. It guides both the trainer and trainees systematically through the various processes of applying FMM. The *MIKE11-GIS Reference and User's Guide* and *MIKE11-GIS Menus* provide the technical and non-technical details of applying and using FMM software.

Based on the experience gained by FAP25 in the development and initial use of FMM, the following suggests an appropriate curriculum for an in-depth training course for future FMM users.

Module 1: Geographic Information System (GIS) - 3 weeks

1. Introduction to GIS and ARC/INFO: Components of GIS; basic functions; representing GIS features; topology; basic ARC/INFO commands; digitising; attribute data and tables.

2. Database Design and Relational Databases: Constructing a database; displaying the data; designing and creating a map; database query and analysis; relational databases.

3. Customising ARC/INFO: ARC macro language; menus; automatic procedures.

4. Advanced Features: Geographic analysis; surface analysis; spatial modelling.

Module 2: MIKE11-GIS - 3 weeks

1. Introduction: Introduction to MIKE11-GIS; role in flood management; preparation for applying MIKE11-GIS.

2. Interfacing a MIKE11 model: Using an existing MIKE11 model and a series of exercises, show how MIKE11-GIS is applied in the first instance; creating MIKE11-GIS coverages; producing flood maps.

3. Modelling Floodplains: Using MIKE11-GIS for developing MIKE11 models with the emphasis on modelling floodplains; different methodologies for modelling floodplains; techniques for computing floodplain storage; extracting floodplain profiles; quasi 2-D modelling.

4. Mapping Flood Impacts: Using MIKE11-GIS as an impact assessment tool; producing impact on flood levels maps; duration depth maps; guidelines for using these maps for flood damage assessments on other sectors such as agriculture.

Module 3: FMM Application - 2 Weeks

1. Case Studies: Review of regional and compartment applications produced by FAP25-FMM; testing hypothetical scenarios.

2. Pilot Study: Setting up an FMM based on a SWMC model.

7 INSTITUTIONALISATION

7.1 Introduction

Like the SWMC MIKE11 models, FMM and its applications must be maintained, improved and upgraded over time as a result of user experiences and demands, new and improved modelling, and computer software and hardware advances. New FMM users must be trained and supported during their FMM applications.

The TOR provides for an institutional framework for continued development, maintenance and application of FMM beyond the FAP25 project. Based on preliminary discussions with personnel carrying out studies on institutional issues and from other organisations, recommendations for FMM institutionalisation have been made.

7.2 Potential Users

A list of potential FMM users and activities is provided in the table below.

User	Purpose
WARPO	Strategic planning.
SWMC (RRI)	Upgrade existing regional models; develop more detailed sub-regional models; present output as flood maps.
BWDB	Area inundation forecasting; planning and impact assessments; design; operation and maintenance.
Disaster Management Bureau	Planning flood relief operations; flood damage assessments; information dissemination.
FPCO / FAP	Planning, feasibility and design of schemes.
Fisheries	Impact assessments on fisheries.
Agricultural Research Institutes	Crop damage assessments; crop planning.
LGED	Rural road planning.
Dept. of Roads, Highways and Railways	Road and rail planning.
Dhaka Municipal Corp.	Flood damage assessments; floodplain zoning.
Rajuk	Urban development planning.

7.3 Surface Water Modelling Centre

The Surface Water Modelling Centre (SWMC) under the River Research Institute (RRI) was established to initiate and ultimately institutionalise the local modelling capabilities through the Surface Water Simulation Modelling Programme (SWSMP). The modelling activities in Bangladesh evolved out of requirements identified in the National Water Planning Project under the Master Plan Organization in 1985 to account for the surface water availability in Bangladesh. The first phase of SWSMP ran from 1986 to 1988.

The four year second phase of the programme (SWSMP-II from 1989 to 1993) concentrated on the development of very large models for regional and national planning. At the end of SWSMP-II many well calibrated models of important national and regional river systems have been developed together with a group of engineers who are skilled in hydrologic and hydrodynamic modelling and the other related activities such as field measurements and data collection.

