
A GIS FOR FLOOD DAMAGE CONTROL PLANNING AND ESTIMATION OF FLOOD DAMAGE

Harold Louw Weepener

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Supervisor: Prof. HJ Messerschmidt

Co-supervisor: Prof. MF Viljoen

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*'Not by might nor by power, but by my Spirit,'
says the Lord Almighty.*

Zechariah 4:6

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INTRODUCTION

1.1 BACKGROUND

After the flood of 1974, Viljoen, Smith, Spies and Vos started developing a methodology for the estimation of flood damage in South Africa (Viljoen, 1979; Smith *et al.*, 1981; Spies *et al.*, 1977; Vos, 1977). Several methodologies from the United Kingdom and the United States of America were investigated. They found that mainly two approaches were followed namely the *ex post* and *ex ante* methods.

With the *ex post* method the real impact of a specific flood is determined. A survey must be done in the area and the flood is related to a specific size and probability. A shortcoming of this method is that floods with different probabilities of return are too few to determine the mean annual damage.

The *ex ante* method on the other hand entails situation simulation methods where flood damage is determined independently of real floods. Flood damage relationships of one or more characteristics of floods such as depth of inundation, duration of inundation, momentum flux and sediment content are required with this method. The damage is given as a financial value and the flood damage relationships are often referred to as loss functions. Several floods of different sizes and return periods can be simulated in the absence of real floods with this method.

The benefits of several different combinations of flood damage control measures can be identified when the flood damages of several floods with different return periods are known. Flood damage control measures are aimed at the minimisation of the physical extent of floods, to lighten the influence of floods on the community and to lower the

probability of flood damage at different areas. Flood damage control measures can be grouped into structural and non-structural measures.

Structural measures are implemented to change the physical nature and extent of floods. The volume of water running down, the flood peak, the form of the flood hydrograph, the extent of the area inundated and the speed and height of the water can for example be affected by these measures. Structural measures mainly include engineering works such as drainage networks, levees, dams and spillways. Examples of non-structural measures are effective warning systems, evacuation plans, flood awareness programs, insurance and training.

By comparing the cost of implementation of a flood damage control measure with the decrease in mean annual damage (MAD), the economic feasibility can be determined. A flood damage simulation model is necessary to integrate the geographic-, economic-, hydraulic- and hydrologic information. A Geographical Information System (GIS) lends itself superbly for this purpose.

Muller and Rungoe (1995) describe Geographic Information Systems as tools for managing, analysing and displaying geographic data and data which can be related to geographic objects. They mention that it is highly beneficial to utilise both flood modelling and GIS technologies to pursue an effective flood management strategy.

1.2 PROBLEM DEFINITION

After the floods of 1988 a new awareness originated and the Minister of Water Affairs requested the revision of the national flood management policy for South Africa. In 1992 Viljoen, Du Plessis and Booyesen (1995) started with the development of a flood damage simulation model (FLODSIM) for the Lower Orange River area. This model was based on GIS technology and was completed in 1994. The main shortcoming of this model was that it was area specific. A successive project was piloted in 1995 for the modification of the model so that it would be generally applicable in flood prone areas. Weiss (1976) had already done extensive work on the estimation of flood damage for the Mfolozi floodplain and it was therefore decided to demonstrate the model on the Mfolozi floodplain.

1.3 MOTIVATION

A benefit-cost analysis is usually done to justify the appropriateness of the implementation of a GIS (Obermeyer & Pinto, 1994:86-99). The purpose of the benefit-cost analysis is to weigh the total benefits of the GIS against the total costs. A ratio greater than one justifies the expenditure.

It is important that the differences between the public and private sectors should be noticed. The main difference between these sectors lies in the fact that a system will only be developed in the private sector when it generates a profit. In the public sector profit is not a motive; instead, serving the public interest takes precedence.

It is difficult to estimate the economic value of goods and services in the public sector because of the absence of a pricing mechanism based on typical supply-and-demand functions (Obermeyer & Pinto, 1994:87). For a government it would for example be important to save lives by implementing flood control measures although it will be difficult to quantify the economic benefits.

Public goods and services may be described as having a place on a continuum, with "pure" public goods on the one end and "impure" public goods on the other (Obermeyer & Pinto, 1994:87-88). Public goods and services are considered as "pure" when all citizens will benefit from it. "Impure" public services are only supplied to those people who wish to participate and they usually pay for the service. An example of an "impure" service is when government land is leased to farmers for grazing purposes. GISs are usually qualified as "pure" goods because governments normally plan to include the whole area in its jurisdiction into the database.

The costs as well as the benefits are usually difficult to determine when a benefit-cost analysis is done for a GIS (Obermeyer & Pinto, 1994:93-99). It is generally accepted that the costs of implementing a GIS extend beyond the purpose of hardware and software. The database must be constructed and maintained and personnel have to be trained. Because GIS is still a relatively new technology the advantages are often over- or underestimated at the time of implementation. The real value of a GIS is normally only realised when the GIS has been in use for some time. Some of the potential benefits of a

GIS are savings in time, increased efficiency, new marketable and non-marketable services, better decisions, intangible benefits etc. Two further remarks about a benefit-cost analysis are that the payback period should be determined and that the benefits as well as the costs should be discounted to present values because of the multiyear life expectancy of a GIS and the resulting fact that GIS costs are also spread over multiple years.

In consideration of the discussion above, the following can be said of FLODSIM (Flood Damage Simulation Model). The main cost is the acquisition of data. The main advantage of the model is to show the benefits of different combinations of flood damage control measures that will improve decisions made by Governments concerning flood damage control measures. Different cross sections are usually taken for each flood damage control measure that is tested. The conventional methods that are used to acquire the cross sections are time consuming. FLODSIM will save time because cross sections of the terrain required by numerical flood models can easily be acquired from the digital terrain model (DTM) in FLODSIM. A DTM represents the spatial distribution of surface attributes such as elevation, gradient and aspect in a landscape (see Chapter 4). The model also has financial benefits when you look at the savings in flood damage caused by the implemented flood damage control measures. FLODSIM can be regarded as a "pure" public good because it is developed to be applicable to other flood prone areas as well.

1.4 OVERALL AIM

The overall aim is to conduct an extensive literature study and to adapt the model developed by Viljoen *et al.* (1995) so that it would be generally applicable in flood prone areas. The model will be adapted and refined on the Lower Orange River area and will then be applied on the Mfolozi floodplain.

1.5 SPECIFIC AIMS

1.5.1 Literature study

The four basic aims of the literature study is to give an overview of:

- GIS in general;
- geographic data and methods used to acquire the data;

- digital terrain models and the methods used to generate digital terrain models and
- flood damage simulation.

1.5.1.1 Overview of GIS

The GIS field will be researched based on the latest technology. The definition and history of GIS will be studied and special attention will be given to ARC/INFO (the software package that was used to develop the model).

1.5.1.2 Geographic data

The purpose of this part of the study is to determine the methods that can be used to acquire geographic data when the model is applied to other areas.

1.5.1.3 Digital terrain models

After the general aspects with regard to the acquisition of geographic data have been investigated, the focus will be shifted to digital terrain models. The digital terrain model forms an integral part of FLODSIM and because of the unique nature of these models it will be handled separately.

1.5.1.4 Flood damage simulation

The most recent international literature on flood damage simulation will be integrated with the research that has already been done in South Africa.

1.5.2 Acquisition of data for the Lower Orange River Area and the Mfolozi floodplain

The model will be applied on the Lower Orange River Area between the Gifkloof Weir and the Manie Conradie Bridge at Kanon Eiland as well as the Mfolozi floodplain from the N2 national road to the St. Lucia estuary. Data would therefore have to be acquired for both these areas.

The topographic data collected by Viljoen *et al.* (1995) will be used for the Lower Orange River Area and interpolation methods will be investigated in order to generate a better DTM from the contour lines and spot heights. The use of video remote sensing to determine land use will also be investigated.

Topographic data for the Mfolozi floodplain will be digitised from 1:10 000 orthophotos. Unfortunately the most recent available orthophotos were created from 1979 photography. The digitised data will therefore be updated with information derived from 1996 air photos and digital data that was made available by Bosch & Associates (1995). A DTM will be created from air photography.

Hydraulic data will be calculated for the Lower Orange River Area and the Mfolozi floodplain in collaboration with the Sub-directorate Hydraulic Studies, Department of Water Affairs and Forestry, Pretoria.

Economic data will be developed for both areas in collaboration with the Department of Agricultural Economics, University of the Orange Free State, Bloemfontein.

1.5.3 Developments in FLODSIM

1.5.3.1 Development of an interface between FLODSIM and a numerical flood model

Hydraulic data forms an integral part of the efficiency of the model and an interface with Mike 11 (a numerical flood model) will therefore be developed. Mike 11 is a professional engineering software package, developed by the Danish Hydraulic Institute (DHI, 1992). It consists of several modules and can be used for the simulation of flows, sediment transport and water quality in estuaries, rivers, irrigation systems and similar water bodies. The core of the Mike 11 system is the hydrodynamic module, which is an implicit, finite difference model for the computation of unsteady flows. The hydrodynamic module is often applied as a flood management tool to simulate flooding behaviour of rivers and floodplains.

Software that was developed by the Department of Water Affairs and Forestry (Tchoukanski, 1996) will be used as basis for the interface. The software will be adapted in order to apply it to FLODSIM and will further be developed to handle different channels and to make provision for other hydraulic characteristics as well.

1.5.3.2 Creation of a program to determine flooded areas

In the original model the flooded areas are drawn by hand. The same area however is not inundated for floods with different probabilities. Floods with a smaller probability of occurrence will flood larger areas. Muller and Rungoe (1995) suggest that automatic methods should be used as the hand method is time consuming and has a larger capacity for errors.

1.5.3.3 Creation of programs for the manipulation of levees

The model will be adapted so that hypothetically, levee heights can be raised and levees added or taken away. Hydraulic properties will change with different structures and the manipulation of levees should be taken in consideration with calculations such as the determination of flooded areas and the taking of cross sections over the river.

1.5.3.4 Adaptation of the model to make provision for different flood probabilities, crop types, etc. in other flood prone areas

Variables will be used instead of constants and the model will be adapted to make provision for different numbers of flood probabilities, crop types, etc.

1.5.3.5 Development of a setup program for FLODSIM

A program will be written with which the user can allocate the variables according to the situation in the floodplain on which the simulation will be done. The program will make provision for the defining of paths to the data and the menus will automatically be adapted by the program to fit the study area.

1.5.4 Application of the model to the Mfolozi floodplain

The model will be applied to the Mfolozi floodplain. The only crop planted in the area is sugar cane. A loss function for sugar cane should therefore be incorporated into the model. Because the damage to sugar cane depends on the period inundated the model should also provide for duration of inundation.

Damage to infrastructure comprises a large proportion of the flood damage to the Mfolozi floodplain and loss functions will therefore have to be developed for infrastructure as well. The loss functions for sugar cane and infrastructure will be developed in collaboration with the Department of Agricultural Economics, University of the Orange Free State, Bloemfontein.

1.5.5 Generation of a user's manual for FLODSIM

A user's manual will be written to assist users with the usage of the model.

1.6 COMPOSITION OF THE THESIS

The thesis consists of seven chapters. Chapter 1 gives an introduction. An overview of GIS in general is presented in Chapter 2. The following chapters will focus on ARC/INFO, the software package used to develop the model. Geographic data, digital terrain models and flood damage simulation are described in Chapters 3, 4 and 5 respectively. The development and application of the model will be described in chapter six. The thesis is concluded in Chapter 7. The user's manual of the model is given in Appendix A.

Algorithms that are given in the thesis will not include general housekeeping rules such as to check whether a file with the same filename exists before a new file is created. In the actual programs coverages are normally duplicated before changes are made to it. This is not mentioned in the algorithms in order to help the reader keep track of the different files by keeping names that are used as few as possible.

AN OVERVIEW OF GIS

2.1 INTRODUCTION

Tomlinson (1984:18-21) gives the following account of the development of the Canada Geographic Information System (CGIS). During the sixties the Canadian Government realised that their natural resources were not limitless. There was a visible decline in the population in rural areas and increasing competition among the potential uses of land within commercially accessible land zones. A special committee of the senate was established to examine land use in Canada. After the Agricultural Rehabilitation and Development Act was accepted by government, the way was prepared for government departments to participate directly in land use changes. The government perceived that it would have to play a more important role in making decisions about land management and in planning the utilisation of natural resources. Changes in land use should also be monitored.

A Canada-wide land inventory was initiated to map the current uses of the land and the suitability of the land for agriculture, forestry, wildlife and recreation. Approximately 3000 map sheets on a scale of 1:50 000 would be needed to cover only the agricultural and commercial forest zones in Canada (about one third of the country). Tests done by the Canada Department of Agriculture in 1965 showed that 556 technicians (Coppock & Rhind, 1991:23) were required for a period of three years in order to overlay the 1:50 000 scale maps of the Canada Land Inventory. Unfortunately Canada did not have the trained people for such a task.

After Roger Tomlinson had convinced the government that computer-based techniques would perform such analyses both faster and cheaper, he became responsible for initiating

and directing the development of the CGIS. Certain technical constraints had to be overcome. No efficient way existed for converting large numbers of maps to numerical form. By today's standards computers still had small storage capacities and slow processing speeds. Most programmers were employees of computer companies or of highly centralised government service bureaus. No one was trained in digital spatial data handling.

According to Coppock and Rhind (1991:28) the CGIS was possibly the first true Geographic Information System (GIS) - and certainly the first to be so entitled. It has been in continuous operation since the sixties and in 1991 it contained a digital archive of some 10 000 maps on more than 100 topics.

2.2 WHAT IS A GEOGRAPHIC INFORMATION SYSTEM (GIS)?

Obermeyer and Pinto (1994:4) define a GIS as a computerised system for the collection, storage, manipulation (analyses) and output of spatially referenced information. The authors mention though, that there is a problem with this definition as it ignores the fact that other types of information systems are also spatially referenced - the inclusion of street addresses instantly makes them so.

The easiest way to define a GIS is by its components. This includes people, data, hardware and software. The most important component must certainly be the people since they are responsible for the design, implementation and usage of the GIS. The data must be accurate and available. Hardware capabilities affect the processing speed, ease of use and the type of output available. The last component, namely software, provides the tools with which digital spatial data can be manipulated and analysed.

With these basic components the following functions can be performed: (ESRI, 1994:2.3)

- Data capture and storage.
- Data manipulation and analysis.
- Display creation and hard-copy output (maps and reports).

2.2.1 Components of a GIS

The components of a GIS function together to form an integrated system. Each of the components will be discussed in more detail in the following paragraphs.

2.2.1.1 Hardware

The computers used for GIS range from personal computers, high performance workstations and minicomputers, to mainframe computers. Currently Unix workstations are the general choice of running GIS software, but according to Matthews (1996:42) and Hobson (1997) there is a trend towards personal computers. The main reason for this trend being the development of more powerful PCs. Another advantage of GIS software running on Windows NT is the fact that the user is familiar with the environment. The user does not need to learn new techniques in all areas but he can often use the software of his choice as long as it supports Microsoft's object linking and embedding (OLE). To give an example he might like to use Microsoft Excel to display graphs. The programming is also easier as the programmer does not need to learn a new language, but is often given the choice of using languages such as Visual Basic, Delphi and PowerBuilder.

Except for the standard input and output equipment, more specialised hardware is needed to handle the input and output of spatial data. The most commonly used hardware for the input of spatial data include scanners and digitisers while wide-format inkjet printers are most widely used to create output documents.

The devices used for digitising are a digitising board or a tablet and a cursor (ESRI, 1996). The digitising board contains a grid of tiny current-carrying wires that run horizontally and vertically. The digitising cursor has an optical viewer with a target (usually crosshairs) that allows the user to visually locate a point on the map. The most common cursor has at least 16 buttons. The operator mounts a map on the digitising table and then uses the cursor to capture the co-ordinates of features on the map by pressing a button on the cursor after a point has been identified. The button that was pressed will

define the action to be taken. Using the recorded x,y co-ordinate location of the point, features in the coverage can be added, selected, deleted or edited.

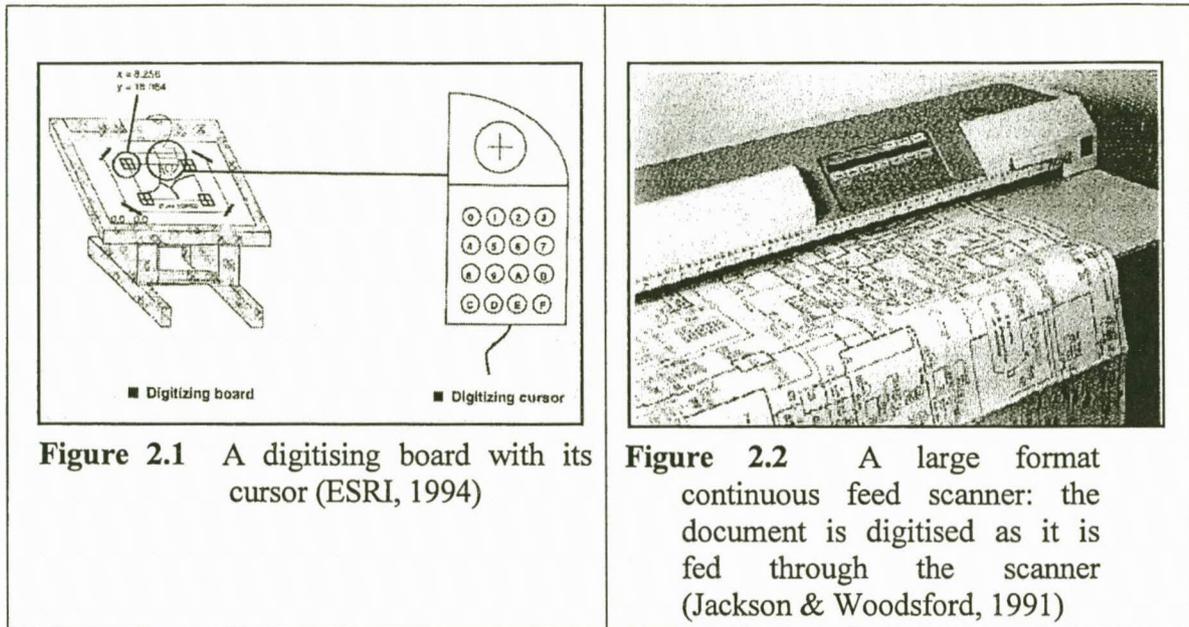


Figure 2.1 A digitising board with its cursor (ESRI, 1994)

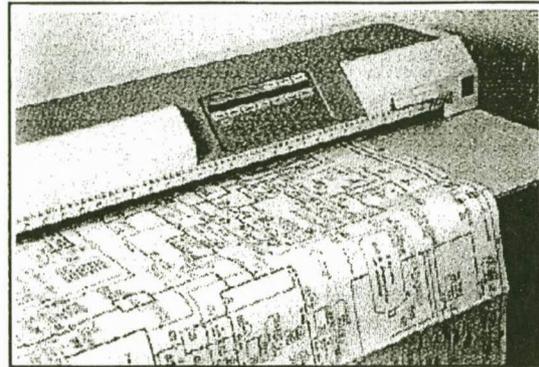


Figure 2.2 A large format continuous feed scanner: the document is digitised as it is fed through the scanner (Jackson & Woodsford, 1991)

A scanner automatically converts analogue source documents into digital format in raster form (Figure 2.2). All scanning involves systematic sampling of the source document by either transmitted or reflected light (Jackson & Woodsford, 1991:243). Most scanners are based on the charge-coupled device (CCD) array. CCD arrays are available as one- or two-dimensional regular rectangular structures of light-sensitive elements. Depending on the design of the scanner, the document or the scanning element is moved during the scanning process.

A GIS must be able to produce output to the screen as well as hard copies. Depending on the size of the output document and the resolution required, almost any printer can be used but for the best results a wide-format printer that can give a high resolution is preferred. According to Spescom MeasureGraph (1996:48) wide-format inkjet printers offer the best benefit cost ratio when compared to other technologies capable of producing wide-format colour images. Pen plotters are up to 50 times slower than inkjet printers while electrostatic and thermal printers are more expensive. Inkjet printers use plain paper that is easy to recycle while thermal papers cannot be recycled and is difficult to be disposed of as it contains various chemical components. A disadvantage of inkjet printers

is the fact that it cannot print over long periods, for example over a weekend, as it quickly runs out of ink.

Tektronix (1997) describes two technologies that are applied to inkjet plotters. The solid ink technology uses solid ink sticks that are melted in a small reservoir to become liquid. The ink is squirted onto paper in the appropriate pattern of dots and it resolidifies as soon as it hits the paper. The image is then run between two rollers to improve the surface texture. With liquid inkjet printing the ink is propelled in fine droplets of liquid ink toward the surface of paper. Specially treated paper can improve the printing quality as the liquid ink tends to soak into the paper.

Laser plotters use light emitting diodes (LEDs) to produce laser quality plots on plain paper (De Sousa, 1995). The speed performance of laser plotters far surpasses any other technologies. Tektronix (1997) is of the opinion that the impact of the laser technology in the colour-printing arena is just in the beginning phase.

Pen plotters can be divided into drum plotters and flat bed plotters (Maguire, 1989:71). In a drum plotter the paper rolls over a drum that acts as a plotting surface. The image is created by one or more pens that move in the y direction as the paper moves in the x direction over the drum. With flat bed plotters the paper is fixed to a flat surface while the pen moves in both an x and y direction.

Electrostatic plotters were designed to handle high volume workloads (De Sousa, 1995:53). Electrostatic plotters use electro-statically treated paper and liquid toners. The toners adhere to the paper after the image area has been electrostatically charged. The technology has been the milestone of plotting for several years, but is rapidly being replaced by colour inkjets.

Thermal plotters rely on special paper that creates lines when exposed to heat (Tektronix, 1997). Thermal plotters are limited to only two colours.

2.2.1.2 Software

Today there are many different GIS software packages and the major software packages have several hundred commands and a wide variety of functions. Maguire (1991:15) lists three basic designs that have evolved over time, namely the file processing, hybrid and extended designs. With the file processing design each data set and function is saved as a different file and these are linked together during analytical operations. Examples of systems using this design are IDRISI and MAP. In the hybrid design, attribute data are stored in a conventional Database Management System (DBMS) while separate software is used for geographical data. ARC/INFO and Deltamap/Genamap are examples of hybrid systems. In the third design type, the extended DBMS, both the geographical and the attribute data are stored in a GIS which is extended to provide appropriate geographical analytical functions. The best known example using the extended design is SYSTEM9 that extends the EMPRESS DBMS.

Another design that is gaining a lot of ground is the object-orientated approach. In this model entities are stored as objects which have properties that are either attributes or methods (Hardy, 1997). The methods provide intelligence embedded within the object. An example of a system using the object-orientated approach is Arcview. Arcview's programming language is Avenue (Van Niekerk, 1996:16). For example, a line segment is an Avenue object with endpoint co-ordinates as attributes. The line segment can supply services such as to move one of its endpoints.

2.2.1.3 Data

The data are usually the most expensive component of a GIS and a large part of development time is spent on the preparation of data. Source data can be in different formats for example map sheets, ASCII formatted files, remotely sensed data in digital format and files in data exchange formats from other software packages. The source data should be chosen with care. The scale, age, projection and method used to prepare the data should be considered when source data are chosen. When data are obtained from another department or agency, the people who were responsible for the data should be

interviewed to make sure that the data are suitable for the envisaged purposes. Aspects essential to your project might not have been important to them.

The scale of a map is the ratio between distances on the map and corresponding distances in real world (Goodchild & Kemp, 1991:2.5). The scale therefore gives an indication of the detail presented on the map. A map with a scale of 1:100 000 will cover a larger area than a map with a scale of 1:2 500 but only the latter will for example show individual houses and lamp posts.

The contents of a spatial database reflects a specific part of the world in a specific way. The world should be represented as close to reality as possible. Shape, area, distance and direction are some of the spatial properties that can be distorted when the curved surface of the earth is projected to a flat plain. Different map projections will minimise distortion of certain properties. It is however possible to convert data from one projection to another.

According to Zietsman (1995:19) the value of any GIS is dependent upon reliable, complete and up-to-date data. Geographical data include spatial as well as attribute data.

2.2.1.4 People

A GIS team normally consists of at least five people including programmers, geographers and experts in gathering data and digitising. It is important that they should be able to function together as a team.

Obermeyer and Pinto (1994:68) gives a three-point approach of attributes that GIS users must possess in order to be able to utilise the full potential of the GIS namely:

- He must have substantial experience in the field where the GIS is to be used.
- Knowledge of GIS techniques is important.
- He must have an understanding of geographic and cartographic principles, at least in rudimentary form.

Digital spatial data make it very easy to create maps. Someone who does not have a background on geographic or cartographic principles can easily create a map and claim that it is correct, while there might be significant errors in it.

The team should work closely together with the local people who will be more experienced on the specific field on which the GIS is applied. After all, they will be the end users and by getting their ideas it will be ensured that the application addresses their real needs.

2.3 APPLICATIONS

There is a wide range of GIS applications and just a few examples will be given to demonstrate the functionality of GIS. Elfick *et al.* (1995) grouped the GIS applications into the following common areas of application:

- Land use planning.
- Natural resource mapping and management.
- Environmental impact assessment.
- Census, population distribution and related demographic analyses.
- Route selection for highways, rapid transit systems, pipelines, transmission lines, etc.
- Displaying geographic distribution of events such as automobile accidents, fires, crimes, or facility failures.
- Routing busses or trucks in a fleet.
- Mapping for surveying and engineering purposes.
- Subdivision design.
- Infrastructure and utility mapping and management.
- Urban and regional planning.