The Surface Water Simulation Modelling Programme entered its third phase on January 1, 1994. In this new phase it is intended to re-orientate SWMC towards becoming an institution which can sustain itself through its own efforts. Over the next three years the SWMC will gradually shift the focus of its activities away from carrying out the tasks described in its donor-financed work programme towards the long-term goal of providing services to paying clients.

The models from SWMC are essentially planning tools used to evaluate the effects of engineering works. However, in the management of flood prone areas, two of the highly time consuming and difficult tasks are delineating flood prone land from flood free land, and examining the impact of alternative flood mitigation and flood protection measures on flood levels and therefore flood extent.

The output from SWMC models gives the variation of water levels and flows in time. The models do not indicate directly detailed areas and depths of inundation. Such information is vital for proper flood management, the aim of which would be to minimise flood damage, including loss of life, property, crops and other consequential effects resulting from various types of river floods or direct rainfall.

7.4 FMM Institutionalisation

The FMM development in FAP25, associated with a high level of "outreach" activities in the form of workshops and training sessions, has generated considerable local expertise for the continuation of FMM activities in Bangladesh. However, for the sustainability of the FMM it is essential that a proper institutional framework exists for this expertise to be retained and developed further.

The greater data needs of FMM also needs to be considered within an institutional framework. DEM data and GIS coverages will typically be acquired on a project by project basis, but will need to be archived for future use. Data which varies significantly from year to year, such as: hydrometric data in the rivers and floodplains; satellite imagery of flooding; and surveys of river cross-sections which are subject to significant morphological changes, need to be collected annually for verification of MIKE11 models and FMM flood maps at a later date. While some of these data are being collected by government and non-government organisations, those which are not should be collected for FMM success and sustainability.

Developed by interfacing MIKE11 with a GIS, FMM is linked to SWMC technology, and most users of the SWMC models are expected to use FMM for pre and post-processing of data and results.

The logical institutional host for FMM after completion of FAP25 is SWMC, which maintains, distributes, supports and improves models in the same way as required for FMM. The participants of the Second FMM workshop as well as the Fifth CAT mission have strongly recommended the institutionalisation of FMM at SWMC.

SWMC is basically a service and consulting organisation capable of assisting many different users, as also required for FMM. It is likely in the future to rely on charging users for the provision of models and services (both public and private); FMM is a logical addition to the products of SWMC and one which in the long run may contribute significantly to its financial sustainability.

The question of sustainability and future institutional framework for SWMC and FMM has been discussed throughout the FAP25 preparation and implementation. A group of senior GOB officials is reviewing the general institutional structure of the water sector in Bangladesh, and no firm proposals have as yet been made. However, it appears that regardless of the overall structure to be adopted, SWMC will continue as an entity, located in Dhaka. The recommendation of placing FMM with SWMC is made under this assumption.

The FMM hardware and software, as well as some of the key technical staff of FAP25, can in principle easily be absorbed by SWMC. However, for SWMC to assume this new responsibility some short term support will be required, both in terms of facilities and additional training of key staff.

7.5 Transfer and Maintenance of FMM at SWMC

FMM training and the establishment of an FMM Unit at SWMC are required if FMM is to be transferred to SWMC. It is also recommended that one or more pilot FMM projects are initiated as part of the process of building up FMM expertise.

7.5.1 Training

A consolidated training program (see Section 6.7) of two months should be conducted for four SWMC staff. The training would be carried out by expatriate and local staff of FAP25 with additional input from GIS experts from outside.

The training course will follow a modular structure including the fundamentals of the FMM and its applications. Actual case studies will be taken during the training to develop dedicated flood management models. Examples of flood impact assessments will also be made.

7.5.2 Establishment of FMM Unit at SWMC

A dedicated unit/group to carry out flood management model activities should be established at SWMC. This unit will be responsible to undertake development of tailored FMMs on client request as well as apply the FAP25 transferred models in actual studies.