The combined power of present day GIS and computers is such that organisations can use a GIS in combination with other data base systems as the core of all its data operations (Muller & Rungoe, 1995). To pursue an effective flood management strategy Muller and Rungoe (1995) utilised both flood modelling and GIS technologies. In the management

of flood-prone areas two of the seemingly simple, yet highly time consuming and difficult tasks are the delineation of the flood-prone land from the flood-free land and the examination of the impact of alternative flood mitigation and flood protection measures on flood levels. The MIKE 11-GIS ArcView interface (MIKE 11-GIS) has been primarily designed for generating 2D and 3D water level and flood inundation maps. The system uses a 3D ground surface or digital elevation model (DEM) and water levels calculated by MIKE 11 to calculate water depth. The system design allows rapid generation of inundation boundaries showing different flood scenarios, for example scenarios with or without flood protection measures.

Demographic analyses can easily be done with GIS in countries where location information on individuals is available. Kohli *et al.* (1997) describes the linkage of individuals that live within areas with high background radon in the province of Ostergötland in Sweden. The Swedish central statistical bureau provided the data on the population register as well as the buildings property register. Each individual's address, age, and sex could be found in the population register. By linking the individual's address with the address in the building property register, each individual could be related to the centroid of the property. By means of a simple overlay with a map indicating different risk levels the individuals living in each risk level could be identified.

The integration of GIS, the global positioning system (GPS), data collection devices and variable rate implements with precision farming are resulting in cost savings, production increases as well as improved stewardship and environmental benefits to farmers (Berry, 1998). Precision farming involves the tailoring of management actions for example fertilisation levels, seeding rates and selection variety to match changing field conditions. Field data are collected by connecting a GPS with a data collection device such as a yield/moisture meter in order to "stamp" the data with its corresponding geographic coordinates. After the data are collected, a "prescription" map of management actions required for each location in a field is created with GIS by analysing relationships among yield variability and field conditions. Finally variable rate implements note a tractor's position through GPS, continuously locates it on the prescription map, then varies the application rate of field inputs such as fertiliser blend, or seed spacing, according to precise instructions for each location.

The combination of the GIS and GPS technologies can also be used to create automatic vehicle location (AVL) systems (Editor, 1995b). Radio Satellite Integrators (RSI) combined GPS with ESRI's Arcview to create an AVL for Park, Ride & Fly SW, an airport parking service and hotel shuttle. RSI chose a VP Encore GPS receiver and an active low-profile micro-strip GPS antenna that could easily be installed onto the vehicles. As the entire service area could be described by a 12-mile radius, RSI was able to use a conventional two-way radio system for communications between the vehicles and the dispatch area. The GIS graphically displays vehicle positions using unique icons and colours that identify each mobile unit. The GPS derived positions are converted by RSI into digital format and placed on the corresponding position on maps. Data are automatically archived and used to evaluate the company's ability to meet contracts with area hotels. The database also allows the company to review its past performance, including problem areas and times, and reallocate vehicles if necessary.

An interesting development is the different possibilities of using geographical data on the Internet. It is easy to publish maps on the web with software such as ESRI's ArcView Internet Map Server (Louw, 1997:40). Australia's national telecommunications carrier integrated a mapping functionality with their White pages telephone directory service on the World Wide Web. After a Web site visitor has described the person or business he is looking for, the telephone number and address is given in an instant to the user together with a graphical display of a map showing the subscriber's location. The main challenge is to allow thousands of users simultaneous access to the maps in seconds. Another advantage of the Internet is the distribution of up-to-date geographical data. The data are maintained by one firm and made available by them on the Internet.

2.4 THE HISTORY OF GIS

To give a complete account of the evolution of GIS all four the components, namely people, data, hardware and software should be taken into consideration. The main focus of this paragraph will however be on the software. It is worth mentioning that the rapid rate at which the computer industry has grown played a major role in the distribution of GISs today. The first GISs could only be found at universities and government departments. The largest machine for early work of GIS (early 1960s) was the IBM 1401

with only 16K of BCD memory (Tomlinson, 1984:20). It processed 1000 instructions per second, cost \$600,000 and weighed more than 3600 kg.

The history of GIS was roughly divided into four periods. The reader should note that there was no abrupt change between the different phases and the classification was only made to give some structure to this paragraph. For example, the CGIS, which was classified into the second period, is still used.

2.4.1 Analogue map documents (At least the previous 4000 years)

The first map was apparently created before the first alphabet and analogue maps were therefore used over an extensive period of time (Marble, 1984). During this time these maps have evolved to a high level of sophistication and today it combines high-density storage with complex, colour based displays. Different elements are usually presented as points, lines or areas depending on the size of the element and the scale of the map. The locations of elements are determined with the aid of a co-ordinate system (latitude, longitude and elevation with respect to sea level).

According to Robinson (1982, as quoted by Antenucci *et al.*, 1991) the development of Cartography dates back to the middle of the mid-eighteenth century when the first accurate base maps were produced. The eighteenth century also saw the refinement of lithographic techniques and the early development of statistical techniques, number theory and advanced mathematics.

Analogue map documents are usually analysed by means of a visual inspection. Spatial search and overlay are the only functions that are provided by GIS software, which are unique to GIS (Cowen, 1988:57). The manual method used with spatial overlay would therefore be a good example to demonstrate the analyses of analogue maps. According to Marble (1984:9) the two or more spatial data sets are firstly transformed to a common map scale. A transparent or translucent overlay has to be created for each data set and it is then registered so that the co-ordinate systems are aligned. At last a composite overlay sheet is manually created to show those locations where the various classes being studied

satisfy the conditions of the query. With larger numbers of data sets this process can become quite complex.

After the advent of the computer in the late 1940s, the use of automated systems was continually driven by several factors for example:

- Extremely large and complex data sets could be both compactly stored and rapidly retrieved with mechanical accuracy (Peuquet & Marble, 1990:5).
- Many of the quantitative and analytical techniques developed in the earth sciences, transport planning, urban planning, and natural resource management, among others, were limited in their practical application without the capacity and very rapid data processing that computers provided to deal with the large volumes of observational data required by these techniques (Peuquet & Marble, 1990:5).
- There was a growing supply of ready-made digital data for example from techniques such as global positioning and remote sensor imagery (Peuquet & Marble, 1990:5).
- Data could be maintained and extracted at a lower cost per unit of data handled (Dangermond, 1983:32).
- Graphic and nongraphic data (i.e. attribute information) could be merged and manipulated simultaneously in a 'related' manner (Dangermond, 1983:32).
- Several map sheets can be combined in order to analyse it as one continuous map on computers.

2.4.2 Custom built systems (1960s and 1970s)

It is only the CGIS of the first GISs that measures up to a strict definition of GIS as a computer-based system for analysing spatially referenced data (Coppock & Rhind, 1991:22). To give an accurate portrayal of the developments of GIS during these early years, it is therefore necessary to take a more general interpretation of GIS for example as systems handling geographic data.

The first GISs were developed to address a specific problem or a narrow field. CGIS (1966) and MAGI (1974) were for example developed to address land use and natural resources planning, the ACG, DIME and TIGER systems were developed respectively for the 1970, 1980 and 1990 censuses in the USA and the Experimental Cartography Unit

(ECU) focussed its attention initially (since 1967) on the computer-assisted production of high quality maps.

2.4.2.1 The Canada Geographic Information System (CGIS)

Roger Tomlinson (1984) started to experiment with maps in numerical form while he was working with an aerial survey company in Ottawa. The results looked promising and in 1962 he proposed that the Canada Land inventory develop such a system. By the end of the sixties the Canada Geographic Information System (CGIS) had addressed and solved many of the basic technical problems to the point where the system could be used productively. It was a polygon based system and contained functions to reclassify attributes, dissolve lines, merge polygons, change scale, measure areas, generate circles, generate new polygons, conduct searches based on attributes, create lists and reports, and carry out efficient polygon-on-polygon overlay. Each map sheet was automatically matched with the others at its edges to form one continuous map coverage of Canada. Some of the inventions during the development of CGIS include the following:

- Large surface (1.22 m x 1.22 m) cartographic digitizer tables with pencils were designed for the input of point data.
- A large format (1.22 m x 1.22 m) cartographic quality drum scanner was invented for the optical scanning of all maps.
- Raster to vector conversion techniques as well as automatic topological coding techniques were invented.

2.4.2.2 The Maryland Automated Geographic Information (MAGI) System

The Maryland Automated Geographic Information (MAGI) System was developed by the Environmental Systems Research Institute for the Maryland Department of State Planning (1979). It was implemented in 1974 to address the land use and natural resource planning problems unique to Maryland. Since 1974 the system has been expanded and significantly improved. MAGI has been used extensively by other state agencies for land and water resources analyses. As a grid-based system MAGI contained functions for data entry, retrieval, manipulation and output. Later developments included an interface

between MAGI and LANDSAT, Automap II (programs which produce choropleth, contour or proximal maps), supplementary grid routines (slope, aspect, cut and fill), ASTEP II (the Algorithm, Simulation Test and Evaluation Program Version II) and capabilities through the Statistical Package for the Social Sciences (SPSS).

2.4.2.3 The ACG, DIME and TIGER systems

Enumerators, visiting every household in the United States to fill out a census questionnaire, collected the data for the 1950 and earlier censuses. For the 1960 census the United States Bureau of the Census initiated a process to replace the traditional method of collecting data with a 'mail-out/mail-back' technique (Marx 1986). For this census the questionnaires were posted to every house, but were still collected by enumerators. The enumerators relied on direct field observation to assign each household to the correct geographic location on a map. The Census Bureau then used a geographic reference file to classify each location into the appropriate tabulation units. In several areas the census bureau experimented with having respondents mail the completed questionnaire back.

In the mid 1960s the United States Bureau of the Census made the decision to use the 'mail-out/mail-back' approach in the future. The address-coding guide ACG was developed to provide a tool that would do the job a map once did for an enumerator. The ACG contained no spatial or earth-position information.

The Geographic Base File or Dual Independent Map Encoding (GBF/DIME) file concept was developed by the Census Bureau for the 1980 census. According to Peuquet and Marble (1990:64) DIME is generally viewed as the historical prototype for all subsequent topological data models. A large amount of data are available today in this form in a number of countries such as the U.S.A., France and Israel. The essence of DIME was a method of describing the urban structure through recording the topological relationships of streets (Coppock & Rhind, 1991:30,31). It therefore provided an automated method of checking the completeness of areas built up of street boundaries. During 1972 the Census Bureau decided to create atlases for the major metropolitan areas. The project required the digitising of some 35 000 census tracts and demonstrated the cost effectiveness of

such an approach. Software was also developed to handle these large amounts of data. A topological edit procedure provided for the accurate computer editing and correcting of structural elements in the coded geographic file (U.S. Bureau of the census, 1970).

The DIME file was replaced with the Topologically Integrated Geographic Encoding and Referencing (TIGER) file to support the 1990 census operations. This file was created to integrate the computer readable map information provided by the U.S. Geological Survey with the geographic attributes needed for census taking purposes.

2.4.2.4 Computerised cartographic drawings

As in the case of North America, it was the work of an individual (D.P. Bickmore) to initiate computer assisted production of high-quality printed maps in the United Kingdom (Coppock & Rhind, 1991:23,34-35). Bickmore persuaded the Natural Environmental Research Council to fund a research unit in automated cartography. The Experimental Cartography Unit (ECU) became fully operational in 1967 and collaborated with the Ordnance Survey (the national mapping agency), national agencies for geology, soils and oceanography and planning agencies. Software was developed for changing projections, editing, data compression, automated contouring and so on. The Ordnance Survey simulated the manual production of its maps as closely as possible. This approach resulted in high quality maps, but the data could not be used in an information system. An attempt was already made in 1974 to restructure the digital data through the development of appropriate software. The national digital coverage was completed in 1995 (Murray, 1997). The national topographic database (NTD) at the Ordnance Survey totalled approximately 80 Gbytes of vector data and a similar quantity of raster data in 1997. Supply to customers annually exceeds 200 Gbytes and on average 10% of the database is being updated at any one time.

In 1996 the Ordnance Survey initiated a project called Landplan, which entails the replacement of the Ordnance Survey's 1:10 000 scale mapping, the largest scale at which the UK is mapped, to a single specification (Editor, 1996). The Agency invested more than £1 million in an Intergraph map production system which included 10 UNIX-based workstations, 40 Windows NT edit workstations and related MGE software (see

Paragraph 2.4.3.2) to support Map Generaliser (used for the creation of small scale maps or on different subjects from a larger scale master database). Landplan involves the revision of 10 566 sheets by a team of more than 50 cartographers. The Agency has set itself the target to complete the project by the end of 1998.

Other systems developed to address the handling of cartographic drawings in the sixties include the Oxford Cartographic system (U.K.), AUTOMAP (Central Intelligence Agency, U.S.A.) and Canadian Hydrographic System (Government of Canada).

2.4.2.5 Other GIS systems in the 1960s and 1970s

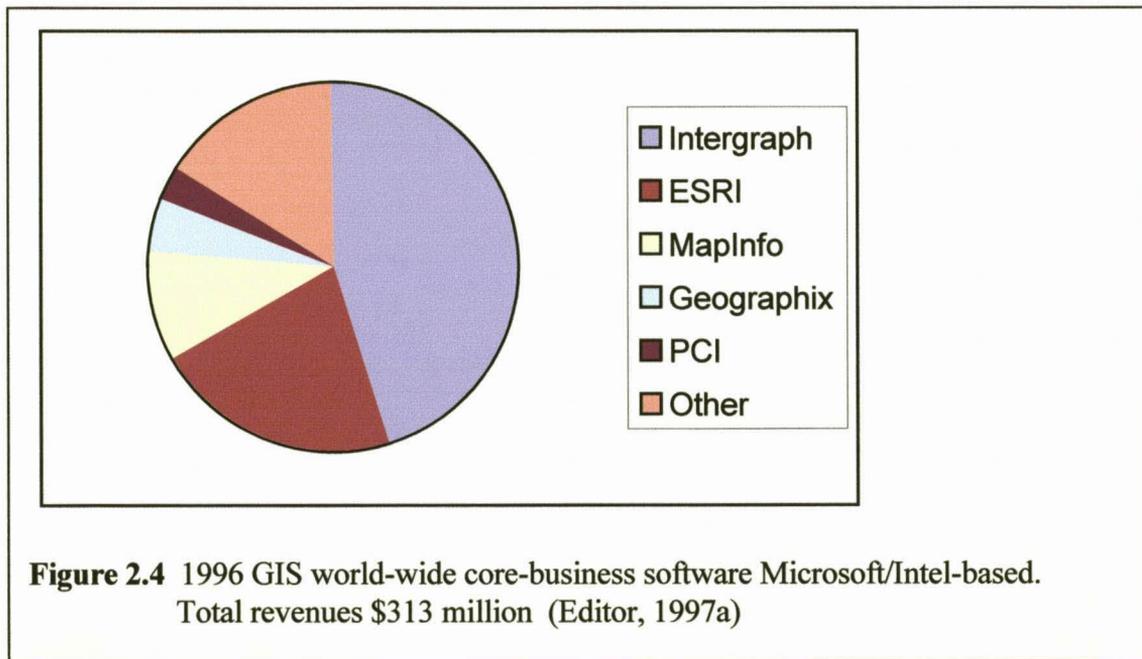
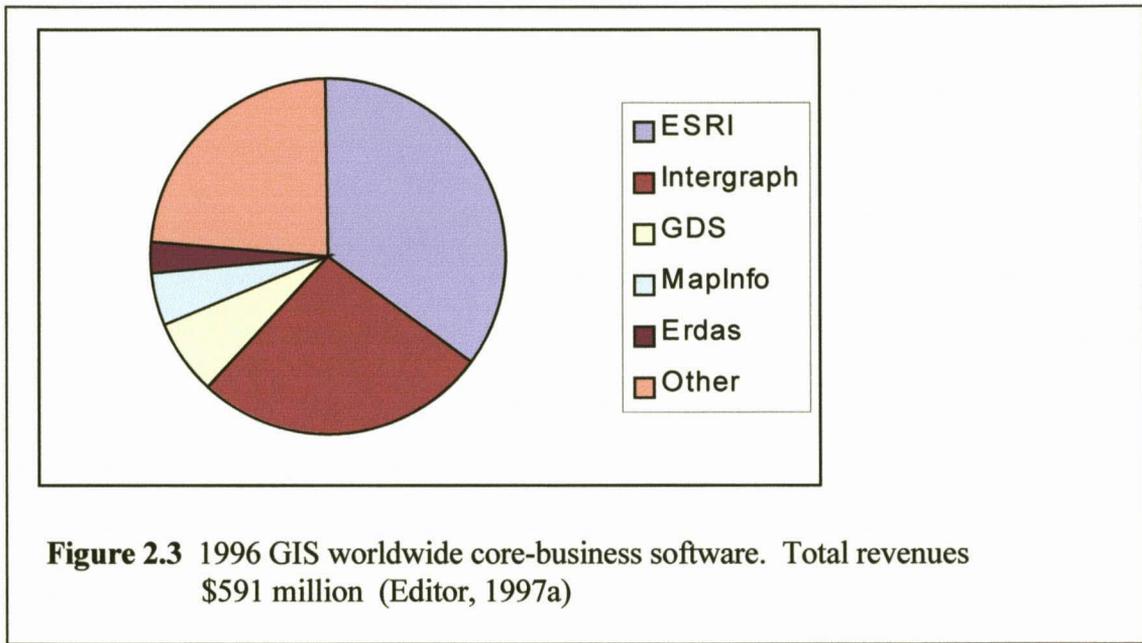
Tomlinson (1984:21) lists the following grid-based systems that were initiated in the 1960s. These systems were principally developed at universities. SYMAP from Harvard University was the most widely known system, others that were developed soon afterwards include MIADS, MIADS2 (U.S. Forest Service), GRID (Harvard University), MLMIS (Minnesota), GEOMAP (University of Waterloo), MANS (University of Maryland), LUNR (New York State), LINMAP and COLMAP (Ministry of Housing and Local Government, U.K), ERIE (Ontario Canada), BRADMAP (Bradford, U.K), NARIS (Illinois), CLUIS (Massachusetts) and CMS (Ozarks Region, U.S.A.).

The IGU inventory of computer software for spatial data handling conducted in the late 1970s described more than 600 programs, amongst which were 80 full GIS systems (Tomlinson, 1984:23). Some of the widely known systems were MAP/MODEL (Washington State), PIOS (San Diego County), GIMMS (Edinburg University), FRIS (Swedish Board for Real Estate Data), ODESSEY (Harvard Laboratory) and GIRAS (U.S.Geological Survey).

2.4.3 General purpose systems (1980s and 1990s)

During the early eighties governmental and commercial research agencies in North America, United Kingdom, Germany, France, Norway, Sweden, Netherlands, Israel, Australia, South Africa, U.S.S.R. and other countries were actively involved in GIS development and usage (Tomlinson, 1984).

During this time, commercial vendors started to play an integral part in the evolution of GIS. The history and products of some of the commercial vendors namely ESRI, Intergraph, Genasys II and MapInfo will be described in this paragraph. Figure 2.3 and Figure 2.4 illustrate the positions of key players in the GIS industry in 1996.



It should be mentioned that the directors of Convergent Group, Englewood, Colo., announced in 1997 that it would curtail future investments in research and development and new products for its affiliate Graphic Data Systems Corporation (GDS) (Editor, 1997b). GDS controlled 6.5 per cent (see Figure 2.3) of the GIS market in 1996. According to Montgomery, CEO and co-chairman of convergent group GDS was not meeting expectations of the board from a financial perspective and that the corporation would rather invest into parts of the business which are growing very rapidly for example systems integration and consulting. Alliances were made with vendors such as Smallworld Systems Ltd., Englewood to help GDS customers to migrate to other platforms

2.4.3.1 Environmental Systems Research Institute Inc.

The Environmental Systems Research Institute Inc. (ESRI) was founded in 1969 by Jack and Laura Dangermond and is still wholly owned by them (ESRI, 1998a). In the 1980s, ESRI moved from a company primarily concerned with carrying out projects to a company building software tools and products. The methods and technologies developed for project work during the 1970s were of great help in the development of commercial software products that others could use and rely on for doing their own projects.

The company's flagship product, ARC/INFO, was launched in 1981 and is the most commonly used GIS software package today. ARC/INFO supports all computer platforms. Other products distributed by ESRI include ArcView (a desktop mapping and GIS tool), MapObjects (mapping and GIS software components for software developers), PC ARC/INFO (the microcomputer version of ARC/INFO), etc. ESRI acquired Atlas GIS from Strategic Mapping Inc. in 1996 (Danielson, 1997).

ESRI, with business partner Miner and Miner, recently designed ArcFM to meet the network management needs of electric, gas, water, and wastewater utilities and other organisations working with land base data (ESRI, 1998b). "Historically, ESRI utility users have had to customise ARC/INFO extensively to make it easily usable and productive within the utility environment," says Jack Dangermond, president, ESRI. "It is our sense that most utility companies want very specific industry applications that work

without a lot of customisation. While most of our customers appreciate generic GIS tools, there are huge productivity gains possible by having an easy-to-use, out-of-the-box solution developed on top of these tools."

ArcFM joined ESRI's family of end user solutions for specific markets (ESRI, 1998b). In 1997 ESRI introduced NetEngine, a collection of developer's tools for geographic network analysis; RouteXpert, a vehicle-routing desktop solution for businesses and organisations that deploy a fleet of vehicles; and ArcView Business Analyst, a powerful desktop mapping solution bundled with extensive data and tools to solve specific business problems.

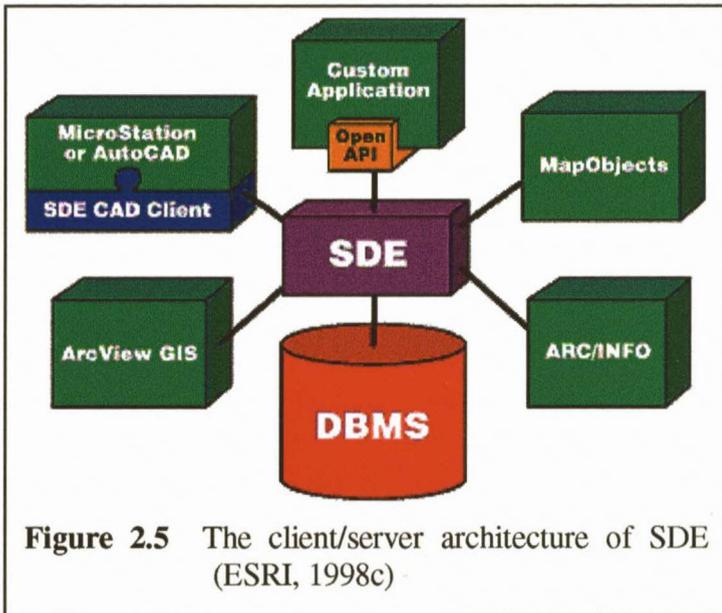


Figure 2.5 The client/server architecture of SDE (ESRI, 1998c)

ESRI's Spatial Database Engine (SDE) is an object-based spatial data access engine implemented in several commercial DBMSs including Oracle, Sybase and Microsoft SQL Server. SDE provides spatial functions that enable the DBMS to store and manage complex spatial data along with other tabular business data. The client/server

architecture of SDE allows for access by multiple client applications for example ARC/INFO, MapObjects, AutoCAD, ArcView, etc. (see Figure 2.5).

2.4.3.2 Intergraph Corporation

Five former employees of IBM founded Intergraph in 1996 as M&S Computing Inc. (Intergraph, 1998). In 1980 the company's name was changed to Intergraph Corporation and they became a publicly owned company in 1981, with common stock traded on the NASDAQ market under the symbol "INGR." Today, Intergraph supply a wide range of interactive computer graphics systems, but GIS and mapping always played an integral

part in the company's strategy. The company's first commercial product, the Interactive Graphics Design System (IGDS), was used for mapping applications. IGDS was first sold to the metropolitan government of Nashville/Davidson County, Tennessee, in 1974. TIGRIS, another early product of the company, was developed for the Defence Mapping Agency (DMA) (Rajani, 1995).

Foreseeing in 1992 that the Intel/Windows platform would become capable of supporting technical computing and other enterprise wide computing environments, Intergraph chose to migrate products from its own Clipper RISC processor to Intel processors and from the UNIX operating system to Windows NT (Intergraph, 1998). Today, Intergraph leads the GIS market on the Windows NT platform. According to a report from Dataquest, Intergraph totalled 80% of the GIS software sales in 1996 for the Microsoft Windows NT platform (Geoplace, 1997).

Modular GIS Environment (MGE) is the front-runner GIS from Intergraph Corporation (1996). MGE was created in 1989 for Unix operating systems and moved to Windows NT in 1994. Other GIS software products distributed by Intergraph are Facilities Rulebased Application Model Management Environment (FRAMME), Mapping Office, GIS Office, VistaMap (a desktop-viewing product built to work with MGE and FRAMME), Geomedia (a customisable geographic data integration system), Geomedia Network (for analysing transportation and logistics networks), Geomedia Web Map (for making data available over an intranet or internet), etc.

2.4.3.3 Genasys II Inc.

According to Rajani (1995) Genasys was founded as Delta Systems in 1976 by Carl Reed, a member of the project team that developed Map Overlay Statistical System (MOSS), a non-topological GIS used by the US government. The company released Genamap, the first UNIX-designed and implemented GIS software, in 1986. Genasys II acquired Delta Systems in 1989.

According to a survey in 1995 Genamap is the fastest growing GIS in the military arena (Editor, 1995a). Genamap is a comprehensive GIS that combines client/server

architecture with easy access to a wide set of functionality (Genasys, 1998). Servers exist for all the main DBMS vendors (ORACLE, Informix, Ingres, Sybase etc.). Other products that extend Genamap include GenaTIN (for TIN based terrain modelling), WebBroker (for full-function spatial analysis on the web), GenaVive (Virtual Image Viewing), GenaCell (for raster image management), Dispatcher API (based on CORBA principles and can be used to integrate third party applications), etc.

2.4.3.4 MapInfo Corporation

Founded in 1986 by four students at Rensselaer Polytechnic Institute (RPI), MapInfo was the first company to develop and market PC-based mapping software for business applications (MapInfo, 1998). MapInfo went public in February 1994 and can be found on NASDAQ/NM under the symbol MAPS.

MapInfo Professional, a comprehensive desktop mapping tool, is the company's flagship product. As a client, MapInfo Professional offers direct read/write capabilities to Oracle, Informix, Sybase and other DBMSs. From within MapInfo Professional, users can issue complex spatial and other relational queries that are processed on the server-side. Only the results of queries are returned, saving processing time and reducing network traffic. Some of the company's other products include MapInfo Desktop, MapMarker, MapXsite (a "find the nearest" application i.e. to integrate mapping functionality into a Web site), MapXtreme (a mapping application server for an Intranet or the Internet) and SpatialWare. Spatialware is an integrated spatial information management system using an Oracle7 database system. Like ESRI's SDE it allows you to combine business and spatial data. The company distributes over 300 application specific products developed by partners in each specific field. These products can roughly be divided into telecommunications, retail, financial services, insurance, utilities and the public sector.

2.4.4 Open systems (in the development phase)

Moore notes in his book, *crossing the Chasm* (1991, as quoted by Kiernan & Black, 1998), that to successfully mature, any technology must bridge the gap between use by a few sophisticated technicians and a much broader market. Mathews (1996) pointed out that the aim is to integrate GIS fully into the core business of the user, which invariably also requires office automation tools and a variety of special applications, usually running on the network. GIS vendors follow several strategies in order to bring the technology closer to widespread market acceptance, for example by moving GIS to the PC, improving the availability and accessibility of data, enhancing performance through interoperability, forming alliances with strategic companies (Wilson, 1997a), optimising opportunities of the internet, etc.

As mentioned previously the data are the most expensive and time-consuming component of any GIS. Existing data can be useful to other agencies and they are willing to pay for its use. The availability of geographical data differs from one country to another. Wilson (1997b) states that the digitisation of national data sets are completed in some countries, ongoing in others and just beginning in some. Although there are countries like the United States where government owned GIS data may be free, it is expensive in most countries while some countries still perceive maps as a matter of national security. Wilson (1997b) declares that if data are to be shared in a collaborative environment, standards are essential. The standards should consider a much broader community than just the federal government. Data compatibility is becoming a reality through efforts among software vendors and organisations such as the Open GIS Consortium (OGC), EUROGI or Japan's National Spatial Data Infrastructure Promotion Association (NSDIPA).

GIS vendors are searching new ways to support data sharing and common data sets. Today there are products like Intergraph's Geomedia that support several data formats and are able to read the data in its native form. Several vendors are supplying tools for the distribution of data over the World Wide Web (Limp, 1997). Autodesk's MapGuide, ESRI's Internet Map Server for MapObjects and for Arcview, Intergraph's Geomedia Web Map, MapInfo's ProServer and Genasys' WebBroker are examples of Web-based

mapping products that provide a new set of tools to enable interaction and response over the World Wide Web. According to Leidtke of Space Imaging EOSAT, the problem is that the telephone network by which GIS users send data has inherent speed limitations based on bandwidth for data transfer (Kiernan & Black, 1998).

The Open Geodata Interoperability Specification (OGIS) project was begun in 1993 with limited support from a few federal agencies and commercial organisations (OGC, 1998). After the original participants determined that a useful specification could be developed, OGC was founded in August 1994. Today key-player commercial organisations, universities and institutes from all over the world (including the United States, Germany, Norway, Switzerland, the Netherlands, United Kingdom, Canada, Italy, Finland, Japan, Czech Republic, South Korea, Greece, Austria, France, Spain, Singapore, Poland, etc.) are members of OGC. ESRI's Beddoe, who has been active on the OGIS technical committee since 1994, says the idea of interoperability is not to develop a super translator or even a common data model (Kiernan and Black, 1998). The specification would rather enable commonly used tools such as SQL, OLE/COM, or CORBA to access data in disparate systems and make them available to users on different platforms.

2.5 ARC/INFO AS AN EXAMPLE SYSTEM

ARC/INFO is a GIS software package with tools for automation, analysis, display and management of geographic information (ESRI, 1997). ARC/INFO was first released in 1982 and today ARC/INFO has world wide support with more than 60 000 users.

ARC/INFO's layered architecture is illustrated in Figure 2.6. The Database Engine forms the basis of the model and it can handle coverages, grids, tables, images and triangulated irregular networks (TINs). Vector data are saved in files called coverages. Grids represent ARC/INFO's spatial data in raster format. Attribute data are stored in tables (also referred to as info files). Item types like whole numbers, decimal numbers, characters and dates are supported in these tables. Images can be divided into two types of information, namely map images such as aerial photographs and satellite imagery, and descriptive images. Supported image formats include TIFF files, ERDAS and IMAGINE images, single-band images, band interleaved by line multiband (BIL) images, band

interleaved by pixel multiband (BIP) images, band sequential multiband (BSQ) images, Sun rasterfiles etc. TINs are used to represent surfaces with triangulated irregular networks.

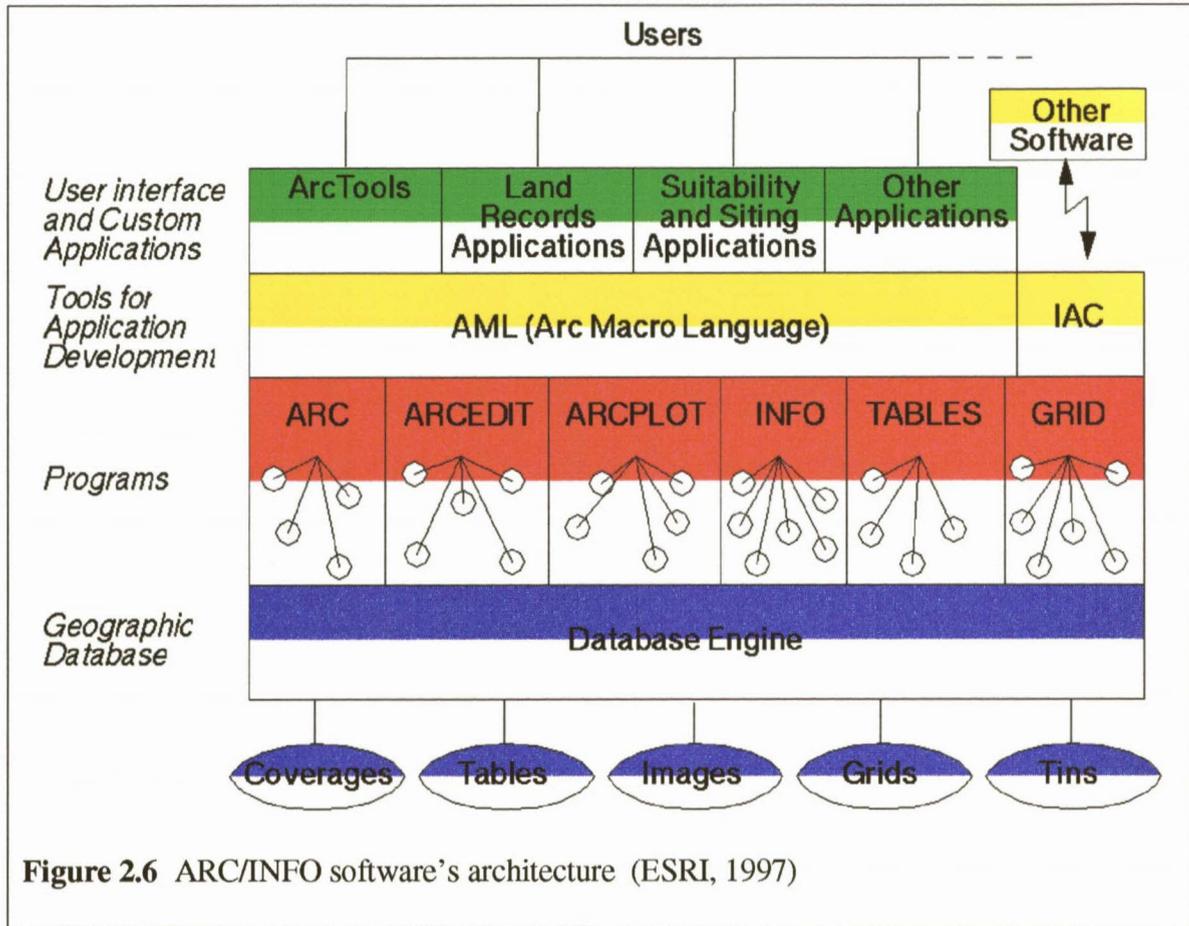


Figure 2.6 ARC/INFO software's architecture (ESRI, 1997)

The functions of ARC/INFO are grouped together into different subsystems/modules. For ease of use some of the functions are duplicated in several subsystems. Inter-Application Communication (IAC) tools make it possible to communicate with other software. The subsystems will be described shortly in the following paragraphs.

2.5.1 Arc

Arc is used for general housekeeping and is the overall manager. It is used to create, copy or delete coverages. Conversions of data from other systems are also done in this module.

2.5.2 Arctools

Arctools are menu driven tools written with the arc macro language. The source code is available to the user and it can easily be changed to suite the user's personal needs.

2.5.3 Info and Tables

Info and Tables are used to manage tabular data. Info is a complete database management system. Although Tables does not contain such a wide variety of functions as Info, it is easy to use when you want something done quickly.

2.5.4 Arcplot

Arcplot is mainly used to display and analyse vector data. High quality maps can be created with Arcplot.

2.5.5 Arcedit

Arcedit is used for the creation and editing of coverages. Coverages can be edited from a digitiser or with the mouse on the screen.

2.5.6 Grid

Raster data are displayed and analysed with Grid. All the Arcplot functions can also be called from Grid and thus vector and raster data can be used together during the analyses process.

2.5.7 Arc Macro Language

The Arc Macro Language (AML) is the macro language of ARC/INFO and it is used to develop applications. AML has its own commands called directives and functions, but any of the commands in the other subsystems can be called from an AML program. The

AML processor interprets each line of an AML program as it is encountered. The AML processor also interprets everything you type while you are using ARC/INFO.

GEOGRAPHIC DATA

3.1 INTRODUCTION

Geographic data can be divided into two categories namely spatial location- and attribute data. Examples of attributes are names, classifications and values. There is a third important characteristic of geographic data namely time. This characteristic makes the management of geographic data quite complicated since the spatial data and attribute data will not necessarily change simultaneously over time. An attribute like crop type might change while the area and position of a field stays the same. It is thus essential that spatial- and attribute data can be adapted individually. The time aspect does not only play a role in the maintenance of databases, but it is sometimes built into models as a fourth dimension where the first three dimensions define the location.

3.2 SPATIAL DATA

Spatial data are usually represented in digital form by vector- or raster data. Figure 3.1 gives an example of vector data and Figure 3.2 gives an example of raster data.

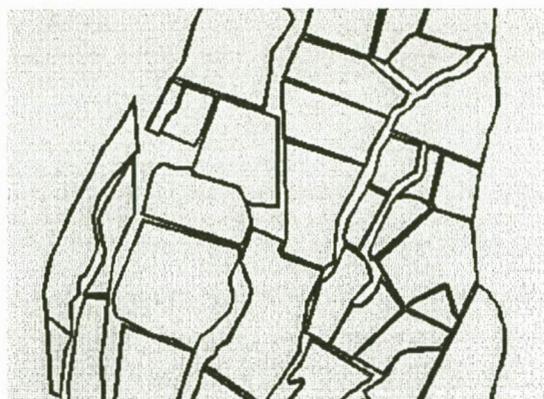


Figure 3.1 Vector data

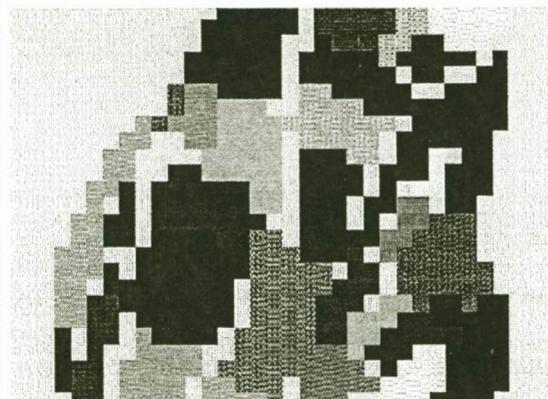


Figure 3.2 Raster data

3.2.1 Vector data

Vector data are saved as coverages in ARC/INFO. Different themes are usually saved as separate coverages. Roads, land-use and levees would for example each be saved as different coverages. Themes can be saved as points, arcs or polygons. Points are the most basic features and each point consists of a single x,y location and its attributes. Depending on the scale of the source, data entities such as trees, houses or even cities can be represented by points. Arcs represent linear features like roads or streams and each arc consists of a sequence of points. The beginning and ending points are referred to as nodes. Aerial themes are homogeneous areas enclosed by boundaries and are represented with closed polygons. Each polygon consists of one or more lines with a label point on the inside. Surfaces have three-dimensions and it can be represented in vector form by contour lines. Chapter four will be devoted to three-dimensional models.

Topology defines the spatial relationships between points, lines and polygons. The direction of an arc is for example determined by the direction from the first node to the last node. When the direction of an arc is known, the polygons on the left and right sides can be identified. Adjacency of polygons can thus be found. Other spatial properties that are defined through topology are the length of arcs, area and perimeter of polygons, connectivity of arcs, etc. There are two commands in ARC/INFO with which topology of coverages can be created namely 'build' and 'clean'.

3.2.2 Raster data

The whole area is covered with a grid of regular squares and a value is assigned to each cell in order to classify the objects. This type of data model is sometimes referred to as the tessellation model since regular and irregular triangles and hexagons have also been used (Zietsman, 1995:29). ARC/INFO's raster data are saved as grids. It is difficult to represent boundaries with the raster model and greater emphasis is therefore placed on the contents of areas rather than the boundaries between them. The dominant feature within a given cell is usually allocated to the cell. It might however be that rare features are given higher weights to ensure that they are included. Remotely sensed data are usually in raster form and can therefore easily be imported into a grid.

Specific colours are assigned to different cell values when a grid is displayed. The colours must be chosen in such a way that the results make sense to the reader. For continuous data like elevation a colour ramp is often used. The shades could for example be from brown to white, depending on the elevation. It is also advisable to emphasise important areas with bright colours.

Most calculations are easier on raster data than on vector data, but vector data gives more accurate answers. For instance the calculation of the area of an object of raster data is simply to count the number of cells, while the area of vector data must be calculated from the co-ordinates of the object.

Functions that can be applied to grids can be divided into five categories namely local-, local neighbourhood-, extended neighbourhood-, zonal- and global functions (Goodchild & Kemp, 1991:5.3-5.9).

3.2.2.1 Local functions

Local functions take only the current cell into consideration and do not depend on the values of the other cells. A new grid is created by applying the function to each cell. Examples of local functions include trigonometric functions, exponential and logarithmic functions and reclassification of values.

3.2.2.2 Functions on local neighbourhoods

With functions on local neighbourhoods a new grid is formed by taking the values of the neighbouring cells for each cell as input. Each cell takes its turn as the centre of a neighbourhood. The original values of previous cells are used when the neighbourhood centre moves over to the next cell. Examples of local neighbourhood functions are the sum, mean, minimum/maximum value, flow direction and standard deviation of the values in the grid for the cells in a specified neighbourhood.

3.2.2.3 Functions on extended neighbourhoods

This includes distance, buffering and visibility functions. It is often necessary to know the distance of each cell from a specific cell, or the nearest cell to several cells. An example of the application of buffer functions is noise buffers around roads. Visibility functions are needed by telecommunication services to implement transmission towers.

3.2.2.4 Functions on zones

A zone is a group of cells containing the same value. All the cells in a group do not have to be connected. Usually there will be two input grids where the first grid gives the areas of the zones while the second grid contains the actual values to be used as input to the calculations within the zones. Examples of zonal functions include identification of zones, area of zones, perimeter of zones, distance from the zone boundary and the shape of zones. Statistics that can be calculated on zones include the mean, standard deviation, minimum/maximum values and the sum of the values.

3.2.2.5 Global or per grid functions

Global functions describe the contents of layers. These functions consist mainly of statistical functions for example the most common value, mean, median etc.

3.3 ATTRIBUTE DATA

The properties (theme, area, length etc.) of objects are represented by attribute data. Chrisman (1997:9) states that S.S. Stevens, a psychologist at Harvard University, published a paper in *Science* in 1946 wherein he proposed a framework on what he called levels of measurement. This framework divided attribute data into four groups namely nominal-, ordinal-, interval- and ratio data.

3.3.1 Nominal attributes

Nominal attributes are used to identify objects. Examples of nominal attributes are names, telephone numbers, land use etc. Objects are classified in groups and nominal measurement is thus based on set theory.

3.3.2 Ordinal attributes

Ordinal attributes give a ranking to objects. Examples include the order of children by age and the places people received in a competition. Since ordinal data can be sorted in some way the objects are often related to numbers. For five soil types ordered from clay to sand the type with the highest clay content will be numbered one while the sand will be numbered five. It is however important to note that this does not necessarily allow arithmetic calculations. In the example of soil types the clay content of the different categories might not differ with the same value.

3.3.3 Interval attributes

On interval scales, the difference (interval) between numbers is meaningful, but the numbering scale does not necessarily start at zero. Intervals can be subtracted but not divided. 20°C is 10 degrees warmer than 10°C but it is not twice as warm as 10°C.

3.3.4 Ratio attributes

The main difference between ratio data and interval data is that ratio data have an absolute zero. Examples of ratio attributes that are common to geographic data are area, length and population. Ratio data can be divided; for example 20 km is four times as far as five kilometres.

3.4 DATA SOURCES

The reliability and quality of data will determine the accuracy of the results of any GIS. It is therefore important that the data source be chosen with care. Data used in GIS can be derived from many different sources and can be in digital or analogue form. Analogue sources have to be converted to a digital form before it can be used.

Depending on the form of the source data, different methods will be used to enter the data (ESRI, 1996). Map sheets are digitised manually on a digitising board or could be scanned automatically. Scanned data might require considerable processing and editing afterwards. ARC/INFO supports several image formats. The scanned data can be converted to a grid or coverage and then it can be edited using GRID or ArcScan software. ASCII formatted files and files from other systems should be converted into an acceptable format. Survey data can be entered from the keyboard or read from a file.

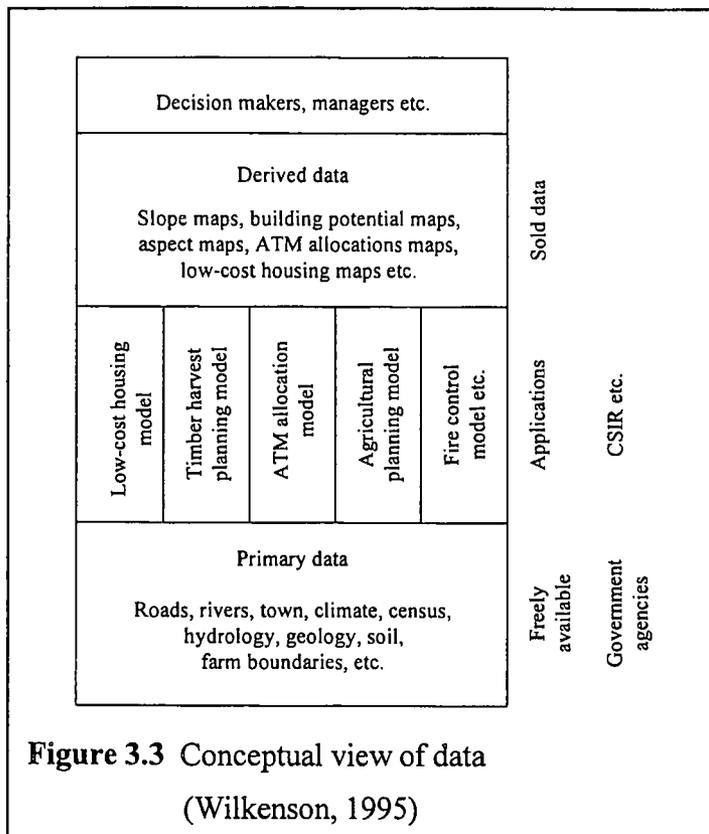
3.4.1 Existing data collections

According to Hine (1997) eighty percent of the cost of a GIS lies in the capture of data. Organisations should therefore interact productively and build on each other's efforts, not duplicate them (Wilkenson, 1995). Hine (1997) mentions that standards and control are important in data capture projects in order to make data sharing possible in South Africa. The conversion of the data is often as expensive as it would be to repeat the capturing process itself. The author mentions that any data captured as part of a federal project in the United States has to be captured to a standard laid down by law. Information such as who captured the data, how and why it was captured, to what level of accuracy, who the

owners are and the cost should be included when an organisation wants other users to utilise the data.

According to Fisher (1991:186) the main source of spatial data for GIS is archived records in government agencies. In the United States, for example, agencies such as the USGS, Bureau of the census, USDA SCS, US Fish and Wildlife Service, NASA, NOAA, etc. have large holdings of data that are available to the public. In the United Kingdom the availability of data is very different since all information is controlled by the Crown copyright. In both the United States and the United Kingdom privacy and confidentiality are also of concern in instances where data may reveal information of individuals. The main advantage of data derived from government agencies is that the data are usually generated by experienced operators to a specific set of published standards.

Obermeyer and Pinto (1994) pointed out that data sharing amongst organisations are usually made possible through alliances. The researchers listed three distinct contexts requiring interorganisation GIS information sharing. The first sharing context is project driven, where two or more agencies come together to work on a common problem that both parties need to address. The two organisations bring their own data and expertise to the table and share data with each other in an effort to successfully solve the problem. The second sharing context is one in which different agencies may be addressing completely different problems but have a need for very similar information. The organisations will then develop procedures and protocols by which they can regularly share and exchange information with each other. The third context of information sharing is based on the development of standardised or generalised patterns of exchange. In this context, information is readily accessible to all parties and can be accessed in useful forms from a central location, such as a data bank.



There are two types of data namely primary and secondary (or derived) data (Wilkenson, 1995:58; Maguire, 1989:16). Decision-makers are not interested in the primary data, but in the derived data. Wilkenson (1995) suggests that primary data should be captured by government agencies and should be freely available (see Figure 3.3). The derived data, because of the specialist application and scientific content,

should be the data that are sold. The major trend today is that all data is sold and exchanged on a market basis in South Africa.

3.4.2 Analogue maps

When there is no digital data available for an area or when the existing data are outdated or for some other reason unsuitable for a project, the only way out might be to digitise analogue maps. According to Fisher (1991:186-187) an organisation has one of two options. They may either set up a digitising program within the organisation, or contract the database preparation to a third party. Digitising devices are described in Paragraph 2.2.1.1.

Each of these options has advantages as well as disadvantages. Staff will have to be trained in software and hardware use when the database is developed internally. The training process will take some time and it might be that at the end of the project the organisation is left with highly skilled digitising technicians with no digitising to do. The

advantages on the other hand are that the organisation has day to day control of data entry and can rapidly respond to requests for fresh information or to altered circumstances. The second option, where a third party is contracted, has exactly the opposite characteristics. The contracting company should have highly experienced staff. The contractor will also handle all data conversion and transfer problems that might rise. The disadvantage of this option is that the organisation may be left without skilled technicians who can maintain and update the database when necessary.

Fisher (1991:186-187) suggests that a combination of the two options be used. The mass digitising should be contracted while a small in-house group is trained to be able to edit and update the data. This group should work closely together with the contracted company.

3.4.3 Collecting data by field observations

Data of the area can be collected by means of *in situ* measurements or it can be remotely sensed. Both of these methods will require highly specialised people and would probably be more expensive than it would be when existing data could be bought or when the data could be digitised from analogue maps. It should be taken into consideration that the digitising process is time consuming.

3.4.3.1 *In situ* data collection

In situ data collection may include personally conducted questionnaires, field notes and readings from instruments such as GPS and data loggers. A description of data loggers and GPS will follow in the next two paragraphs. The paragraph on data loggers will focus on data loggers that are mounted at specific sites of which the locations are known. The sites are usually represented with a point coverage in ARC/INFO and these applications are excellent examples where time is implemented as the fourth dimension in a model. Portable data loggers will be mentioned briefly in the following paragraph because it is usually used in conjunction with GPS when GIS data are gathered.

3.4.3.1.1 Data loggers

Data collection systems, for example automatic weather stations, usually consist of a data logger with connected sensors and a telecommunication system with which the data can be remotely downloaded. According to Campbell Scientific (1996) data loggers are used in the following applications:

- In meteorology for long-term climatological monitoring and routine weather measurement applications.
- In agricultural applications such as plant water research, canopy energy balance, crop management decisions, frost prediction, irrigation scheduling and integrated pest management.
- For the monitoring of hydrologic measurements for example water level, ionic conductivity, water quality etc. It is also often used for flood warnings.