In addition to FMM itself, this unit will provide support to the hydrodynamic modelling group in refining the MIKE11 models. The topographic data module of FMM will produce area elevation functions for flooded areas and thus will help in restructuring the various models in floodplain representations. In addition, this unit will also be responsible for all the mapping and digitising activities of SWMC.

The FMM unit/group will consist of trained local staff and their work will be supervised by an expatriate expert on a short-term basis. The group would also carry out marketing activities by developing ideas and advising prospective clients on the use of FMM. FMM demonstrations and presentation seminars would be organised regularly.

7.5.3 Pilot Studies

It is recommended that one or more pilot FMM projects be initiated in consultation with relevant agencies. For example, a pilot FMM for part of the Dhaka Area. In addition to urban planning, flood damage analysis and flood disaster preparedness, the Dhaka FMM would ultimately be used in real-time operation of the proposed FCD schemes designed to protect the metropolitan area from flood disasters. Collaboration will be sought with JICA, RAJUK, WASA and UNDP Metropolitan Development Project for developing and implementing a prototype FMM for the Greater Dhaka Area.

Another suitable area would be that of the South West Region where a pilot FMM could be used for drainage and agriculture master planning due to the pronounced shortage of water. Methodologies for flood impact assessment on agriculture would be further developed during the pilot study.

7.5.4 Multi-Sectoral Studies

GIS for floodplain management extends beyond flood modelling and into other sectors such as agriculture, fisheries and infrastructure. These sectors are not primarily concerned with the flood models themselves, but only in their output, especially flood maps. The most logical process would be for flood modelling experts to use MIKE11 and FMM to produce flood maps and export these maps to other sectors for their own analysis. The export media can be in formats readable by other GISs, or if requested, as hardcopy maps. Flood maps would be available in several forms, such as flood extent, flood depths, duration depths and the change or impact on flood extent, depths and duration because of man-made or natural causes.

SWMC, as the likely custodian of FMM software, would need to consider a practical arrangement for transfer of FMM output for use by other sectors, and may need to consider employing a number of specialists from relevant sectors. However, many agencies or projects may find it more convenient to allow SWMC to carry out a complete analysis or develop dedicated models for specific areas. This may be seen as a practical and an attractive arrangement from computer hardware and software, expertise and financial considerations.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The FMM study was directed to the need for more detailed information on floodplain flooding and the development of a new approach to flood management in Bangladesh. Over the two year duration of the project, all major objectives have been attained and FMM now provides the framework for a range of comprehensive analysis tools for flood management.

The MIKE11-GIS interface forms the core of FMM. Linking the MIKE11 hydrodynamic model to a GIS not only enhances the clarity of the output, but it also simplifies the MIKE11 model construction. The ability to present the results of hydrodynamic modelling in map form, which is almost universally understood, clearly provides an indispensable tool for the public participation processes essential to the Flood Action Plan.

Because the output of FMM draws on the results of the hydrodynamic model, the accuracy and representativeness of the maps produced depend on the accuracy of the hydrodynamic model. This is itself dependent on the quality of the input data, (hydrologic and topographic), and the state of calibration of the model. It is therefore essential that the user appreciates the quality of the MIKE11 output when assessing the resulting flood maps. Unless the major elements, (DEM, Hydrodynamic model data, calibration), are suitably representative, resulting mapping could be misleading.

The greater data needs of FMM needs to be considered within an institutional framework. DEM data and GIS coverages will typically be acquired on a project by project basis, but will need to be archived for future use. Data which varies significantly from year to year, such as hydrometric data and satellite imagery of flooding, need to be collected annually for verification of MIKE11 models and FMM flood maps at a later date. While some of these data are being collected by government and non-government organisations, those which are not should be collected for FMM success and sustainability.

Flood maps generated from MIKE11 models must be interpreted by the engineer responsible for the model, an experienced hydraulic engineer familiar with the model, and reviewed by an expert with an in-depth understanding of the study area's hydrology and hydraulics. The engineers must be satisfied that the flood map gives a sufficiently accurate representation for its intended purpose. It is also their responsibility that recipients of the map are made aware of its deficiencies.