Data loggers contain a microprocessor, memory and input and output keypad for data logger interrogation (Savage, 1998:2). Data loggers record data over time (Campbell Scientific, 1996). Measurements are usually processed and stored as hourly and daily summaries (e.g., maximum, minimum, averages, etc). The data are received from attached sensors that give the measures in analogue form. The data logger does an automatic analogue to digital conversion on the signals and can also be programmed to do certain calculations on the measurements. According to Savage (1998) some types of data loggers not only allow for sensor measurement, but also for actions based on measurements for example the control of solenoids for irrigation and alarm systems. Triggered by measured conditions or time, the data logger can initiate on-site alarms or activate pagers. A data logger requires a power supply and batteries charged by solar panels are usually used. The solar panel should recharge the battery fully on an average day and the battery that is used should be able to power the system for at least a week. Some data loggers are able to automatically switch on and off when measurements are taken to save energy.

Sensors are typically used to measure solar irradiance, air temperature, relative humidity, wind speed, wind direction, precipitation, rainfall intensity, soil temperature, leaf wetness,

water content, etc. The thermistor for example is a device that changes its electrical resistance with temperature (Strahler & Strahler, 1997). By measuring this resistance, the temperature may be obtained automatically. Instruments that measure relative humidity use a thin layer of a special material bonded to a metal film. The material absorbs water vapour in an amount depending on the relative humidity. The water vapour affects the ability of the film to hold an electric charge. This ability is sensed by an electronic circuit and can be converted to a direct reading of relative humidity. Inaccurate or uncalibrated sensors will result in bad data and maintenance of the sensors is therefore important. Several sensors can usually be connected to a data logger.

The use of telecommunication systems enables one to obtain real-time data from a number of different sites (Savage, 1998). A computer, modem and telephone line is often used, but the telephone line gives problems as lightning can damage the data logger. Alternative methods of communication include radio frequency (for which a line of sight with a radius of 25 km between the data logger and computer is necessary), satellite communication and the use of cell phones. Despite the high initial cost of the equipment for the radio frequency option, in the long term it is less expensive than cell phones because of the high running costs of the cell phone.

The data from the data logger are saved in a text file and conversion programs can be written to import the data into a GIS. Some post processing of the data might also be necessary before it is imported into the GIS.

3.4.3.1.2 The Global Positioning System (GPS)

Martin Mur and Dow (1997) describe the origin of GPS. Characteristics of the orbits of early satellites were determined by the variations of signals that were being radiated by the satellites. Within a short time the idea of using the inverse process was developed; if, by knowing your position you could determine the orbit of a satellite, it should also be possible to use the signal transmitted by satellite in a known orbit in order to determine your own position. This concept was implemented in a series of satellites sponsored and operated by the US Armed Forces. Firstly the Transit satellites were deployed, then the Timing and finally the NAVSTAR Global Positioning System. In response the Soviet

Union developed and deployed similar Global Navigation Satellite Systems namely Tsikada and GLONASS. The European Geostationary Navigation Overlay Service (EGNOS) is still in the development stage and will give increased integrity and accuracy to users in Europe. The NAVSTAR GPS is the most widely used of these systems and is usually referred to as GPS.

GPS can be divided into three segments namely the space, control and user segments (Dana, 1998). The space segment consists of 24 satellites: 21 navigational space vehicles (SVs) and three active spares that orbit the earth in 12-hour orbits. The satellites repeat the same track and configuration over any point approximately every 24 hours (four minutes earlier each day). The satellite constellation provides the user with between five and eight SVs visible from any point on the earth.

The control segment consists of a system of tracking stations located around the world (Hawaii, Ascension Island Diego Garcia, Kwajalein and Colorado Springs). The master control facility is located at Falcon Airforce Base in Colorado. These monitor stations measure signals from the SVs that are incorporated into orbital models for each satellite. The orbital models compute precise orbital data and SV clock corrections for each satellite. The master control station uploads orbital data and clock data to the SVs and the SVs then send subsets of the orbital data to GPS receivers over radio signals from space.

The User segment consists of the GPS receivers and the user community. GPS receivers convert SV signals into position, velocity and time estimates. At least four satellites are required to compute the four dimensions of x,y,z (position) and time. Accuracy is intentionally degraded for non-US military and government users by a time varying bias, called Selective Availability (SA). Differential corrections can be used to overcome this problem as the SA is a changing bias with low frequency terms in access of a few hours.

The differential GPS technique uses two receivers, where the position of the one receiver (a reference receiver or base station) is known. The base station computes corrections for the bias errors of each satellite signal received by the differential receiver. According to Graham (1997) differential GPS should be used to achieve accuracy better than 100 meters. Depending on receiver design and operating conditions accuracy less than a centimetre can be achieved.

GPS receivers automatically store measured positions in the field and some receivers also provide for attribute data. GPS receivers are often combined with portable data loggers. When the sensor data and positional data are not saved together it can be combined with a post processing system. The data from most systems can be saved in DXF format and can therefore easily be converted to ARC/INFO coverages.

Real-time mapping software packages exist that combine structured data collection with GPS positioning. The ASPEN software (Trimble, 1997) will be used to describe the process, but several other software packages exist that can be used. Graham (1997) evaluated PenMap, GeoLink, PowerMap, AgDirect and Aspen field software.

The windows-based Aspen software runs on both pen and notebook computers (Trimble, 1997). The software is designed for use with Trimble's Pathfinder Card and a GPS receiver. Existing background maps can be displayed on the field computer to provide a visual reference for a data collection session.

Point, line and area positions can be collected. Point features are collected by visiting the feature and recording the GPS data and attribute information. For line features GPS positions are recorded periodically as you move along the feature. The positions can be logged by distance or time intervals for example every meter or second respectively. The software will join these positions to form a line and then attributes can be allocated to it. Area features are collected in the same manner as line features with the exception that the last position is automatically connected to the first position.

Real time differential correction or post-processed differential correction can be applied. Aspen software supports the use of laser range-finders and external sensors such as digital cameras, magnetometers and echo sounders. The sensor data are saved as attribute values. Several other functions exist for quick and efficient data logging, but lies outside the scope of this paragraph. Aspen software supports ARC/INFO coverages.

3.4.3.2 Remotely sensed data

Floyd and Sabins (1978:1) define remote sensing as the collection of information about an object without being in physical contact with the object.

3.4.3.2.1 The electromagnetic spectrum

In a remote sensing system sensors usually record electromagnetic radiation that was in interaction with the surface of the earth (Curran, 1985; Floyd & Sabins, 1978; Cracknell & Hayes, 1991; LO, 1986; Jensen, 1986; Richards, 1993). Cracknell and Hayes (1991:2) however mention that there are other means of seeking or transmitting information apart from using electromagnetic radiation as the carrier of the information in remote sensing activities. For example ultrasonic waves are usually used for under water remote sensing.

Electromagnetic energy refers to all energy that moves with the velocity of light in a harmonic wave pattern (Floyd & Sabins, 1978; Oppenheimer, 1997). The electromagnetic spectrum (see Figure 3.4) is the continuum of electromagnetic energy ranging from gamma rays with wavelengths smaller than 0.03 nm through x-rays, microwave and radio waves, the 5000 km waves radiated by electric power lines

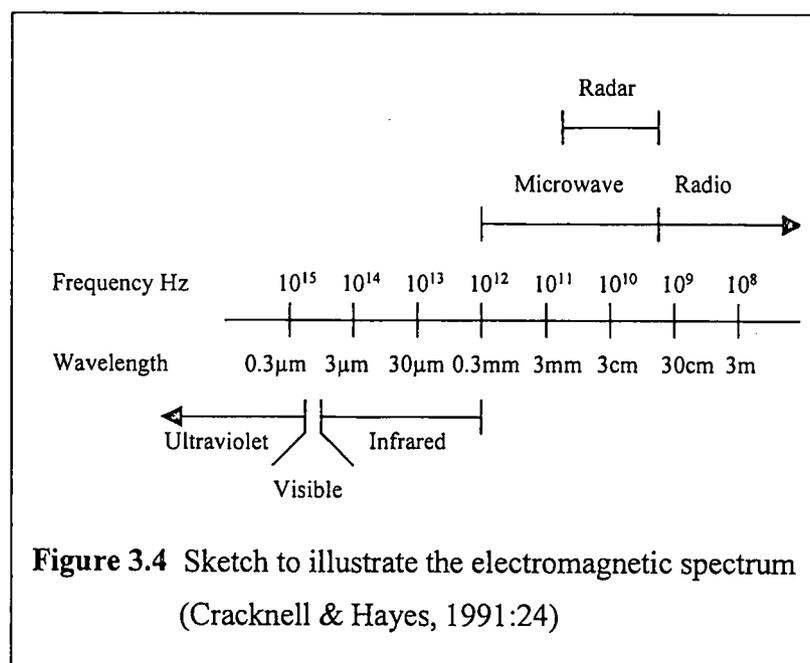


Figure 3.4 Sketch to illustrate the electromagnetic spectrum (Cracknell & Hayes, 1991:24)

to still longer waves. Radiation from only part of this range of wavelengths is useful for the remote sensing of the surface of the earth (Cracknell & Hayes, 1991).

Sensors measuring electromagnetic radiation can be mounted on either aircraft or satellite

platforms. Reflected or emitted electromagnetic radiation is measured on different ranges of the electromagnetic spectrum, depending on the type of sensor used. The most commonly used ranges in the electromagnetic spectrum (see Figure 3.4) are the visible, infrared and microwave bands. The visible band extends from blue light with a wavelength of about 0.4 μm to red light with a wavelength of about 0.75 μm .

These sensors normally produce two-dimensional images of a part of the surface of the earth. According to Richards (1993) the images are spatially composed of discrete picture elements, or *pixels* that are radiometrically quantised into discrete brightness levels. Variations in the image field may denote variations in the colour, temperature or roughness of the area viewed (Cracknell & Hayes, 1991:22). Different characteristics are usually measured in different ranges of the electromagnetic spectrum. A thermal infrared (4-12 μm) sensor can for example measure the temperature of a rock or water body by measuring the radiant flux emitted from the surface of the material while the roughness of cover types is determined in the microwave range. Curren (1985:23-26) gives an example of the interaction of visible, near infrared and middle infrared wavelengths of electromagnetic radiation with vegetation. The major differences in leaf reflectance between species, are dependent upon leaf thickness that affects both pigment content and physiological structure. The region of pigment absorption lies in the visible waveband (0.4-0.7 μm), while physiological structure is visible in the near infrared waveband (0.7-1.3 μm). Water content is visible in the near and middle infrared waveband (0.9-2.6 μm).

Jensen (1986:2) listed nine biophysical variables that may be remotely sensed namely: planimetric (x, y) location, elevation, object colour, vegetation chlorophyll absorption characteristics, vegetation biomass, vegetation moisture content, soil moisture content, temperature and texture or surface roughness.

The main source of electromagnetic radiation is the sun. Passive sensors detect the reflected and emitted radiation from the earth's surface. Radiation emitted from the earth's surface is usually measured at night. In an active instrument the radiation is generated by the instrument, transmitted downwards to the surface of the earth, reflected back to the sensor and the received signal is then processed to extract the required information (Cracknell & Hayes, 1991:22). Satellite remote sensing systems operating in

the visible and infrared parts of the electromagnetic spectrum are passive, while microwave instruments can be either passive or active. Active instruments operating in the visible and infrared parts of the electromagnetic spectrum are however flown on aircraft.

3.4.3.2.2 Satellites versus aircraft as platforms for sensors

A satellite has the advantage of regularity of coverage and a scale of coverage (in terms of area on the ground) that could never be achieved from an aircraft (Cracknell & Hayes, 1991:22). On the other hand it could be said that aircraft flies so much lower than satellites with the result that far more detail of the ground can be provided by sensors mounted on aircraft than from sensors on satellites. There is also a great difference between the altitude stability of aircraft and the stability of a satellite in orbit (Richards, 1993:17-18). Because of atmospheric turbulence, variations in aircraft altitude can lead to excessive image distortion. The field of view (FOV) which is the scan angle either side of the nadir over which data is recorded, can cause significant distortions in image geometry, at the edges of the scan, from aircraft altitudes. In the case of aircraft scanning the FOV is typically 70° to 90° while that for LANDSAT satellites four and five is about 15°.

The user can often select the wavebands of interest in a particular application, with the use of airborne multi-spectral scanners and small bandwidths can be used (Richards, 1993:18). Also, the mission can be flown to specific user requirements.

Table 3.1 lists several remote-sensing sensors to illustrate the difference in spatial-, spectral and temporal resolution between different systems. According to Carlson (1997) a new generation of imaging satellites was scheduled to be launched during 1997 and 1998. These satellites would offer spatial, spectral and temporal resolutions that were never before available to the public.

Table 3.1 Resolutions of various remote-sensing sensors (Eloff *et al.*, 1998)

Instrument or sensor	Spatial resolution	Spectral resolution	Temporal resolution (pass-over cycle)
NOAA satellite, Avhrr	1 x 1 km	5 bands	1 day
Landsat satellite TM	30 x 30 m	7 bands	16 days
SPOT satellite: -multi-spectral -panchromatic	20m 10m	3 bands 1 band	26 days
Airborne Multi-spectral Videography (DMSV)	3m – 0.75m	4 bands	On demand

NOAA = National Oceanographic and Atmospheric Agency satellite, USA

Avhrr = Advanced Very High Resolution Radiometer

TM = Thematic Mapper instrument on American Landsat satellite

SPOT = French earth observation satellite

DMSV = Digital Multi-Spectral Videography System

3.4.3.2.3 Processing of remotely sensed images

Morel and Solimini (1995) defines digital images from a mathematical viewpoint as functions $g(x)$ where x is a point of the image domain Ω (the plane) and $g(x)$ is a real number representing the brightness of the image at point x . This image is unstructured and the different objects have yet to be identified. Jensen (1986) describes the image processing considerations an image analyst should consider in Table 3.2.



Table 3.2 Overview of image processing considerations

1. Statement of the problem <ul style="list-style-type: none"> • Identify criteria • Formulate hypothesis 	6. Pre-processing <ul style="list-style-type: none"> • Radiometric correction • Geometric correction
2. Data acquisition <ul style="list-style-type: none"> • Digitise data or • Collect or purchase digital data 	7. Image enhancement <ul style="list-style-type: none"> • For further digital analyses • For visual analyses
3. Image processing system <ul style="list-style-type: none"> • Select or configure appropriate technology 	8. Thematic information extraction <ul style="list-style-type: none"> • Identify criteria • Perform supervised or unsupervised analyses • Evaluate accuracy
4. Initial statistics extraction <ul style="list-style-type: none"> • Compute univariate and multivariate statistics to access image quality 	9. Geographic information system <ul style="list-style-type: none"> • Place thematic information in raster or vector based GIS
5. Initial display <ul style="list-style-type: none"> • Video or hardcopy display to access image quality 	10. Solve problems <ul style="list-style-type: none"> • Accept or reject hypothesis

The pre-processing and thematic information extraction, mentioned in Table 3.2, will be described in more detail.

Pre-processing includes radiometric- and geometric correction. Radiometric correction is necessary because electromagnetic energy is distorted and scattered when it passes through the atmosphere. The design and operation of the sensor system can also cause radiometric errors (Richards, 1993:42). Radiometric correction involves the rearrangement of the digital numbers, representing the brightness of pixels, in an image so that all areas of the image have the same linear relationship between the digital numbers and either radiance or backscatter (Moik, 1980 as quoted by Curran, 1985:190). According to Walsh *et al.* (1998:187) the histogram-adjustment approach or the regression approach are usually followed.

There are several factors that cause geometric distortion. According to Lo (1986:8-12) the central perspective projection in vertical aerial photographs gives rise to relief displacements caused by the heights of the terrain from the datum plane. This displacement causes objects for example buildings to "lean" away from the centre of the

photograph, with the amount of displacement at greater radial distances from the centre (Floyd & Sabins, 1978). Greggor (1995) mentions that geometric displacement can also be due to perspective stretching when the camera is tilted and to variations in the terrain heights. According to Curran (1985) geometric correction can involve a large number of image manipulations, like the correction of predictable sampling errors that arise from changes in aircraft or satellite altitude, or the alteration of image projection to produce a stereo pair of images, or the distortion of an image to make it fit onto another image or map (often referred to as rubber-sheeting (Greggor 1995)). Stereoplotters and Digital Photogrammetric Workstations (DPW) can be used to produce a stereo pair of images and will be described in Chapter 4.

According to Richards (1993:229,234) unsupervised classification is the technique whereby an image is segmented into unknown classes. Pixels within a given group are usually given a symbol to indicate that they belong to the same spectral class. Using these symbols a cluster map can be produced from which the user can label the classes. The analyst therefore plays no part until the computational aspects are completed, except for giving the number of classes into which the picture should be classified.

Land use ground control data are used in supervised classification to cluster image elements (Zietsman *et al.*, 1996). Richards (1993) lists the following steps that are usually followed:

- Decide on the set of ground cover types (e.g. water, urban regions, croplands, rangelands etc.) into which the image is to be segmented.
- Choose representative pixels (training data) from each of the desired set of classes. Training data can be established using site visits, maps, air photographs etc.
- Use the training data to estimate the parameters of the particular classifier algorithm to be used. This set of parameters for a given class is sometimes called the signature of the class.
- Use the classifier algorithm to classify every pixel in the image into one of the required ground cover types.

Digital data from multi-spectral scanners with N channels can be regarded either as an array where the elements of the array are n dimensional vectors, or as a set of N co-registered arrays (Cracknell & Hayes, 1991:173). Coloured images can be generated when N is equal to three. According to Marion (1991:248-250) mixing the three primary colours can reproduce any colour. By convention one band is assigned to red, another to green and a third to blue. The image will represent the true colour of the original object or scene when the red, green and blue ranges in the visible band are used. False colour images attempt to display "in colour" views of the scene using different bands of the spectrum. In the case of data from the multi-spectral scanner on the LANDSAT series of satellites, for example, bands one, two and four are often assigned to the colours blue, green and red respectively (Cracknell & Hayes, 1991:174). Terrain with healthy vegetation that has a high intensity of reflected radiation in near infrared (band four) and very little reflection in yellow-orange (band one) will appear red, while areas of water, with very little reflected radiation in near infrared (band four) will appear blue.

It is wasteful to load every waveband of data into the image processor, as the use of highly correlated wavebands will increase computing time rather than classification accuracy (Moik, 1980 as quoted by Curran, 1985). According to Zietsman *et al.* (1996) the selection of optimum band combinations became a critical means of reducing the amount of data and the high dimensionality of satellite data. The authors identified the following band selection techniques:

- Sheffield algorithm (Sheffield, 1985 as quoted by Zietsman *et al.*, 1996).
- Jeffreys-Matusita distance (Mausel *et al.*, 1990 as quoted by Zietsman *et al.*, 1996).
- Divergence (Mausel *et al.*, 1990 as quoted by Zietsman *et al.*, 1996).
- Transformed divergence (Mausel *et al.*, 1990 as quoted by Zietsman *et al.*, 1996).
- Bahattacharyya distance (Mausel *et al.*, 1990 as quoted by Zietsman *et al.*, 1996).
- Mutual information analysis (Conese & Maselli, 1993 as quoted by Zietsman *et al.*, 1996).
- Optimum index factor (Lourens, 1990 as quoted by Zietsman *et al.*, 1996).

3.5 APPLICATIONS IN FLODSIM

The reliability and quality of input data will determine the accuracy of the results that Flodsim will give when it is applied to other floodplains. The source data should therefore be chosen with care. The methods described in this chapter can be used to acquire data representing land use, infrastructure, buildings etc. Remote sensing can be of great value in updating land use patterns. A video-based survey was conducted in collaboration with Environmentek (Thomas, 1996) to determine land use for the Lower Orange River floodplain. The procedures that were followed will be described in the following paragraphs.

3.5.1 The use of video remote sensing to determine land use for the Lower Orange River floodplain

3.5.1.1 Survey execution

A Canon UC-40 HI-8 format colour video camera was mounted to a custom-made steel construction secured to the aircraft's floor using the passenger seat's rails that were accessible by removing the passenger seat (Thomas, 1996). This served two functions in providing a means to:

- Securely fasten the camera to the aircraft
- Reduce the transmission of aircraft vibration to the camera

The survey was performed from approximately 1.5 km above ground level. Throughout the flight, the pilot flew a route downstream along a course that followed the centre of the river and used the live pictures from the on-board monitor. Where significant areas of irrigation lay outside the swath (approximately 2.35 km) on the ground, parallel overlapping flights were flown to cover the whole area. The flying conditions during the flight were stable, but cloud-cover was approximately 80 percent.

A field reconnaissance was performed by car through visiting a number of locations within the survey area, referencing the crop-types, and marking these locations on 1:50 000 maps.

3.5.1.2 Data conversion

Framegrabbing was performed on a PC using a programme called *Micro Video DCI* (Thomas, 1996). A capture rate of one video frame per every 30 seconds was applied to give an approximate 10 percent linear overlap of the survey area. The images were saved as an Audio Video Interleaved (AVI) file. This file was then converted using a programme called *Graphic workshop 95*, to Joint Photographic Expert Group (JPEG) format files. The resultant file size was 0.2 MBytes each, and displayed 256 colours. The whole of the survey area was covered by 72 separate images, amounting to approximately 14.2 MBytes of digital data.

3.5.1.3 Classification of crops

ERDAS Imagine image processing software was used to investigate supervised- and unsupervised classification techniques (Thomas, 1996). The digitally based classification was abandoned because:

- Inter-class colour inconsistencies were found due to variable lighting conditions caused by the cloud cover
- Intra-frame lighting variation was caused by lens effects

Erdas Imagine was then used in an attempt to use an automatic edge detection technique to find field boundaries. This procedure worked well for fields with high contrasting boundaries, but poorly where lighting conditions provided low boundary contrasts. Cloud cover often determined the extent of contrast, and because of these inconsistencies, this approach was also abandoned. It was then decided to use a process called air photo interpretation (API) where the analyst uses his own ability to differentiate cover classes from shape, size and human reasoning.

The following procedures were carried out before API could be applied:

- Each image was printed in colour using a HP DeskJet 1200 printer
- The hardcopy images were then mosaiced by overlapping sequential frames on a surface, referencing and overlaying common features in overlapping areas. The sections were then secured in position using sellotape
- The images were then overlaid by transparent acetate sheets on which annotation could be done by using a mapping pen

The annotated acetates were then digitised using PC ARC/INFO to create a polygon coverage. Common features like prominent field boundaries, road junctions, bridges, and buildings were located in both the image mosaics and 1:50 000 map sheets and used as ground control points for geo-referencing. Approximately 175 well-distributed ground control points were used.

Geometric distortion was caused by the use of an angle lens at a 5.4 mm focal length during the survey. The distortion increased in magnitude away from the centre of the frames.

3.5.1.4 Comparison of the video-based survey with the original data

In a survey conducted by Viljoen *et al.* (1996) in 1992 all the cultivated fields were visited by means of a vehicle and the crop types were recorded. The life expectancy of vineyard varies between 15 and 50 years (Viljoen *et al.*, 1995:110). The cultivated fields that were classified as vineyard by means of the video remote sensing could therefore be compared with the original data with a small margin of error.

The video survey covered a narrower area than the original land use coverage. In order to be able to compare the two surveys, the coverages had to cover the same area. The cultivated fields in the area that was photographed were selected from the original land use coverage and saved as a new file. When two or more fields with the same crop type lay next to each other the boundaries were often not recognised and the fields were then regarded as one field. The video survey therefore showed only 992 fields where there should have been 1 224 fields.

The original land use coverage was then updated with the data from the video survey by using the zonal functions in ARC/INFO. Both coverages were converted to grids. The original data land use data were regarded as the zones, while the crop type from the video survey that occurred the most in each zone were assigned to the corresponding zone. The results were saved in an INFO file and could then be related to the original land use coverage.

When the original land use coverage is updated with the data from the video survey only 293 from the original 634 vineyard fields stayed the same. An accuracy of approximately 46 percent was therefore found with the classification. The accuracy of the classification could be increased by flying lower in sunny weather and a time of the year when contrasts in land coverage is at its best. This would increase the resolution of the images and the texture of cultivated fields for instance the rows in which vineyards are planted would be better distinguishable. Direct sunlight would also improve the accuracy.

DIGITAL TERRAIN MODELS

4.1 INTRODUCTION

A digital elevation model (DEM) represents the spatial distribution of elevations above some arbitrary datum in a landscape (Moore *et al.*, 1991:3). Other surface attributes such as gradient and aspect may be derived from the DEM and stored as a digital terrain model (DTM) (Skidmore, 1990:33).

Mainly three structures are used to represent elevation data namely triangular irregular networks (TINs), grids and contour lines (De Vantier & Feldman, 1993; Moore *et al.*, 1991; Carrara *et al.*, 1997; Tachikawa *et al.*, 1994:9). It is important to consider the way in which the surface representation is to be used (Moore *et al.*, 1991:4). The ideal structure for a DEM may be different if it is used for a dynamic, hydrological model than if it is used to determine the topographic attributes of the landscape.

Most commercial GISs have the ability to transform between contour lines, grids and TINs (De Vantier & Feldman, 1993:249). Contour-based methods require an order of magnitude more data storage space, so that the transformation is typically from contour lines to other forms.

Topographic attributes such as slope, specific catchment area, aspect, plan and profile curvature can be derived from all three types of DEMs (Moore *et al.*, 1991:5). However the most efficient DEM structure for the estimation of these attributes is generally the grid-based method. The irregularity of the TIN makes the computation of attributes more difficult than for the grid-based methods. According to Tachikawa *et al.* (1994) contour-based methods have a great advantage for hydrologic modelling in considering the

directions of water flow, but it requires heavy data storage and much computation time. A grid-based DEM is used in FLODSIM and the main focus of this chapter will therefore be on the grid-based DEM.

4.2 TRIANGULAR IRREGULAR NETWORKS

Mirante and Weingarten (1982, as quoted by Buys, 1991:9) defines a TIN as a mesh where the three dimensional co-ordinates are linked into non-overlapping triangles of irregular size. Delauney triangulation is usually used to allocate a unique set of triangles to describe the terrain and ensure bounded errors on the interpolation of bi-variate data at randomly sampled points (Tsai, 1993). The triangles are selected on the criteria that no data point lies inside the circumcircle of any other triangle. One of the advantages of the TIN model is that it can describe a topographic surface at different levels of resolution.

Streams can be defined in terms of triangle boundary segments (De Vantier & Feldman, 1993:249). This allows a more continuous description of stream paths. By comparison grid data tend to produce zigzag paths for streams on up-slope portions of a watershed.

4.3 ALTITUDE GRIDS

The regular grid has become the most available form of DEM because of the ease with which matrices can be handled in the computers and its computational efficiency (Burrough & McDonnell, 1998:122). Britain, Australia, the USA, etc. are completely covered by coarse matrices derived from 1:250 000 scale topographic maps.

Grid-based methods may use a regular spaced triangular-, square- or rectangular mesh or a regular angular grid such as the three arc-second spacing used by the U.S. Defence Mapping Agency to represent elevation data (Moore *et al.*, 1991:4).

A grid in ARC/INFO is composed of square cells that are all of the same size for a given grid (ESRI, 1993:1.3). An elevation is assigned to the cell that covers the location where a measurement was taken.

Moore *et al.* (1991:4) lists several disadvantages of grids:

- They cannot easily handle abrupt changes in elevation.
- The size of gridmesh affects the results obtained and the computational efficiency.
- The computed up-slope flow paths used in hydrologic analyses tend to zigzag and therefore are somewhat unrealistic.
- Precision is lacking in the definition of specific catchment areas.
- Since regular grids must be adjusted to the roughest terrain, redundancy can be significant in sections with smooth terrain.

4.4 CONTOUR LINES

According to Moore *et al.* (1991:5) contour based methods consist of digitised contour lines that are stored as digital line graphs (DLGs) in the form of x, y co-ordinate pairs along each contour line of specific elevation. The DLGs can be used to subdivide an area into irregular polygons bounded by adjacent contour lines and adjacent streamlines and are based on the stream path analogy first proposed by Onstad and Brakensiek (1968, as quoted by Moore *et al.*, 1991:5).

The contour interval is usually constant over the entire area of interest, while the distance between contour lines is inversely proportional to the terrain slope (Kraus, 1994:457). The accuracy of the contour lines in the XY-plane can be obtained by the following formula:

$$\sigma_{zp} = \frac{\sigma_z}{\tan \alpha} = \sigma_z \frac{\Delta Z_p}{\Delta Z}$$

Where:

- $\tan \alpha$ is the maximum terrain slope at a specific point
- ΔZ is the contour interval
- ΔZ_p is the distance to the neighbouring contour lines in the XY-plane.

4.5 GENERATION OF DIGITAL ELEVATION MODELS

The sources used to derive DEM data vary from ground surveys, photogrammetry and existing contour maps to radar or laser altimetry. The source used will determine the quality and cost of the DEM. According to Weibel and Heller (1991:271), a DEM constructed from ground surveys is very accurate seeing that surveyors usually adapt the survey to the character of the terrain in measuring significant terrain points. Unfortunately, ground surveys are time consuming and are usually only applied to small areas. Laser technology is relatively new, but according to Schutte (1997b) the accuracy is quite impressive and current users achieve 15 centimetre elevation accuracy. According to ESCOM's estimate the cost of acquiring DEM data using an airborne laser system is in the order of 25 percent to 40 percent that of acquiring the same amount of DEM data by aerial survey methods (Schutte, 1997b). If contour maps of the area exist it is perhaps the cheapest way to acquire a DEM, but with a loss of accuracy. The main disadvantage of contour maps is that an excessive number of points are sampled along contours and no data is sampled across contours (Weibel & Heller, 1991).

4.5.1 Ground surveys

Elfick *et al.* (1995:1) defines surveying as the science and art of determining relative positions of points above, on, or beneath the surface of the earth. It is the researchers' experience that photogrammetry has replaced ground surveys in many kinds of projects, except for small areas. Conventional ground methods are still used to acquire horizontal and vertical control points when photogrammetry is used (Elfick *et al.* 1995:6).

Surveying is a specialised field and it should only be done by professional surveyors who are familiar with the different kinds of measurement errors, their sources and expected magnitudes under varying conditions and the manner of propagation (Elfick *et al.*, 1995:13).

Total station instruments (also known as electronic tacheometers) are usually used for ground surveys (Elfick *et al.*, 1995:72-81). A total station instrument consists of an electronic distance measuring instrument (EDM), electronic digital theodolite, and

computer in one unit. EDM's determine lengths by measuring the time it takes laser or infrared light to travel from the total station instrument to a retro-reflector and back. The travel time multiplied by the velocity yields the distance. The electronic digital theodolite automatically measures and displays horizontal and vertical angles. The horizontal and vertical angles together with the slope distance are automatically transmitted to the built in computer where the horizontal and vertical distances are computed and stored.

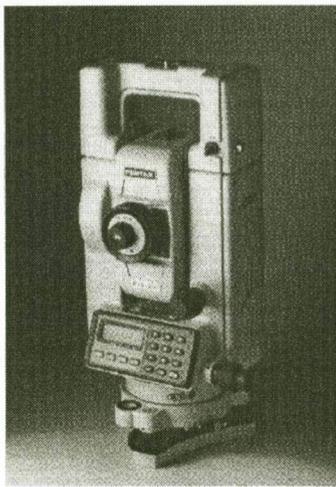


Figure 4.1 The Pentax PTS III-05 total station instrument (Elfick *et al.*, 1995:81)

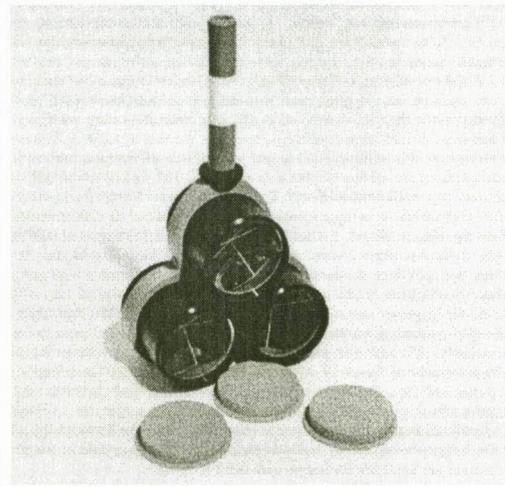


Figure 4.2 Triple retro-reflector (Elfick *et al.*, 1995:77)

A grid method or irregular method can be used in the field for collecting DEM data (Elfick *et al.*, 1995:243). In the grid method elevations are determined on points which conform to a regular square or rectangular grid while elevations of all low and high points as well as points where slopes change are determined with the irregular method.

When a DEM is created with a total station instrument the data should be saved as a DXF file that can easily be converted to an ARC/INFO point coverage with the 'dxfarc' command. If the grid method was used in the field, the point coverage can be converted into a grid with the 'pointgrid' command. With the irregular method the 'topogrid' command should be used to create a grid.

A new approach to surveying is the satellite surveying systems of which the current system is called the Global Positioning System (GPS) (Elfick *et al.*, 1995:321-349). GPS is based upon signals transmitted from satellites whose orbits are precisely known (see Paragraph 3.4.3.1.2). Accurate distances from the satellites to the receivers are determined from the signal information, enabling receiver positions to be computed. After the field observations are done the data is transferred to a computer to do the final processing.

GPS can also be used for establishing ground control points for photogrammetric mapping (Elfick *et al.*, 1995:464). This is usually done with two receivers where the one receiver is stationed at the ground control point while the other is taken with the camera in the aircraft. The camera's position is therefore precisely measured for each photo that is taken.

According to Elfick *et al.* (1995:344) GPS equipment is cost effective despite the fact that the initial cost is relatively high compared to other traditional surveying equipment. These systems will become smaller, more accurate and less expensive as technology improves.

4.5.2 Photogrammetry

An advantage of aerial photographs is that when taken as overlapping pairs, they can provide a three dimensional view of the earth's surface (Curran, 1985:86-88). This is made possible by the effect of parallax that the brain uses to give us the perception of depth. The view from an aircraft can therefore be simulated by viewing the left-hand photograph of a pair of aerial photographs with the left eye and the right-hand photograph with the right eye.

Analogue stereo-plotting instruments (see Figure 4.3) and later analytical stereoplotters (see Figure 4.4) were the principal photogrammetric technologies in recent years, but according to Gordon (1997:18) the Digital Photogrammetric Workstations (DPW) increased in importance since its commercial advent in 1988 to be the analytical plotter's

major competitor today. Gordon (1997), Wong (1997) and Schutte (1997b) agree that the DPW will become the dominant photogrammetric technology in future.

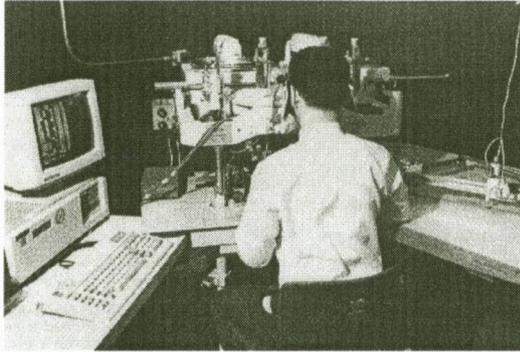


Figure 4.3 Kern PG-2 mechanical projection stereoplotter (Elfick *et al.*, 1995:460)

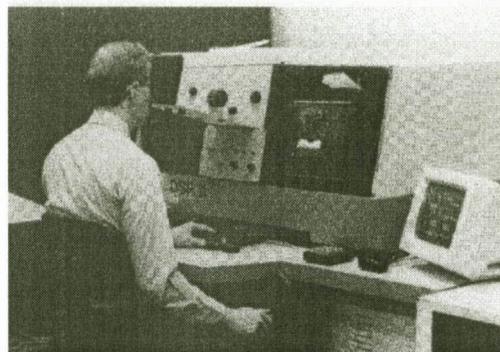


Figure 4.4 Kern DSR11 Analytical plotter (Elfick *et al.*, 1995:459)

Vertical aerial photographs are usually taken in sequences along the aircraft's line of flight in such a way that forward overlap is in the order of 60 percent (Curran, 1985:83; Floyd & Sabins, 1978:29). This is necessary for stereoscopic viewing. To ensure that a whole area is covered the aerial photographs also overlap sideways by around 30 percent. This means that each point on the ground appears at least twice in a block of aerial photographs.

The aeroplane flight path, height above ground, camera tilt and lens details are accurately detailed at the time the photograph is taken (Szecsei, 1995). This information is used in both stereo plotters and DPW's to create stereoscopic models.

Observing DEM's on an analytical stereoplotter is a semi-automatic procedure and although it is time consuming, the operator has the ability to differentiate between objects observed in the stereoscopic model (Schutte, 1997b). A reliable and accurate DEM is therefore provided. A digital data file is created with the stereoplotter and it can be exported to a DXF- or text file.

Madani (1996:1) defines an integrated digital photogrammetry system as hardware and software configurations that produce photogrammetric products from digital imagery

using manual and automatic techniques. The two major differences between analytical stereoplotters and DPWs lie in the input data and the level of automation. Analogue diapositives are used with stereoplotters while digital images are used as input for DPWs. The digital image files are extremely large. Image tiling-, image pyramid- and image compression techniques are used to handle these large files. Image pyramids are used to display imagery at all zoom levels very quickly. Automatic measurement and image matching techniques are provided by the new digital technologies and Madani (1996:2) considers this to be of great value to photogrammetry.

According to Mayr (1997) digital photogrammetry is now available for all basic photogrammetric tasks. Digital Photogrammetric Software is used to set up stereoscopic models, to import necessary project data, for the preparation of imagery for extraction, to display images, to perform various image enhancement operations, to extract terrain and feature data from imagery, to create products such as orthophoto's, perspective scenes, etc. and to export softcopy data-bases and hardcopy products (Schutte, 1997b).

As opposed to the method using analytical stereoplotters, the DEM is automatically extracted with digital photogrammetry after the initialising photogrammetric procedures are completed (Schutte, 1997b). This process is significantly faster. The main drawback however, is that it fails completely in extreme vegetation and water areas, where direct operator observations are needed to compensate for the error in the measurements of elevation.

The height accuracy obtained from aerial photography is directly proportional to the scale of the photography (Schutte, 1997b). A rule of thumb is that planimetric (xy) accuracy is 10 μm at the photo (image) scale, while the height (z) accuracy is 0.01 per cent of the flying height of the aerial photography. It is thus estimated that an accuracy of approximately 0.5 m in height can be expected for 1:30 000 aerial photography (with a flying height of $\pm 4\ 550$ m), but for extensive vegetation coverage the accuracy can be reduced up to two to four times.

4.5.3 Creating a DEM from contour maps

Generally raw elevation data in the form of stereo photographs or field surveys, and the equipment to process these data, are not readily available to potential end users of a DEM (Moore *et al.*, 1991:4). An alternative is to use public topographic maps. The contour lines can be digitised manually on a digitising board or can be scanned automatically on a scanner. Interpolation is used to derive a DEM from contour lines. Oliver and Webster (1990) provide the rationale for interpolation when they describe the nature of natural properties of the earth. The values of properties at sites that are close together in space are more likely to be similar than those further from one another because of the fact that the properties are continuous. The properties are therefore depending on one another in a statistical sense. The authors mention that the variation from place to place of most properties is usually so erratic that no simple mathematical expression can describe it and he is of the opinion that the properties behave as essentially random variables rather than as mathematical ones.

4.5.3.1 Interpolation methods

Interpolation methods can be divided into two main groups namely global and local (Oliver & Webster 1990:314). Global methods take all the elevation data into account when the elevation at a new point is determined, while the fitted surface at a point depends only on nearby data when a local method is used. The main advantage of global methods is the reasonable continuity that is derived (Hutchinson, 1989:214). A disadvantage however, is the high computational cost of $O(n^3)$. Local interpolation methods are not as computational intensive as global methods but have the disadvantage that spurious edge effects can be generated.

Local interpolation methods incorporated into ARC/INFO include inverse distance weighted interpolation (IDW), kriging and splines (ESRI, 1997). ARC/INFO provides one global method namely the trend surface interpolation; IDW interpolation can however be shifted from local to global by changing the 'power' option. These four methods are general-purpose interpolation methods and take point coverages as input. The vertices in the arcs should therefore be converted to points if one of these methods is used. A fifth

interpolator 'topogrid' is optimised for creating hydrological correct DEMs and is based on an interpolation method that was developed by Hutchinson (1989). Additional local interpolation methods can be acquired by first applying Delauney triangulation with the 'createtin' command. The triangulated irregular network (TIN) can then be converted into a grid using linear- or bivariate quintic interpolation by using the 'tinlattice' command. The 'topogrid' and 'createtin' commands accept both contour lines and spot heights as input.

A linearly weighted combination of a set of sample points is used with IDW interpolation to determine the cell values of a grid. The weight is a function of inverse distance. A major disadvantage of IDW observations is that the range of interpolated values is limited to the range of measured elevations (Watson & Philip, 1985:320). IDW will therefore not be able to interpret local trends for example hill tops and valley bottoms correctly.

Kriging is based on the regionalised variable theory that assumes a constant local mean and a stationary variance of the differences between places separated by a given distance and direction (Oliver & Webster, 1990:314). A plus point of kriging is the fact that the estimation variances can be determined and mapped and the reliability of the estimates can therefore be calculated by assuming a particular distribution. The term kriging embraces a set of methods including ordinary kriging, co-kriging, universal kriging and disjunctive kriging. Ordinary kriging and universal kriging are implemented into ARC/INFO (ESRI, 1997). Ordinary kriging assumes that the variation in cell values is free of any structural component. Universal kriging should be used when the spatial variation in cell values in the data is suspected to contain local trends.

A spline is a two-dimensional minimum curvature interpolation resulting in a smooth surface that passes exactly through the input points (ESRI, 1997). The method ensures a smooth (continuous and differentiable) surface together with continuous first-derivative surfaces. The algorithm was first developed as the solution to the problem of a thin plate which is forced to pass through certain points (Franke, 1982).

The trend surface interpolator uses a polynomial regression to fit a least-squares surface to the input points (ESRI 1997). According to Oliver and Webster (1990:314) this approach has several shortcomings:

- It loses detail because of powerful smoothing.
- Outliers or observational errors can cause instability.
- Variation in one part of the region affects the fit of the surface everywhere.

A procedure developed by Hutchinson (1989) is incorporated into the 'topogrid' command in ARC/INFO. 'Topogrid' uses coverages of contour lines, streamlines, sample points, and known sinks to create a hydrological correct DEM. The advantages of both local and global interpolation methods are implemented in the procedure in the sense that it has the efficiency of local methods without sacrificing the continuity and rotation invariance of global methods. The approach couples a drainage enforcement algorithm with an iterative finite difference interpolation technique that is based on minimising a terrain specific, rotation invariant roughness penalty. The drainage enforcement algorithm automatically eliminates spurious sinks.

4.5.3.2 Using a TIN to convert a contour coverage to a grid

Building triangulated irregular networks (TINs) from contour maps is one of the most common methods of building surface models for regions where elevation data is not available in digital form (ESRI, 1997). Unfortunately, contour lines is also one of the most difficult data sources from which to build a good TIN. The 'createtin' command implements Delauney triangulation to build a TIN. Caution must be taken that the density of the vertices representing the contour lines is less than the distance between contour lines (ESRI, 1997). If the vertices are too dense, triangles will be formed along the same contour, resulting in flat triangles. The 'weed_tolerance' option in the 'createtin' command can be used to reduce the number of vertices that will be used in the triangulation process. This process is automatic and important vertices might be ignored. Extra points may be included into a point coverage to ensure that the surface is represented correctly at these places. The TIN can be converted into a grid using linear- or bivariate quintic interpolation with the 'tinlattice' command.

In linear interpolation only the nodes of the triangle, within which the surface value to be interpolated lies, are used (ESRI, 1997). The surface value is obtained by the intersection of a vertical line, at the position of the required value, with the plane defined by the three nodes. With quintic interpolation a smooth surface will be derived. This is accomplished by considering the geometry of the neighbouring triangles. The 'tinlattice' command employs a breakline bivariate quintic interpolation using a fifth-degree polynomial in x and y . Both these methods honour the z values at the triangle nodes. The linear interpolation method is quicker and the results are more predictable, but abrupt changes in slope might occur at triangle edges. The breakline bivariate quintic interpolation method produces more realistic results, but is computationally more intensive than linear interpolation. The linear facet is planar (see Figure 4.5), while the quintic facet is curved (see Figure 4.6) and can be concave or convex depending on the behaviour of its adjacent triangles.

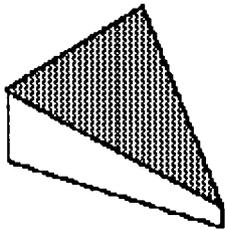


Figure 4.5 The planar facet of the linear interpolation method (ESRI, 1997)

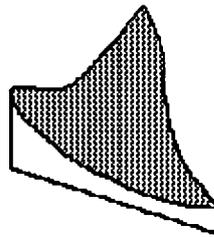


Figure 4.6 The curved facet of the quintic interpolation method (ESRI, 1997)

4.5.4 Laser altimetry

Airborne laser scanning is a relatively new method to create DEMs. The development of airborne laser systems started in the 1980's in the USA without reaching a breakthrough until 1987 (Ackermann, 1996:24). These systems are efficient in difficult cases such as forest areas (Hoss, 1996:28), coastal geology where it is necessary to differentiate between beaches and dunes (McCaskill, 1997), mountain glaciers (Echelmeyer *et al.*, 1995) and shallow coastal water surveys (LADS Corporation, 1997). The laser pulses are capable of at least partly penetrating through vegetation to reach the ground.

Three different sensors are used in airborne laser systems (see Figure 4.7). Differential GPS provides the co-ordinate reference, inertial navigation system (INS) the spatial direction of the aeroplane and the laser the length of the vector from the pulse emitter to the ground. A ground reference station that is also recording GPS data determines the

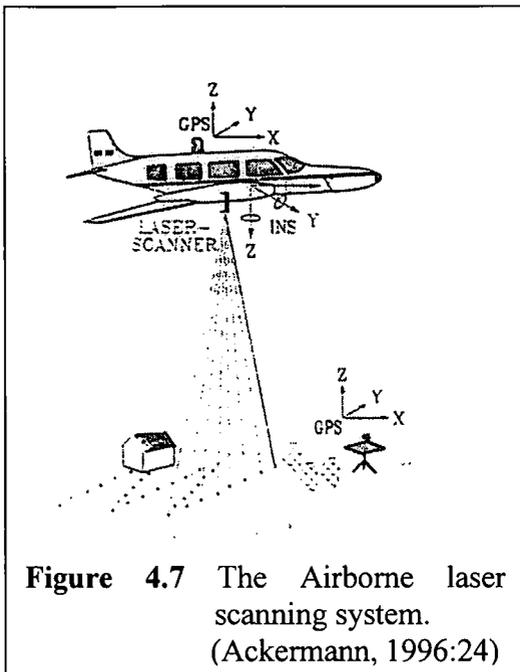


Figure 4.7 The Airborne laser scanning system. (Ackermann, 1996:24)

position of the differential GPS. Precise time tags are supplied by the differential GPS. The INS measures various attitudes of the aeroplane for example roll, pitch and heading information. The laser records the time difference between the emission of the beam and the reception of the reflected laser signal in order to measure the length to the ground. In cases of dense vegetation the laser beam is often divided into several distinguishable return signals as it penetrates the vegetation. The last return signal is usually recorded because in many cases it refers to the terrain surface.

The main improvement on laser scanners is the considerably higher measuring rate. The Spectra Physics TFR laser of the airborne topographic mapper used by NASA for example is operated at 2 000 to 5 000 pulses per second (Krabill, 1995; McCaskill, 1997). The laser beam is oscillated perpendicular to the flight direction and a swath width of 540m is reached from 1 000 m flying height above the ground (Ackermann, 1996:25). The TopScan / Optech system gives a swath every 3 m when the scan rate is set to 10 Hz, at a flying velocity of 215 km/h and a flying height of 1 000 m above the ground. With a set scan angle of 2×15 deg and a measuring rate of 2 kHz there is 100 points within each swath, at an average distance of 5 m. The vertical accuracy of a laser point is in the order of 10-20 cm, but results better than 10cm were obtained in ideal laser reflection on smooth surfaces.

The data from the different sensors is calibrated, synchronised and integrated with a post processing system to provide a precise horizontal and height location for each laser pulse. Processing rates of $2\text{-}5\text{km}^2/\text{h}$ have been quoted for topographic DEMs.

4.6 EXTRACTING TOPOGRAPHIC ATTRIBUTES FROM DEMS

A summary of attributes that can be computed from DEMs is given in Table 4.1. The derivation of some of these attributes will be described in the following paragraphs. Methods will only be described for a raster-based DEM, but as mentioned previously some attributes can be computed from all three types of DEMs.

Table 4.1 Summary of attributes that can be computed from DEMs (Moore *et al.*, 1993 as adapted by Burrough & McDonnell, 1998)

Attribute	Definition
Elevation	Height above mean sea level or local reference
Slope	Rate of change of elevation
Aspect	Compass direction of steepest downhill slope
Profile curvature	Rate of change of slope
Plan curvature	Rate of change of aspect
Local drain direction (ldd)	Direction of steepest downhill flow
Upstream elements / area / specific catchment area	Number of cells / area upstream of a given cell / upslope area per unit width of contour
Stream length	Length of longest path along ldd upstream of a given cell
Stream channel	Cells with flowing water / cells with more than a given number of upstream elements
Ridge	Cells with no upstream contributing area
Wetness index	$\ln(\text{specific catchment area} / \tan(\text{slope}))$
Stream power index	$\text{Specific catchment area} * \tan(\text{slope})$
Sediment transport index	$(n+1) (A_s / 22.13)^n (\sin\beta / 0.0896)^m$
Catchment length	Distance from highest point to outlet
Viewshed	Zones of inter-visibility
Irradiance	Amount of solar energy received per unit area

4.6.1 Gradient and aspect

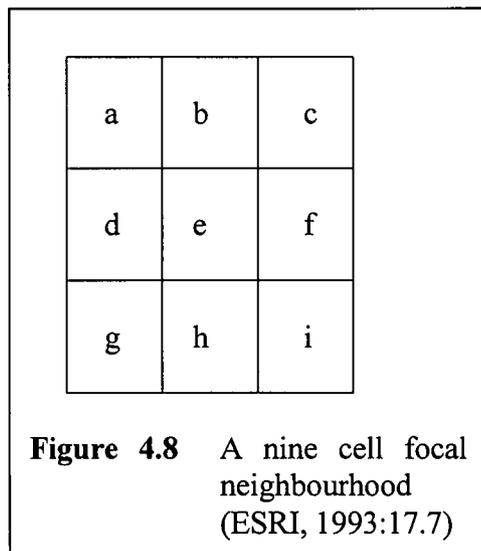
The 'slope' and 'aspect' functions in ARC/INFO produce continuous grids that represent surface gradient (slope) and the direction of surface gradient (aspect) (ESRI, 1993:17.7).