The project has demonstrated the uses of FMM on three levels: National, regional and compartment level. The FMM's produced were each based on a MIKE11 model at the appropriate resolution.

The coarse National FMM, based on the SWMC General Model and GIS data supplied by FAP19 is capable of producing flood maps for the majority of the country, with statistical information for regional and local level government administrations. However, due to the rough representation of floodplains in the General Model, it is limited in its applicability for flood mapping.

The demonstration applications carried out with the NCR-FMM show its usefulness in regional level flood management studies, including flood forecasting. Regional flood mapping using FMM is shown to be practical and the results usable at a level associated with planning and pre-feasibility studies. Due to present computational limitations, there may be an upper limit on the amount of detail that can be sensibly included in the regional model and the user must be aware of the implications of this in interpreting the resulting flood maps.

For compartments and sub-compartments, FMM will be extremely useful in micro level water management applications. This has been shown by the applications carried out with the Tangail Compartment FMM. Sub-compartment scale modelling allows much detail to be represented, since data collection is generally over a limited area and may be done in detail without the commitment of the large resources that would be needed at, say, regional level.

The FAP25 TCM is detailed to a level which incorporates all required structures and can simulate their operation with sufficient accuracy to permit simple operation rules to be tested. The TC-FMM presents the impacts of these structure operations in a form that is readily appreciated by both technical and non-technical users.

FMM presently requires sophisticated computer hardware on which to operate. However, rapid technological advances are being made in the computer industry, in both software and hardware. Therefore, it is reasonable to assume that present day constraints which define the scope and detail of a model will be removed in the very near future and that model complexity will not be a computational issue.

Expansion of the scope of FMM into other sectors, such as fisheries and environment, will require further commitment to data collection and model verification. Nevertheless, from the initial results obtained in this project and the considerable interest generated among other sectors in the FAP, the usefulness of FMM is self evident.

8.2 Recommendations

- This project has taken the first steps in FMM. It is clear that there is great potential for such a tool in the future but, depending on its actual use, further work may be needed on the basic flood models to more correctly represent floodplain inundation and to produce accurate flood maps.

- The National Level FMM, based on the General Model with its coarse definition of floodplains, is of limited use, except for its original purposes such as defining boundary conditions for regional models. It should not be used to provide detailed flood depth information. No further development of this FMM should be undertaken in the short term. When more powerful computers are available, however, it is feasible to contemplate enhancing the detail of the General Model to a level that would permit the National FMM to be used for floodplain planning.

- Depending on the purpose, the NCRM calibration may need to be improved if the NCR-FMM is to be used for more detailed investigations. The DEM of the region should be updated as new survey information becomes available, and hydrologic data collection in the region should continue. Further detailed topographic information on secondary embankments, roads, railways, bridge openings and culverts would help improve the description of flow on the floodplains.

- The Compartment level model shows the greatest promise for development into other sectors, such as fisheries and environment. Before such use, however, detailed discussions should be held among specialists to define specific data and output needs.

- Further development should be carried out using FMM flood maps for inundation forecasting. Initially, such work should be done in limited areas on a regional level model. It is very important that accurate and reliable topographic mapping is available since the credibility of maps used for forecasting must be of the highest order.

- The technology of radar imaging appears promising with respect to the improvement of our understanding of floodplain behaviour. The use of this imagery for assistance with model calibration should be followed up.

- To ensure that the technology developed in this project is maintained and sustained, FMM should be transferred to SWMC and annual data collection programmes should be supplemented or established to cover data special to FMM. At the conclusion of this project, a comprehensive training programme should be carried out for selected staff of SWMC, using staff from FAP25, to establish both the concepts and methodology of FMM within SWMC.

- Future users of FMM should have a sound understanding of the principles of hydrodynamic modelling to ensure the proper interpretation of the FMM output. GIS expertise will be needed in parallel with future developments.

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SWMC/3 *SWSMP Phase II North Central Regional Model Verification* Surface Water Modelling Centre, December 1993.