The algorithm used to calculate gradient for the central cell within a 3x3-submatrix is:

$$\tan(\text{gradient}) = \sqrt{\left(\frac{\Delta z}{\Delta x}\right)^2 + \left(\frac{\Delta z}{\Delta y}\right)^2}$$

Where:

- Δ means the change in
- z represents the latitude
- x represents the distance in the x direction
- y represents the distance in the y direction



The calculation of the change in z values and x, y values will be described with the aid of Figure 4.8.

The following calculations is with respect to cell e :

$$\left(\frac{\Delta z}{\Delta x}\right)_e = \frac{(z_c + 2z_f + z_i) - (z_a + 2z_d + z_g)}{8 * \text{cell size}}$$

$$\left(\frac{\Delta z}{\Delta y}\right)_e = \frac{(z_a + 2z_b + z_c) - (z_g + 2z_h + z_i)}{8 * \text{cell size}}$$

The formula used to calculate aspect is:

$$\tan(\text{aspect}) = -\left(\frac{\Delta z / \Delta y}{\Delta z / \Delta x}\right)$$

where the change in z values with respect to x and y is calculated in the same way as is done for gradient.

4.6.2 Flow direction

Several routing algorithms exist to determine the way in which flow (water, sediment, nutrients) is transferred to adjacent points or areas (Desmet & Govers, 1996:41-42). Within a 3x3-submatrix the neighbours to which the central cell are draining has to be found and then the fraction of flow that has to be transferred to each downslope neighbour has to be determined. Quin *et al.* (1991, as quoted by Desmet & Govers, 1996:42-43) proposed a multiple flow direction algorithm in which the receiving fraction transferred to each cell downslope of the central cell of the submatrix is proportional to the product of the distance weighted drop and a geometric weight factor, which depends on the direction:

$$A_i = \frac{A(\tan \beta_i * L_i)}{\sum_{j=1}^k (\tan \beta_j * L_j)}$$

Where:

A_i = fraction draining towards neighbour i

A = upslope area available for distribution

β_i = gradient towards neighbour i

L_i = geometric weight factor (0.5 for cardinal and 0.354 for diagonal directions) for flow towards neighbour i

$\sum_{j=1}^k$ = summation over all lower neighbours

With single flow algorithms the steepest decent direction algorithm is frequently used (Desmet & Govers, 1996:43). After calculation of the gradients between the central cell and all lower neighbours, all flow is directed to the neighbour corresponding to the steepest gradient. The 'flowdirection' function in ARC/INFO computes the direction of flow for every cell to its steepest down-slope neighbour (ESRI, 1997).

4.6.3 Flow velocity

According to Maidment (1993) flow velocity can be computed when the slope and land cover are known. Sircar *et al.* (1991, as quoted by Maidment, 1993:185) have shown how this can be done using a velocity function of the form $V = aS^b$, where S is the land surface

slope and a and b are taken from McCuen (1982, as quoted by Maidment, 1993:185) based on procedures of the USDA Soil Conservation Service.

4.6.4 Spurious sinks

A depression is an area surrounded by higher elevation values (Jenson & Domingue, 1988:1593). Depressions are sometimes referred to as sinks or pits in the literature (Weibel & Heller, 1991:278; Hutchinson, 1989:213; Nelson & Jones, 1995:38; Petras *et al.*, 1997; ESRI, 1997). The term used in ARC/INFO, namely sinks, will be used for the purposes of this report. The presence of spurious sinks in a DEM makes it inappropriate for the calculation of certain surface characteristics such as drainage networks and catchment areas.

Sinks are rare in nature (Hutchinson, 1989:212) and are therefore usually referred to as spurious. There are however, places such as the prairie pothole region in the upper Midwest of the United States, where sinks dominate the hydrologic response of the landscape (Moore *et al.*, 1991:8). Spurious sinks can usually be attributed to mistakes in the input data, unsuitable interpolation routines or the interaction of grid spacing with contour spacing and valley orientation.

The process of removing spurious sinks manually is time consuming and subject to errors from the operator (Hutchinson, 1989:213). Mainly two approaches are followed to eliminate spurious sinks with automatic methods, namely the smoothing of the DEM data or the filling of depressions (Jenson & Domingue, 1988:1593). Deeper sinks will remain when the smoothing process is used and another disadvantage is that all the elevations are affected. With the second approach the elevation of cells within the depression are raised to the lowest value on the boundary of the depression. The 'Fill' command in ARC/INFO uses this approach. Well-defined surface features are often over smoothed with these methods and it is therefore better to eliminate the spurious sinks during the interpolation process from the original points.

The drainage enforcement algorithm implemented into the 'topogrid' command automatically eliminates spurious sinks. Natural sinks represented with a point coverage

can be given as input to this procedure to ensure that these sinks are not removed. Depending on the tolerances used, 'topogrid' may or may not remove all spurious sinks.

4.6.5 Stream networks

The 'flowaccumulation' function in ARC/INFO can be used to create a drainage network (ESRI, 1997). The 'flowaccumulation' function is used to add up the number of upstream cells for each cell in the drainage network. Most cells will have a small value, but cells falling on major streams will accumulate very large values quite quickly. A

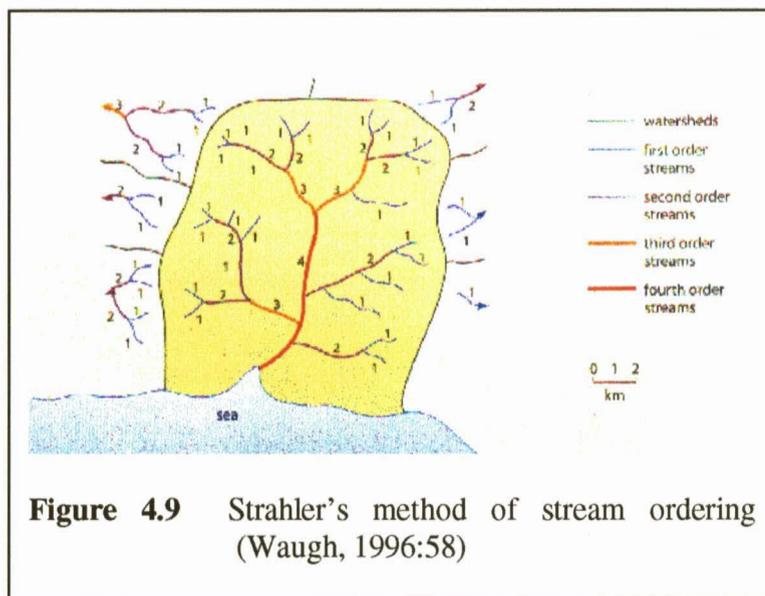


Figure 4.9 Strahler's method of stream ordering (Waugh, 1996:58)

threshold value can be used to select cells with high accumulation to provide a stream network.

The 'streamorder' function assigns Strahler or Shreve order values to stream grids created with the 'flowaccumulation' function (ESRI, 1997).

The user can define the method that should be used. A stream order value of a stream segment indicates its position in the hierarchy and can be used to infer the size of a stream. In both the Strahler and Shreve methods exterior links are always assigned an order of one. In the Strahler method (see Figure 4.9), stream order increases after streams of the same order intersect, while the orders are additive in the Shreve method.

4.6.6 Watersheds

Waugh (1996) defines a watershed as the boundary of a drainage basin. A drainage basin is an area of land drained by a river and its tributaries. A ridge of high land beyond which any precipitation will drain into adjacent basins marks the boundary.

The 'watershed' and 'basin' functions both delineate drainage areas (ESRI, 1997). The functions differ only in the definition of the pour point. The 'watershed' function finds the uphill area that contributes runoff to the set of user specified pour points. The 'streamlink' function can be used to create the source grid that specifies the pour points. This will result in uniquely identified watersheds around each stream as the 'streamlink' function assigns unique numbers to the links of a stream network.

The 'basin' function is similar to the watershed function, except for the fact that it automatically finds all the pour points where the water leaves the grid. It will compute watersheds for all these points.

4.7 APPLICATIONS IN FLODSIM

The DEM plays an important role in FLODISM and the pains taken during the development of a good DEM will be rewarded with better information from FLODSIM. Any of the four methods described in Paragraph 4.5 can be used to create a grid-based DEM for the study area. During the development of FLODSIM, DEMs were created for the floodplain of the Orange River between Gifkloof Weir and the Manie Conradie Bridge at Kanon Eiland and for the Mfuluzi floodplain between the national Road Bridge east of Riverview and the river mouth in the Indian Ocean.

Contour lines and spot heights were digitised from 1:5 000 maps for the Orange River floodplain. Such large data sets almost inevitably contain errors. The coverages were therefore thoroughly checked and corrected with the source maps. A DEM was then created from the contour lines and spot heights with the 'topogrid' command in ARC/INFO.

Two methods were applied to obtain a DEM for the Mfolozi floodplain from aerial photography. With the first method digital photogrammetry was used (see Paragraph 4.7.1). The results from this method were unreliable due to the dense vegetation. A second DEM was created with an analogue stereoplotter. With this method points within cultivated fields could be ignored. The points obtained from each stereoscopic model were saved in a DXF file and then converted to an ARC/INFO

coverage with the 'dxfarc' command. The different coverages of the stereoscopic models were combined and then converted to a grid with the 'topogrid' command.

4.7.1 The acquisition of a DEM for the Mfolozi floodplain with the aid of digital photogrammetry

The Helava Digital Photogrammetric Stereoplotter installed on a Sun Ultra computer was used to obtain a DEM for the Mfolozi floodplain from controlled aerial photography with a scale of 1:30 000 (Schutte, 1997a). As explained in Paragraph 4.5.2 a vertical accuracy of approximately 0.5 m can be expected for aerial photography with a scale of 1:30 000.

A photogrammetric scanner was used to convert the analogue diapositives into a digital image format used by the Helava system, namely VITEC. It is worth mentioning that these files are quite large. Each image is approximately 85 Mbytes when scanned at a 25 micrometer resolution. The 31 images with their pyramid and data files used 5.6 Gbytes of disk-space. Caution must be taken when ground control points are entered to ensure that the different images will connect at the same level.

Schutte (from the Department of Water Affairs and Forestry, directorate Geomatics) did the necessary photogrammetric procedures. These procedures included the following:

- Importation of the 31 images and building of the pyramids.
- Performing the interior orientation for each image.
- Set up the ground control point file.
- Performing the Aerial Triangulation process.
- Defining the DEM polygons for each stereo model.
- Initiation of the automatic DEM extraction process.
- Interactive editing.
- Terrain analysis (Quality checking).
- Merging of all the DEM files.
- Interactive editing.
- Generation of orthophotos.

The DEM can be exported to an ASCII file from the Helava system. These files are then converted into a format that is acceptable to ARC/INFO. A DEM with a cell-size of seven meters was created and the resultant ASCII file was 259 Mbytes.

Since the Mfolozi's primary landuse type is sugar cane, which is a dense vegetation type, the height of the sugar cane must be taken into account. Sugar cane for different cultivated fields is not cut simultaneously and different values must therefore be subtracted for each cultivated field.

4.7.1.1 The importation of the output-file from the Helava system into ARC/INFO

The ASCII-file from the Helava system describes each point on a different line. The description entails four space-delimited numbers. The first three numbers represent the x,y,z co-ordinates of the point and the fourth number is used for internal calculations in the Helava system. In order to be able to import the DEM into ARC/INFO it had to be converted into a format that ARC/INFO supports. Since the z value is stored as an attribute in ARC/INFO, the file is imported in two phases where the first phase entails the creation of a point-coverage containing the xy co-ordinates and an info-file containing the z-values. In the second phase the point-coverage and the info-file are joined to form a new point-coverage with attributes. The 'generate' command is used to create the point coverage while the 'add' command in tables is used to add the z-values into the info-table after it has been defined. The input-file for the 'generate' command consists of an id-number together with the xy co-ordinates of the point while the input-file for the 'add' command consists of an id-number with the z co-ordinate of each point. A program doing the conversions to the two input-files was written in Delphi. Since ARC/INFO runs on a UNIX-based computer, these two files must also be converted from DOS-format to UNIX-format before they can be used in ARC/INFO. The Helava system is designed for the northern hemisphere and the x and y co-ordinates must be multiplied by -1 in order to transform the co-ordinates into the correct quadrant. A constant must also be added to the y co-ordinate as only five digits were used for the co-ordinates in the Helava system.

A grid can be created from the point coverage by using the 'pointgrid' command in ARC/INFO.

Another method was examined to import the DEM into ARC/INFO, but the above mentioned method was by far the quickest and it used less disk space. ARC/INFO's code written in the Arc Macro Language (AML) is interpreted and the required actions performed, as each line is encountered (ESRI, 1992:1.7). This makes some procedures very slow and it is therefore better to use precompiled programs when large volumes of data have to be processed. In the second method that was examined, the ASCII-file from the Helava system had to be divided into several smaller files. These files are then added to an info file with attributes for each of the four columns in the ASCII-file. The constant must be added to the y- co-ordinate. A text file consisting of a '1' in the first column, followed by the x- and y co-ordinates of each point is then created with the print command in Info. This file can be imported with ARCEDIT into a coverage as follows:

- Set the co-ordinate to: keyboard xy.
- Create a coverage dtm_points.
- Give at least four tic points.
- Enter the initial boundary.
- Set the edit feature to label.
- Set autoincrement to on.
- Type Add.
- Run the text file.
- Save the coverage.

Use 'dropitem' to remove the three redundant columns in the info file to keep only the z-values. The info-file can now be used to give the z-values as an attribute to the coverage named dtm_points by using the 'joinitem' command with the 'link' option. The coverage is now used to create a grid with the 'pointgrid' command in grid.

4.7.1.2 Subtracting the height of sugar cane from the DEM

There are several situations that must be taken into consideration when the height of sugar cane is determined. As mentioned previously sugar cane for different cultivated fields is

not cut simultaneously and the height of the sugar cane will therefore differ for separate cultivated fields. The aim is to find the difference between the elevation on the inside of the cultivated field and the elevation at the boundary. There is not always an area between cultivated fields where the ground can be seen. Another situation might be that a drain is situated next to the cultivated field.

Algorithm to subtract the height of sugar cane from the elevations given in the DEM

- 1 Find the boundaries for each cultivated field.
- 2 For each cultivated field:
 - 2.1 Determine the average height of the sugar cane at each segment from the boundary of the cultivated field. Excluding the segments next to drains.
 - 2.2 Find the boundary where the sugar cane is the highest and use this value as the average height of the cultivated field.
 - 2.3 If the average height of the cultivated field is greater than the average height of mature sugar cane then set the average height of the cultivated field to the average height of mature sugar cane.
 - 2.4 Subtract the average height of the cultivated field from the elevation of each cell in the DEM that is within the boundary of the cultivated field.
- 3 Assigning the median of surrounding cells to each cell can smooth the data. This should however only be done over areas where sugar cane is planted; rivers and hills for example should keep their original values.

The cultivated fields, which are mentioned in step one, were digitised from orthophotos. The sides of a cultivated field define the segments of the boundary; a field in the form of a rectangle would for example have four segments.

The third step in the algorithm is necessary for cases where the area between two fields was recognised from the photography as having the same height as the field itself. After the height of sugar cane is subtracted, this area will still be higher and a spurious wall is thus created. Another problem is that the sugar cane's real height is sometimes only reached several meters inside the cultivated field with the result that the value that is subtracted at the boundary is too large, forming a spurious drain at the boundary of the cultivated field. The areas that should be included were digitised from orthophotos. The

result of this process is illustrated with Figures 4.10 and 4.11, where the same area is drawn three-dimensionally before and after sugar cane has been subtracted.

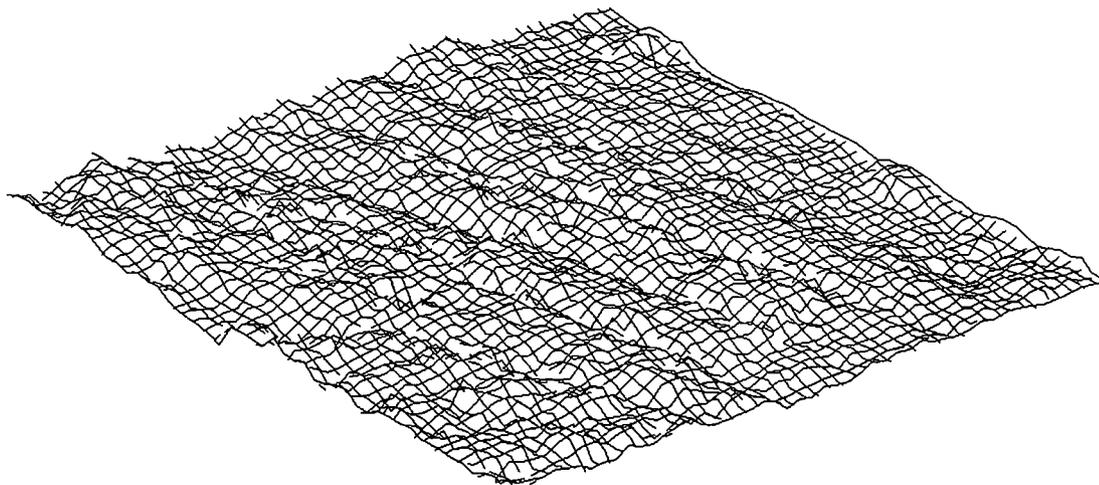


Figure 4.10 Section of DEM before sugar cane is subtracted

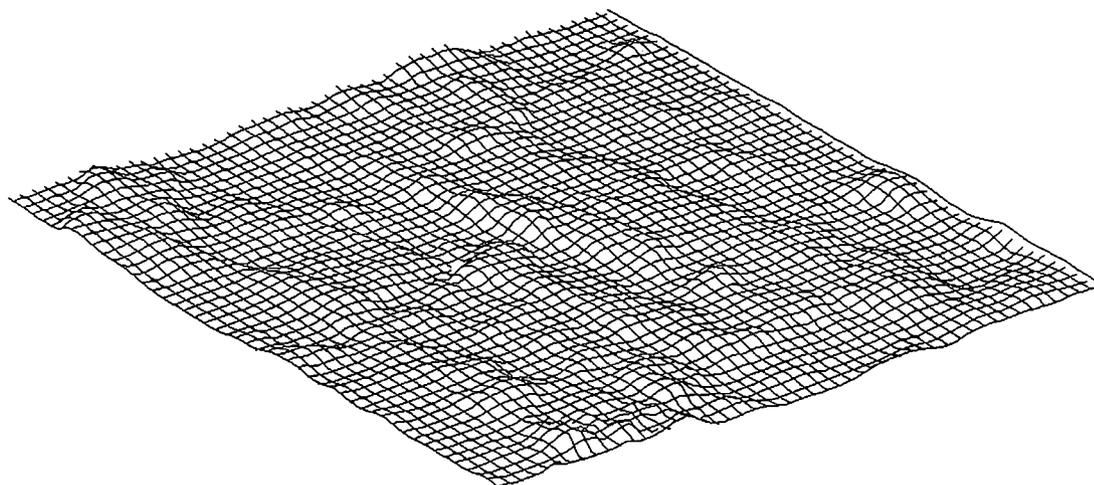


Figure 4.11 Section of DEM after sugar cane is subtracted

FLOOD DAMAGE SIMULATION

5.1 INTRODUCTION

Simulation is the process of designing a model of a real system and conducting experiments with the model for the purposes of describing, explaining and predicting the operation of the system (Maguire, 1989:111-112). A number of different types of simulation models are normally recognised. For example, scale models, conceptual models and mathematical models. This chapter will be devoted to mathematical models.

Mathematical models are normally classified as either deterministic or probabilistic, but it is perfectly possible for a simulation model to combine elements of both deterministic and probabilistic modelling strategies. Deterministic models are based on the notion that the subject under study can be described exactly using mathematical relationships. The attributes that were calculated from DEMs in Paragraph 4.6 will for example be classified as deterministic. Probabilistic models on the other hand are based on the notion that the subject under study has some random element. The equations of probabilistic models are based on the expected probabilities of certain events and processes occurring. The estimation of flood damage with the aid of loss functions which will be described in Paragraph 5.8 is an example of a probabilistic simulation.

5.2 FLOOD DAMAGE IN SOUTH AFRICA

According to Flood Management Consultants (FMC, 1998:4.6) the mean annual flood damage in South Africa amounts to R112 million, expressed in 1990 values. This value was derived by using information that was recorded for the floods over the 21-year period from 1968 to 1988. More than 1 200 people lost their lives during this period, on average

about 60 per annum. In addition, many thousands of people have been left homeless for various periods of time as a result of flooding. The value of direct losses to agriculture amounted to R1 450 million over the 21-year period. When considering the consequential losses to the agricultural sector as a whole as a result of the interruption of economic activities during floods, the total losses could be about R1 750 million or on average about R83 million per annum.

Flood damage control measures are often applied to mitigate social disruption and damage caused by floods in specific rivers. Table 5.1 illustrates possible structural and non-structural measures that should be considered in flood management studies as suggested by the New South Wales Government (1986:9). It is essential that new developments be designed and constructed in a way that will minimise flood damage without making flooding conditions worse at other properties.

Table 5.1 Floodplain management measures (New South Wales Government, 1986:9).

	Water control measures	Land use control	Financial relief	Disaster avoidance
Structural measures				
Flood mitigation dams	X			
Levees	X			
By-pass floodways	X			
Channel improvements	X			
Retarding basins	X			
Non structural measures				
Flood proofing of buildings		X		
Zoning		X		
Building and development controls		X		
Voluntary purchase		X	X	
Flood insurance			X	
Public information and education				X
Flood forecasting, warning and evacuation planning				X

Comprehensive flood management studies have to be completed before flood damage mitigation measures can be implemented. The main precondition for implementing a flood damage measure is usually that the cost of implementation must not exceed the estimate of flood damage that can be avoided.

5.3 THE RATIONALE BEHIND FLOOD DAMAGE SIMULATION

Conley *et al.* (1994:1) mentions that reliable information is a prerequisite for management decisions in flood management studies. Information that is required for management decisions includes topographic-, hydrologic-, hydraulic and economic aspects.

Topographic information is not only needed to derive hydrologic and hydraulic information for the floodplain, but the topographic location of a site also influences the amount of loss due to floods. Penning-Rowsell (1997:18) states that the location of a risk site is a prime determinant of whether or not it will become immersed. Even an otherwise highly vulnerable risk site is unlikely to incur losses if it is at a safe elevation from the flooded area, and vice versa.

Hydrology is the science of water (Hipel & McLeod, 1994:20). In particular, hydrology deals with the distribution and circulation of water on the surface of the land, underground and in the atmosphere. Typical hydrologic aspects required for flood management decisions are the flood discharges for floods with varying probabilities. Discharge is the rate of flow of water measured in terms of volume over time (New South Wales Government, 1986:i-iv). It therefore gives an indication of how much water is moving rather than how fast the water is moving. A hydrograph shows how the discharge changes with time at any particular location.

Hydraulics, on the other hand, is the term given to the study of water flow in a river, in particular, the evaluation of flow parameters such as stage and velocity (New South Wales Government, 1986:i-iv). The hydraulic information should be integrated with the topographic information in order to calculate flood characteristics such as the depth and duration of inundation.

If the elemental areas comprising the floodplain can be categorised according to land use or occupancy and if, for each category flood damages can be expressed as functions of depth and duration of inundation, thickness of sediment deposition, degree of erosion etc. then it should be possible to develop a numerical model to predict, for each elemental area the damage likely to result from the given flood event (Weiss, 1976:6.1).

An integrated approach to mathematical flood plain modelling as proposed by Weiss (1976) is illustrated with Figure 5.1. Topographic information in the form of cross-sections and hydrologic information such as flood hydrographs are given as input to numerical flood models in order to derive hydraulic characteristics. Loss functions are then used to estimate the flood damage for a specific flood event. The process should be repeated for several floods of different sizes and return periods, so as to calculate the mean annual flood damage. This value is then used to do benefit cost comparisons for different combinations of flood damage control measures.

A typical example of a benefit cost comparison is found with decisions concerning investment of capital in flood protection works (Conley *et al.*, 1994:1). An estimate of flood damage that can be avoided by the proposed management action is weighed up against the cost of the management action.

The risk of failure of a structure is a function of the exceedance probability (the probability that a discharge will be exceeded in any one year) as well as the structure's resistance to failure (FMC, 1998:2.3). Complete safety can never be guaranteed, and consequently there is always some risk of damage due to floods. The determination of an acceptable level of risk is therefore a policy decision, not a result of an engineering calculation.

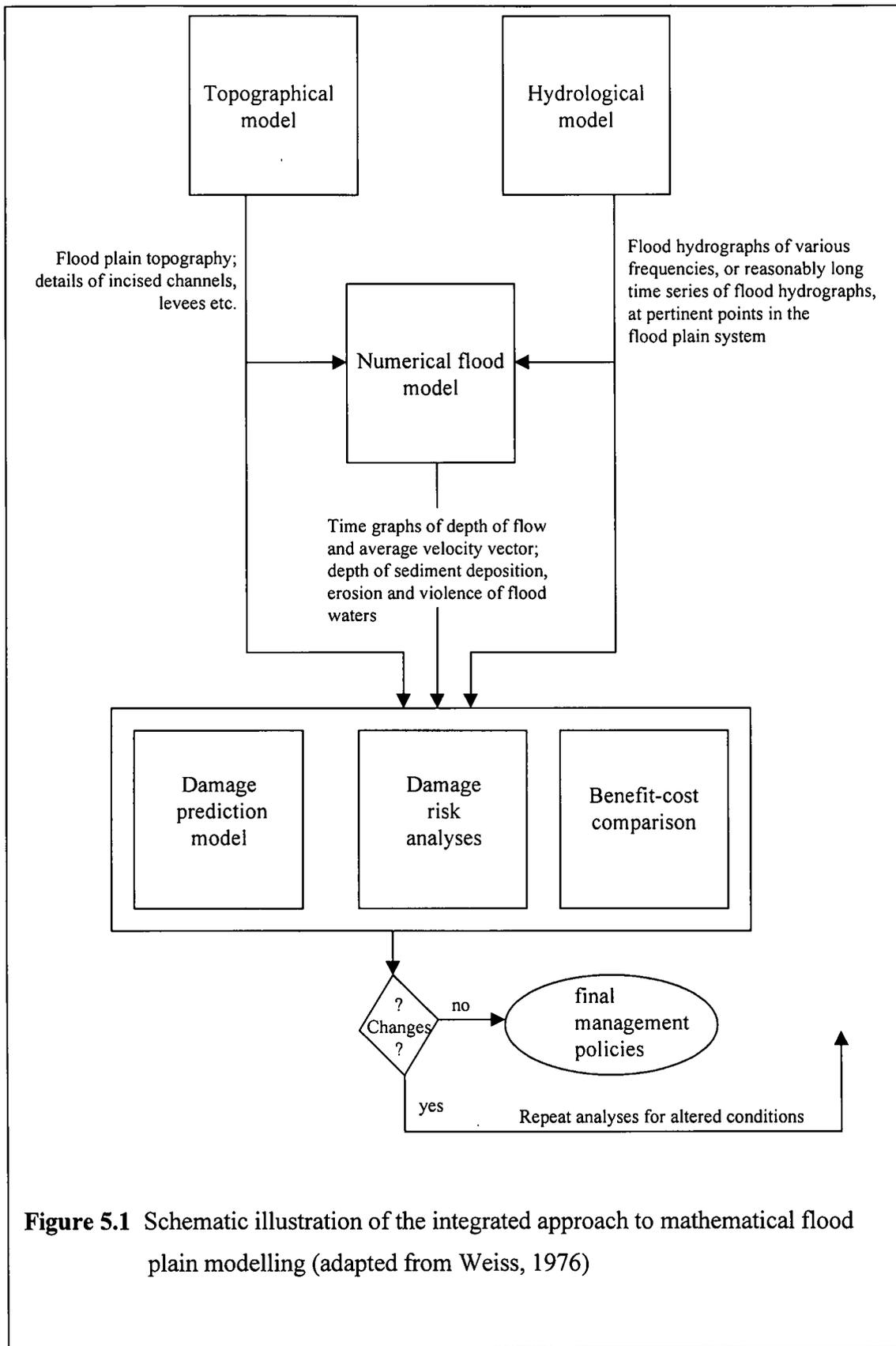


Figure 5.1 Schematic illustration of the integrated approach to mathematical flood plain modelling (adapted from Weiss, 1976)

5.4 DERIVATION OF FLOOD HYDROGRAPHS

According to Waugh (1996:54-57) a hydrograph shows how the discharge of a river responds to an individual rainfall event. The form of hydrographs will therefore differ for different rainfall events. Myburgh (1998) mentions that hydrographs might vary considerably in shape according to variables like available data, methodology employed, personal judgement etc. The single most likely variable is the base width being adopted. The base width is regarded as reasonable when it varies between two and four times the so-called time of concentration [i.e. the time taken from run-off to reach a measuring point (Penning-Rowell, 1997:40)] of the catchment. Floods of different return periods will also have different hydrographs because floods with higher return periods have smaller discharge levels. Figure 5.2 illustrates a typical storm hydrograph. A graph of the rainfall that caused the flood is drawn on the same time scale as the hydrograph.

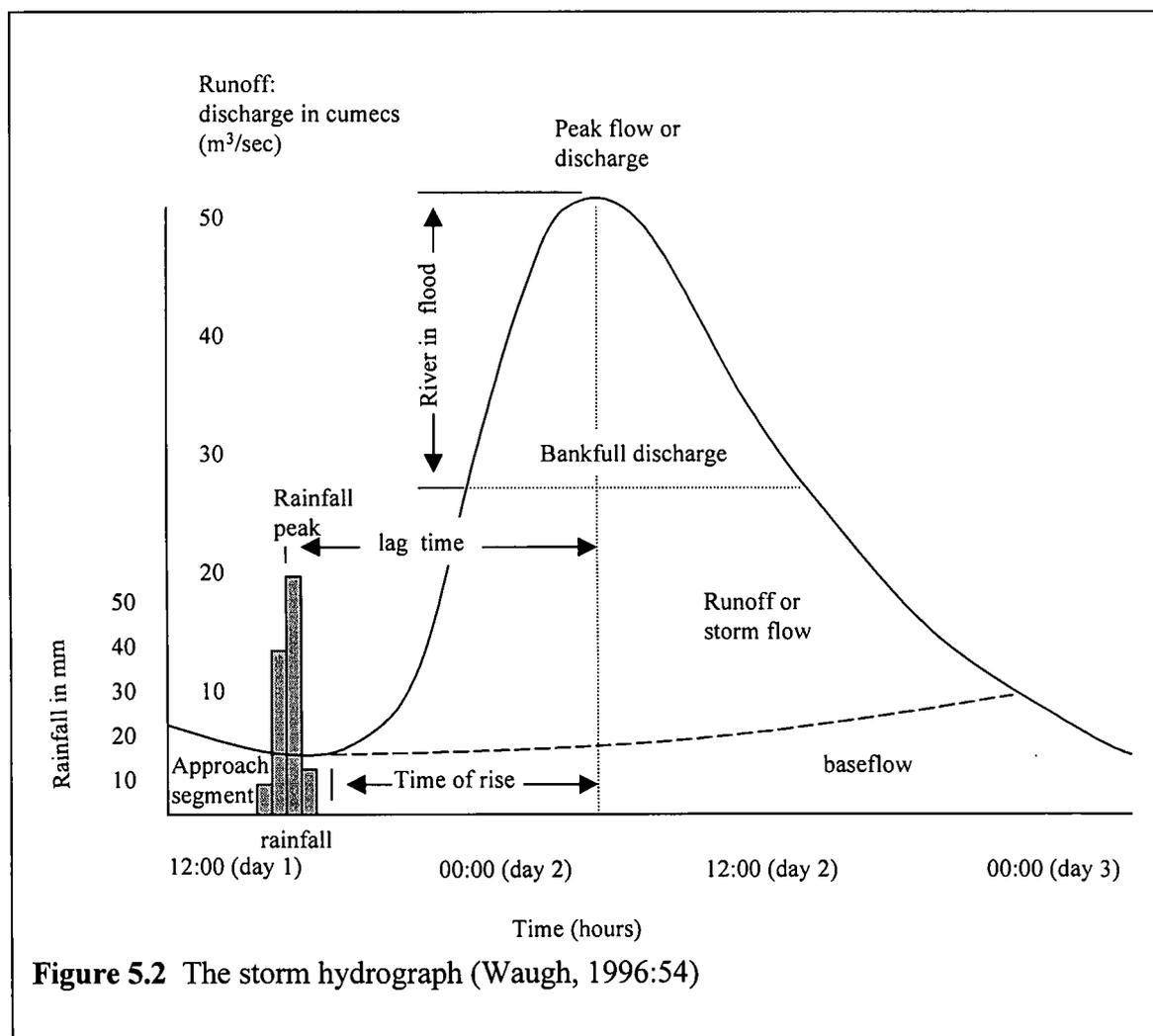


Figure 5.2 The storm hydrograph (Waugh, 1996:54)

The approach segment, which is the discharge of the river before the storm, is also shown in Figure 5.2 (Waugh, 1995:54). The peak discharge (peak flow) occurs when the river reaches its highest level. The period between maximum precipitation and peak discharge is referred to as the lag time. Conditions within the drainage basin, e.g. soil and rock type, slope and size of the basin, drainage density, type and amount of vegetation and water already in storage will influence the lag time. Hydrographs therefore differ for different rivers. Rivers with a short lag time tend to experience a higher peak discharge and are more prone to flooding than rivers with a long lag time. Figure 5.2 also illustrates bankfull discharge that occurs when the river's water level reaches the top of its channel; any further increase in discharge will result in flooding of the surrounding land.

Discharge can be expressed as:

$$Q = A * V$$

Where:

Q = discharge measured in cumecs

A = cross-sectional area of the river (m^2)

V = velocity of the river (m/sec)

Current hydrographs should be used to incorporate changes in hydrology caused by human interference for example urbanisation, as well as for changes in climate. Researchers are concerned that there might be a change in global climate trends. Penning-Rowse (1997:55-59) summarises global climate trends in the past and present and gives a prediction of what could happen in the future. The changes recorded so far, are still within the statistical ranges of natural variability and only if such data are recorded over a longer period of time will there be scientific evidence of climatic change. The main causes of concern are seasonal changes such as El Niño/Southern Oscillation (ENSO) and the more permanent greenhouse effect. Schulze (1997) explains the impact of global climate change on hydrology in Southern Africa.

Global warming, caused by greenhouse warming, may have a variety of effects, including increases in average global sea level, the frequency and severity of precipitation, and the frequency of ENSO-like events (Penning-Rowse, 1997:58). In turn ENSO-like events may affect the timing, duration and distribution of rain and snowfall.

The second aspect that may influence the form of hydrographs is urbanisation (Strahler & Strahler, 1997:376). An increasing percentage of the surface becomes impervious to infiltration as it is covered by buildings, driveways, walks, pavements and parking lots. Another change caused by urbanisation is brought about by the introduction of storm sewers that quickly carry storm runoff from paved areas directly to stream channels for discharge.

5.5 FLOOD EXCEEDENCE PROBABILITIES

The peak discharge or highest stage of a river usually measures the magnitude of a flood during a period of flooding (Strahler & Strahler, 1997:379). Large floods occur less frequently than smaller ones; that is, the greater the discharge or the higher the stage, the less likely is the flood.

The probability of occurrence of a flood of specific magnitude is the statistical chance that an event of equal or greater magnitude will occur in a particular year (FMC, 1998). This probability can be expressed in several ways for example:

- Return period of twenty years.
- Recurrence interval of twenty years.
- The 1:20- year flood.
- Five percent annual exceedance probability.
- 1:20-year annual exceedance probability.

The fourth definition (the five percent annual exceedance probability) is the most precise definition, but the third definition (1:20-year flood) is most commonly used as it is most readily understood.

Available methods for estimating flood probabilities are detailed by Alexander (1990 as quoted by FMC, 1998:3.1) and comprise three categories, namely, direct statistical analyses of recorded data, deterministic methods based on rainfall data and empirical methods which have neither a statistical nor a deterministic foundation.

5.6 NUMERICAL FLOOD MODELS

There are two main types of hydraulic models, namely, numerical models and physical models (New South Wales Government, 1986:G3). In numerical models, a computer is used to solve the equations representing the flow of water down a river system and so to predict water levels and velocities. A physical model is a scaled down version of the actual river system being studied. This paragraph will focus on numerical models.

The primary input for numerical flood models¹ is the river topography, hydrographs, roughness values and initial water levels (Chunnet Fourie and Partners, 1993).

Topographic data for numerical flood models usually consist of a river network and cross sectional profiles. Examples of numerical flood models that use cross-sections to describe the topography are HEC-RAS (US Army Corps of Engineers, 1997:B.12- B.14), CFP (ECC, 1987:5-6), XP-SWMM, MIKE 11 (DHI, 1995:2.1-2.36) and WSPRO (Van Bladeren, 1998). Mike 11 and XP-SWMM are dynamic models while HEC-RAS, CFP and WSPRO are steady state models. The difference between dynamic models and steady state models lies in the absence of the time dimension in steady state models. A dynamic model takes a hydrograph as input while a steady state model takes only the peak discharge as input. Dynamic models should be used when duration of inundation is required by the loss functions.

Roughness values give an indication of the energy lost due to frictional resistance. Chezy's formula and Manning's formula are often used in numerical flood models to determine frictional resistance of surfaces. Rough surfaces characterised by outcrops of rock, trees, tree roots, fallen logs and tangled and matted vegetation produce much greater frictional resistance than smooth surfaces such as grass, croplands and concrete lined channels (New South Wales Government, 1986:G3). Chunnet Fourie and Partners (1993) mention that the roughness value may change in different stages of the flood for example when vegetation is washed away by the flood. Unique roughness values may normally be given to each cross section.

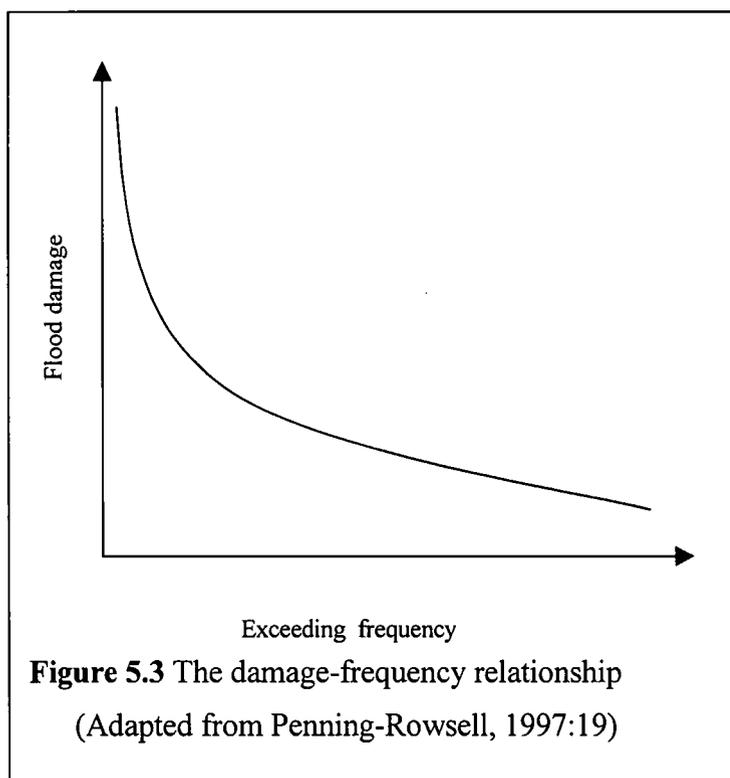
¹ Also known as backwater packages.

Numerical flood models are usually calibrated by adjusting various parameters in the model to obtain agreement between recorded and simulated water levels (New South Wales Government, 1986:G3).

5.7 CALCULATING THE MEAN ANNUAL FLOOD DAMAGE

According to the US Army Corps of Engineers (1988:3), the expected annual flood damage computations may be performed by two distinctly different approaches. One is to develop a chronologically long period of annual damage values and compute the average value. The value may be derived either from historic records of incurred damage or simulation of damage as it might occur on an annual basis.

Another approach is to develop the data in a way that determines the potential for damage from specific flood events and weights the damage values with the probability that these events might be exceeded. The simplest way to develop the final frequency-damage



relationship is to relate stage or flow to damage and to relate stage or flow to frequency. The first relationship (between stage and damage) is known as stage damage curves, but the relation can actually be between flood damage and any other flood characteristic and therefore the term loss function is preferred.

The damage-frequency relationship is illustrated by

Figure 5.3. The area under the curve gives the mean annual flood damage (Ramirez & Adamowicz, 1988, as quoted by Du Plessis, 1994:140; Viljoen, 1979:152). The regional

maximum flood line as well as a flood line where no damage would occur, should be included in the graph.

5.8 LOSS FUNCTIONS

According to Smith *et al.* (1981:19) a loss function defines the relationship between flood damage and certain flood characteristics such as depth of inundation, duration of inundation, area inundated, momentum flux and silt content of floodwaters for a specific damage category. These relationships could be expressed algebraically, graphically or in tabular form. Different loss functions are usually developed for different land use types.

Viljoen (1979:160-161) suggests that a combination of inductive- and deductive methods be used to develop loss functions. Reported damages of real floods are used with the inductive method, while flood damage is determined independently of real floods with the deductive method. The main advantage of the inductive method is that the relationships are based on real floods. With the deductive method relationships for different frequencies of floods can be determined in the absence of historical data.

Loss functions for residential areas will be described in the following paragraph to illustrate the relationship between flood damage and depth of inundation, then sugar cane will be used as example to illustrate the relationships between flood damage and other flood characteristics. Finally an example will be given of loss functions for infrastructure where the frequency of floods is directly related to damage.

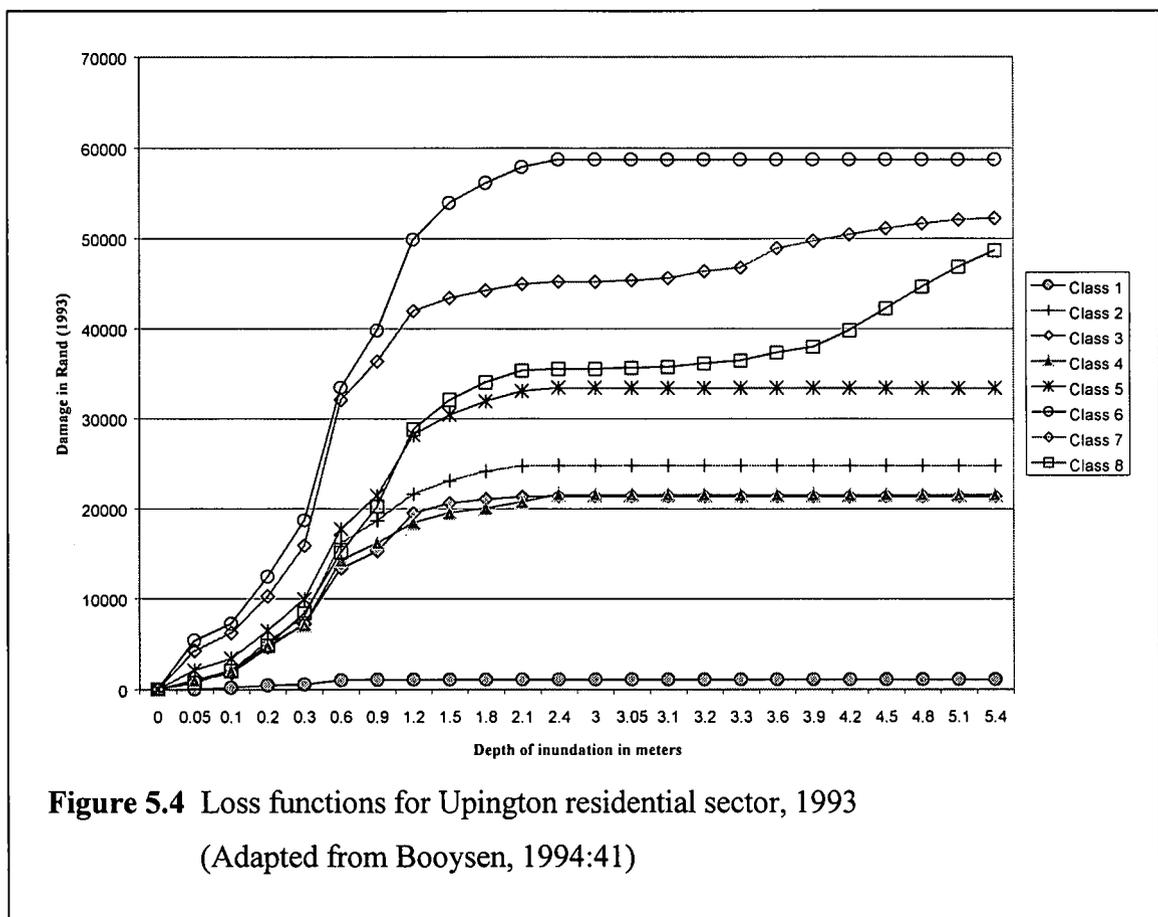
5.8.1 Loss functions for residential areas

Loss functions were initially developed for residential areas and are perhaps better known as stage damage curves, because of the relationships that are defined between flood damage and depth of inundation. The concept of stage damage curves were first described in the USA and is associated with the name of an American, Professor Gilbert White (1945, as quoted by Smith, 1984:56). His initial study remains the basis for contemporary work in this field. These curves however, are not readily transferable to

other countries due to differences in building construction and property types and because the American data is based upon house valuations.

Stage-damage curves were further developed by Penning-Rowsell and his co-workers in the UK (Smith, 1984:56). They produced very detailed sets of stage damage curves applicable to a range of residential and commercial properties.

Figure 5.4 illustrates loss functions developed by Booyesen (1994:41) for Uppington. Booyesen (1994:33-41) divided the houses into different classes where shacks are represented by class one to double storey buildings represented in classes seven and eight.



5.8.2 Loss functions for sugar cane

Several characteristics of floods, for example velocity of water, depth of sediment deposition, duration of inundation and depth of inundation, can be used to estimate flood damage to sugar cane. All varieties of sugar cane deteriorate rapidly after varying periods

of complete submergence (Satoris & Belcher, 1949 as quoted by Weiss, 1976:6.4). The main cause of damage to sugar cane therefore is the duration of inundation in combination with the depth of inundation. The loss functions developed by Weiss (1976) for velocity of floodwaters and sediment deposition will first be described. Loss functions for depth of inundation and duration of inundation developed by Berning (1998), based on the work of Weiss, will then be described. Berning (1998) divided the damage into damage to crops and damage to the harvest.

5.8.2.1 Velocity of the water

Fast flowing water may cause damage simply by bending down the stalks, thus increasing the susceptibility to prolonged submergence (Weiss, 1976:6.5). It is difficult to distinguish between degrees of damage resulting from violence of the floodwaters and one must simply assume that for a given velocity there will be either complete destruction or zero damage depending on the height of the sugar cane relative to the depth of inundation. According to Weiss (1976) fully submerged cane of height h or less would be destroyed at water velocity V if:

$$h < 1.8 \left(\frac{V - V_{\min}}{V_{\max} - V_{\min}} \right)^n$$

in which 1.8 m is assumed to be the average height of mature cane

V_{\max} = velocity assumed to be fatal to grown cane, say 2.0 to 2.5 m/s

V_{\min} = velocity tolerable even to young cane, say 0.3 to 0.6 m/s

n = an exponent to account for non-linearity, ranging from say 0.5 to 1.5.

5.8.2.2 Sediment deposition

Weiss (1976:6.6) is of the opinion that damage to sugar cane may result from deposition of sand, depending on the height of the cane at the time. Table 5.2 illustrates the loss function.

Table 5.2 Estimated cost of land reclamation (Weiss, 1976:6.6)

Depth of sand deposited (m)	Cost of reclamation (R/ha)
0-0.9	250
0.9-1.8	1 000
>1,8	3 000 (land permanently out of production)

5.8.2.3 Damage to the harvest caused by inundation

According to Berning (1998) damage to the harvest (DH) is calculated as the decrease in income due to destroyed sugar cane (D), minus the resultant decrease in cost (B) (harvesting cost saved as a result of the smaller harvest), plus the decrease in income due to lower sucrose content (P):

$$DH = D - B + P$$

The decrease in income due to destroyed sugar cane (D) is calculated as follows:

$$D = \sum_{L=0.1}^N D_L$$

$$D_L = A_L * A * \frac{H_L}{H} * C * S_h * GI_S$$

Where:

D (R)	=	Decrease in income (destroyed sugar cane)
N (m)	=	Depth of inundation
D _L (R)	=	Decrease in income for sugar cane with height L
A _L (%)	=	Percentage area with destroyed sugar cane of height L
A (ha)	=	Total area sugar cane
H _L (m)	=	Height of destroyed sugar cane (0.1m - 2.4m)
H (m)	=	Average height of mature sugar cane (2.1m)
C (tons/ha)	=	Tons sugar cane per hectare
S _h (%)	=	Percentage sucrose
GI _S (R/ton)	=	Gross income per ton sucrose

The lower yield obtained because of a flood, results in lower marketing (harvesting) costs, since destroyed cane need not be harvested nor transported to the mill. The decrease in

cost (B) is a direct function of firstly the amount of ton sugar cane destroyed and secondly the marketing cost per ton. The relationship is depicted in the formula below:

$$B = \frac{D}{GI_C} * M_C$$

Where:

B (R)	=	Decrease in marketing costs
D (R)	=	Decrease in income (destroyed sugar cane)
GI _C (R/ton)	=	Gross income per ton sugar cane
M _C (R/ton)	=	Harvesting cost per ton sugar cane

Partially damaged sugar cane refers to cane that can still be harvested after the flood, but whose quality has deteriorated as a direct result of the flood. Sucrose content serves as a measure of the quality of sugar cane. Since farmers are paid per ton sucrose delivered and not per ton of sugar cane, a decrease in sucrose content adversely affects income. The decrease in income caused by partially damage sugar cane can be calculated as follows:

$$P = A_P * (1 - A_D) * A * C * (S_H - S_L) * GI_S$$

Where:

$$A_D = \sum_{L=0.1}^N A_L$$

P (R)	=	Decrease in income (partially damage sugar cane)
A _P (%)	=	Percentage of area not destroyed, where sugar cane has been partially damaged
A _D (%)	=	Percentage area with destroyed sugar cane
A (ha)	=	Total area sugar cane
C (ton/ha)	=	Tons sugar cane per hectare
S _H (%)	=	Normal (higher) sucrose content
S _L (%)	=	Lower sucrose content after flood
GI _S (R/ton)	=	Gross income per ton sucrose
N (m)	=	Depth of inundation
A _L (%)	=	Percentage area with destroyed sugar cane of height L

Figure 5.5 shows stage damage curves for sugar cane in the Mfolozi floodplain based on damage to the harvest that occurs at various depths of inundation. A different curve has been constructed for each month of the year since the area:cane height relationship varies greatly between months. In order to keep the graph simple only six months have been represented in the graph.

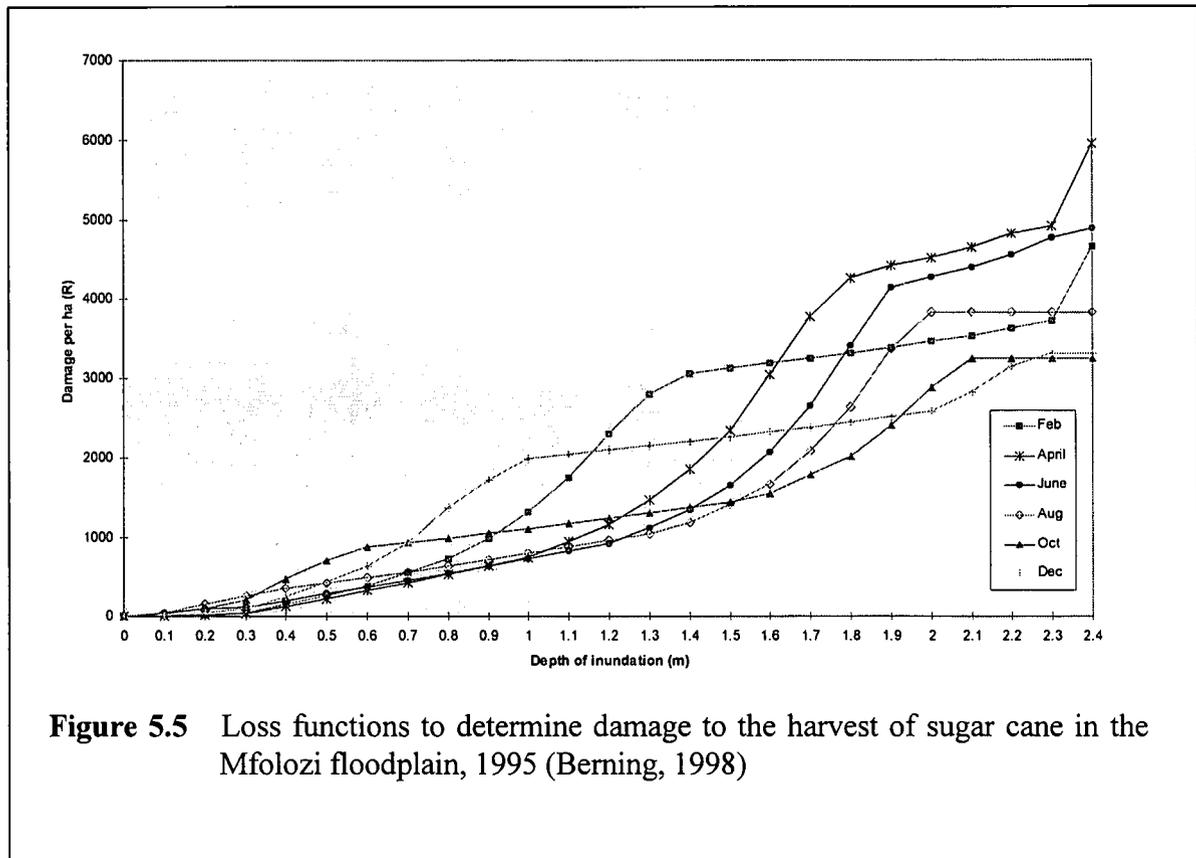


Figure 5.5 Loss functions to determine damage to the harvest of sugar cane in the Mfolozi floodplain, 1995 (Berning, 1998)

5.8.2.4 Damage to the crop caused by inundation

In the case of perennial crops such as sugar cane, damage to crops can occur besides damage to the harvest (Viljoen, 1979:182-186). The effect of damage to the crop is usually spread over a number of years and can be reflected by lower-than-normal yields for a few years following the flood. In a questionnaire survey by Berning (1998) several farmers in the Mfolozi floodplain indicated that they generally establish sugar cane on ten percent of the farm annually in the absence of floods and the assumption is made that this applies to all farmers in the area. Thus for the calculation of damage to crops, a period of ten years is considered. From the questionnaires it appeared that yields are generally

lower than normal only during the first two years following the flood. On average yields decreased with twenty and ten percent during the first and second year, respectively.

In order to calculate the value of the loss in income due to damage to the crop, the gross margins of future yields must be discounted to present values (PV) and added together to get the net present value of the gross margin (NPV_{GM}). The difference between the NPV_{GM} without a flood and the NPV_{GM} with a flood is regarded as the damage to the crop. When establishment does not take place, the damage to the crop is the difference between the net present value of the gross margin for the ten years following the flood and the income that would have been realised in the absence of a flood, during the same period. If sugar cane is re-established, the damage to the crop is the net present value of the difference in gross margin for the ten years under consideration.

After a flood the farmer has to decide whether he wants to re-establish sugar cane or not. His decision depends largely on the extent of damage. Assumptions were made by Berning (1998) with regard to the option that the farmer will choose:

- When less than 30 percent of the sugar cane is destroyed, farmers will not re-establish and production will continue with less than optimal yields in the following two years.
- When more than 30 percent of the sugar cane is destroyed, farmers will re-establish sugar cane.

Hence damage to the crop if the farmer does not re-establish sugar cane is calculated as

$$IC = NPV_1 - NPV_2$$

and damage to the crop if the farmer does re-establish sugar cane is calculated as

$$IE = NPV_1 - NPV_3$$

Where:

$$NPV_1 = (0.1 * NPV_{1.1}) + (0.1 * NPV_{1.2}) + \dots + (0.1 * NPV_{1.10})$$

$$NPV_2 = (0.1 * NPV_{2.1}) + (0.1 * NPV_{2.2}) + \dots + (0.1 * NPV_{2.10})$$

$$NPV_3 = NPV_{3.1} = PV_{3.1.1} + PV_{3.1.2} + \dots + PV_{3.1.10}$$

$$NPV_{I,J} = PV_{I,J.1} + PV_{I,J.2} + \dots + PV_{I,J.10}$$

$$PV_{IJK} = GM * ((1 / (1 + i))^n)$$

I = 1 ... 3	1 = normal production pattern 2 = production with damaged sugar cane 3 = re-established sugar cane
J = 1 ... 10	year of sugar cane establishment
K = 1 ... 10	year
GM	= gross margin
i	= discount rate
n	= number of years

5.8.3 Loss functions for infrastructure

The extent of damage to infrastructure depends on the size of a flood, rather than characteristics of a specific flood such as depth and duration of inundation (Berning, 1998). Thus the size of a flood and the distances of roads etc. within the boundaries of each flood, are the most significant determinants of the extent of damage. The loss functions developed by Berning (1998) are given in Table 5.3.

Table 5.3 Loss functions (1995 values) for infrastructure categories in the Mfolozi floodplain (Berning, 1998)

Infrastructure	Stage damage curve*	Adjusted coefficient of determination (R^2)
Drains	$D_D = (6.12 * 10^{-07}) * F^{1.9020}$	0.983
Levees	$D_L = (1.45 * 10^{-14}) * F^{3.8948}$	0.917
Roads	$D_R = (9.17 * 10^{-09}) * F^{2.4563}$	0.997
Tramlines	$D_T = (1.86 * 10^{-14}) * F^{3.8167}$	0.833
Spillways	$D_S = (1.53 * 10^{-09}) * F^{3.0309}$	0.979
Bridges	$D_B = (9.92 * 10^{-11}) * F^{3.2145}$	0.984
Total	$D_{TOT} = (3.76 * 10^{-09}) * F^{3.1151}$	0.982

* The F-test statistic and coefficients of all estimated functions are significant at 5% levels

D: Damage { D_D , D_L , D_R , D_T and D_S in (R/m); D_B and D_{TOT} in (R'000)}

F: Flood peak (cumecs)

5.9 INTERFACES BETWEEN GIS, NUMERICAL FLOOD MODELS AND OTHER RELEVANT MODELS

A GIS can be used to integrate the hydrologic, hydraulic, topographic and economic aspects, so as to compute the estimated flood damage. According to Myburgh (1998) hydrologic- and hydraulic modelling is closely related and assumptions made for hydrologic models can usually be applied to hydraulic models (for example numerical flood models) as well.

De Vantier and Veldman (1993) mention that connections with GIS can be expected in the hydrologic engineering field since large parts of hydrologic analyses are linked to processes on the surface of the earth. Spence *et al.* (1995) supports this statement and adds that GIS can bring a spatial context to hydrologic models that lacked in the past. The authors are of the opinion that the input data to hydrologic models should also be enhanced, seeing that the models are becoming more complex and are describing more physical processes. The output data from hydrologic models are complex and the large volume of data makes it difficult to relate the results directly to locations (Muller & Rungoe, 1995). GIS can therefore provide the input data for hydrologic models and it can make the process of analysing the output data more efficient. Maidment (1993) is of the opinion that researchers should be rethinking hydrologic modelling in spatial terms.

Coupling environments can be categorised in isolated-, loose-, tight-, and integrated environments (Wolff-Piggott, 1994). Isolated and loosely coupled systems are based on a file transfer method where the user is expected to exchange the files from the one system to the other. With tight coupling the file transfer is performed automatically by the software and in an integrated system the GIS and hydrologic model have been developed as a single software system.

An example of an integrated system is the GIS-based hydrologic model that was developed by Maidment (1993) for the computation of hydrographs. Stream networks, watersheds, flow direction and flow velocity are automatically delineated from a DEM (see Paragraph 4.6). The grids of flow direction and flow velocity are then used to create a grid of travel times where the value in each cell is the time taken for water from that cell

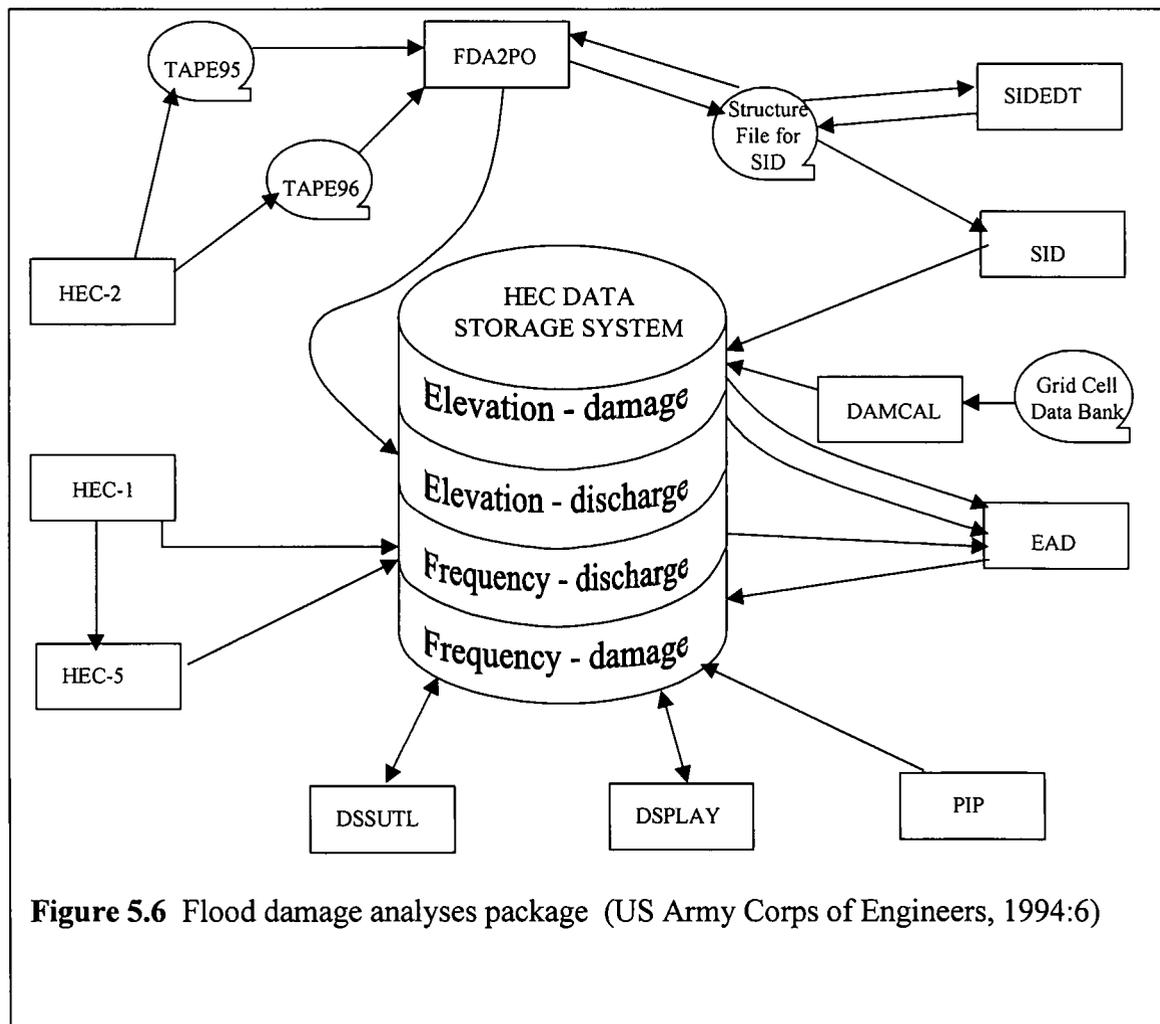
to flow to the watershed outlet. The cells may then be classified into zones i , $i = 1, 2, \dots$ whose travel time t falls into time intervals Δt . The line bounding the outer limit of cells of a zone is called the isochrone of time of travel $t = i\Delta t$ to the watershed. The total area of cells in zone i is A_i . The isochrone that has the maximum time of flow to the outlet is the time of concentration of the watershed, t_c . The ordinates U_i of its unit hydrograph of duration Δt are given by $U_i = A_i/\Delta t$.

5.10 HEC'S ROLE IN METHODOLOGIES FOR APPLICATIONS IN FLOOD DAMAGE REDUCTION STUDIES AND GIS/HYDROLOGY DEVELOPMENT

According to De Vantier and Veldman (1993:256) the Hydrologic Engineering Center (HEC) played an important role in the development of computer methods in hydrology. Some of the earliest work by HEC related to GIS hydrology in automating the data preparation process for HEC developed software, which often included extensive manipulations of map data (Guide manual, 1987 as quoted by De Vantier and Veldman, 1993). The raster-based organisation chosen was called the grid cell databank. The grid cell databank approach was among others used by a program called HYDPAR for the extraction of hydrologic parameters.

Davis (1978) describes a pilot study undertaken by HEC to develop and test analytical methodologies for an application in comprehensive floodplain information studies. The spatial data management and comprehensive analyses system (HEC-SAM) comprised of a family of special purpose, utility computer programs. About one third of the couplings between the different programs were fully automatic. This system was based on the grid cell databank approach. Grid topographic data could be created from digitised contour lines with two programs called Topo and Lines. Polygons were registered to the base grid co-ordinates by the Register program. GRID (refer to Paragraph 2.4.2.5) was used to display data in the grid cell format while Automap II (refer to Paragraph 2.4.2.2) was used to display data digitised in the polygon format and to generate grid cell data from polygon format data. Other programs in the system included HYDPAR, HEC-1, DAMCAL, RIA, STORM, etc.

A following system, the flood damage analyses package (FDA) (US Army Corps of Engineers, 1994; US Army Corps of Engineers, 1988), was highly automated and is schematically illustrated in Figure 5.6. HEC has developed a data storage system (DSS) that allows the user to transfer data between programs. The application programs were modified to utilise the system. Two alternatives are possible for development of elevation-damage relationships using programs in this package. One is conventional structure inventory based (SID) (US Army Corps of Engineers, 1989) and the other is spatially based (DAMCAL) (US Army Corps of Engineers, 1979) using a grid cell databank. Both these programs use stage-damage curves (see Paragraph 5.8.1) to compute potential flood damage.



The flood damage analyses package is comprised of the following programs:

- *HEC-1 Flood Hydrograph Package* simulates rainfall-runoff, simple reservoirs and hydrologic channel routing and is used to develop flow-frequency functions.
- *HEC-2 Water Surface Profiles* computes steady-state, uniform flow profiles and is used to develop discharge-elevation functions.
- *HEC-5 Simulation of Flood Control and Conservation Systems* simulates complex reservoir systems and is used to develop flow-frequency functions.
- *SID, SIDEDT and DAMCAL* are flood damage analyses programs that are used to develop elevation-damage relationships.
- *EAD, Expected Annual Damage Computation* computes expected annual damage and inundation reduction benefits. It is used to compare flood damage mitigation plans.
- *FDA2PO* computes the reference flood elevation at structures and stores stage-flow rating curves in a HECDSS data file.
- *PIP, DSSUTL and DSPLAY* are used for data file management. These programs allow the user to directly enter paired function relationships to a DSS data file, for example, an elevation-damage relationship derived by hand from field data.

Version 1.0 of HEC-FDA, a next generation flood damage analyses program, was scheduled to be released in December 1997 (Dotson & Burnham, 1997). This program would use risk-based analyses procedures for formulating and evaluating flood damage reduction plans. Uncertainty in discharge-frequency, stage-discharge and stage-damage functions would therefore be quantified to be incorporated into economic and performance analyses. It would be possible to import water surface profiles from two numerical flood models namely HEC-RAS and HEC-2 or to enter the water surface profile data manually when another numerical flood model was used.

5.11 APPLICATIONS IN FLODSIM

The same process of determining flood damage as described in this chapter is followed in FLODSIM. Hydraulic properties are read from a text file that is defined in such a way that the output file from the numerical flood model can easily be converted to it.

Several loss functions were implemented into FLODSIM. This includes loss functions developed by Du Plessis (1994) for vineyard, lucerne and rotational crops; loss functions developed by Berning (1998) for sugar cane and infrastructure and loss functions developed by Booysen (1994) for buildings. The mean annual flood damage can be calculated with FLODSIM and benefit-cost comparisons can therefore be done for both structural and non-structural measures.

Normally a team consisting of hydrologists, hydraulic experts, economists, civil engineers, sociologists, geographers and urban and regional planners would work together in flood management studies that are done with FLODSIM. The hydrologist would determine the flood hydrographs and flood probabilities of different floods while the hydraulic expert would do the simulations on numerical flood models. Economists would usually develop the loss functions for different land use types. Civil engineers would suggest the different structural flood damage control measures that can be used and they might also determine the risks associated with these structures. Sociologists, geographers and urban and regional planners would be concerned with non-structural flood damage control measures.

DEVELOPMENTS IN FLODSIM

6.1 INTRODUCTION

The flood damage simulation model (FLODSIM) which was developed for the Orange River (Viljoen *et al.*, 1995) was location specific and had to be adapted and refined to improve the ease with which it could be applied to other areas. A Setup program was written to facilitate the process with which the necessary input for a new area can be defined.

Programs were also written to speed up the process of acquiring new hydraulic information after levees were added or removed. This includes programs with which topographic data that are required by numerical flood models can be extracted from the DTM and with which the hydraulic data that were computed with the numerical flood model can be imported into FLODSIM. An interface with Mike 11 was also developed to illustrate the coupling between FLODSIM and numerical flood models. Other enhancements of the model include programs for the manipulation of levees, loss functions for sugarcane and infrastructure and a program that computes the flooded areas.

6.2 THE SETUP PROGRAM

A Setup program was written to be able to adapt the model according to the different situations of floodplains. The Setup program prompts the user to indicate the features that should be included in the model and then it guides the user through a series of menus to

define the variables that are required to include the specified features. Features that can be included into the model include a DTM, levees, contours, spot heights, cultivated fields, infrastructure and buildings. Flood damage can be computed for cultivated fields, infrastructure and buildings.

The AML (arc macro language) program files and menu files are rewritten while the Setup program is running. This is made possible by the fact that AML programs are not compiled as a whole, but interpreted line by line as it is encountered. A file has however to be rewritten before it is called. The same can be done with menu files that are also saved as text files.

Other information that can be defined with the aid of the Setup program includes the following:

- Directories where the files can be found.
- The flood frequencies of floods with different sizes.
- The dates that floods can occur.
- The loss functions for buildings.
- Descriptions and shade symbols that should be used for different crop types.
- Descriptions and line symbols that should be used for different infrastructure types.
- Variables required to estimate the direct impact.
- Variables required to estimate the secondary impact for the region.
- Variables required to estimate the secondary impact nationally.

The graphical user interface of the Setup program is described in detail in Chapter 2 of the user's manual in Appendix A.

6.3 HANDLING OF DIFFERENT CROP- AND INFRASTRUCTURE TYPES

The same principles were applied for the different infrastructure types and crop types of cultivated fields. To simplify matters the word crop should be read as crop and infrastructure for the rest of this paragraph except when an explicit distinction is made.

As a starting point the usage of the same program to determine damage to different crop types was investigated. There were no major differences between the programs that were developed during the first phase of this project for vineyard, lucerne and rotational crops. It seemed to be possible to use only one set of programs that would use different inputs for different crop types. During the development of loss functions for sugarcane the researcher realised that the existing programs could not be used for sugarcane because of extensive differences between the loss functions of sugarcane and the existing functions. Different programs should rather be used for different crop types as the loss functions are not always based on the same flood characteristics. The loss functions for vineyard is for example based on the depth of inundation while the loss functions for sugarcane depends on the duration of inundation.

A new method to provide for additional crops was therefore initiated. It was decided that unique programs should be written for each crop type. A naming convention should be used with which FLODSIM would be able to recognise the programs. Standard input and output variables should also be used in these programs. This method would require additional programming for new crop types, but the advantage would be that the loss functions would be unique for each crop type and not generalised as in the previous method.

A symbol consisting of two letters is used to identify the crop- or infrastructure types. The AML program filenames for harvest-, crop- and soil damage are for example *hd_crop.aml*, *cd_crop.aml* and *sd_crop.aml* (*crop* should be replaced with the two letters of the crop symbol). The filenames for flood damage to infrastructure would be *fd_infra.aml* (*infra* should be replaced with the two letters of the infrastructure symbol). A menu file with the name *impact_c_crop.menu* and *impact_i_infra.menu* can be used as interface with the user

(*crop* and *infra* are again the symbols for the entities). These menus will be called from the primary impact menu in FLOODSIM. The values that are acquired can be written to a file with the name `defaults_c_crop.aml` or `defaults_i_infra.aml`. These files are called by `defaults.aml` if they exist.

A naming convention is also used for variable names. The Setup program will automatically check the cultivated fields and infrastructure coverages for the different symbols that are used. The number of crop symbols that are found is allocated to a variable called `.c_number`. The Setup program numbers the crop symbols and each individual crop symbol is allocated to `.c_symbol_i` (where *i* is the number that is assigned to the specific crop type). The user will be prompted to give a description and colour value for each crop type that will be saved as `.c_type_i` and `.c_value_i` respectively. The variable names for infrastructure are `.i_number`, `.i_symbol_i`, `.i_type_i` and `.i_value_i`.

Each AML program file (`hd_crop.aml`, `cd_crop.aml`, `sd_crop.aml` and `fd_infra.aml`) should have an argument for the number that was assigned to the crop type. This number should be used in the variable name for the expected total damage that was calculated by the program. The variables that are used to save the total harvest damage, total soil damage or total crop damage for the first crop type would for example be named `.tot_hd_1`, `.tot_cd_1` and `.tot_sd_1`.

FLOODSIM will first check if the program exists before it will try to run it. If the program does not exist the damage will be considered as zero. This might be the case for annual crop types where there is no damage to the crop, but only damage to the harvest and the soil. At the moment programs exist to determine flood damage to vineyards, lucerne, rotational crops and sugarcane.

It is difficult to quantify the amount of work that will have to be done to construct new loss functions and it will differ for different crop types. The most time will however go into the research work that has to be done by an economist. The programming of additional loss functions after it was constructed will not take long.

6.4 PROGRAMS THAT WERE DEVELOPED TO SIMPLIFY THE ACQUISITION OF HYDRAULIC DATA

Programs were developed to speed up the process of acquiring new hydraulic information after levees were added or removed. Topographic data required by numerical flood models usually consists of a river network and cross section profiles of the floodplain. Previously the cross-sections were acquired by means of ground surveys or aerial photography. Both these procedures are tedious and time consuming. The river network and cross section profiles can now easily be extracted from the DTM in FLODSIM and saved as a text file. After the hydraulic data were computed with the numerical flood model they are re-imported into FLODSIM by means of a text file.

An interface with Mike 11 was developed as an example system to illustrate the coupling between FLODSIM and numerical flood models. The interface can be categorised as an isolated system. The software that converts the input and output data is independent of both models. It is therefore possible to create interfaces between FLODSIM and other numerical flood models as well.

Software that was developed by the Department of Water Affairs and Forestry (Tchoukanski, 1996) was used as basis for these programs. The software first had to be adapted in order to apply it to FLODSIM and then it was further developed to handle the different channels of the Lower Orange River and to determine the duration of inundation for sugarcane in the Mfolozi floodplain.

6.4.1 Defining the river network and cross-sections in FLODSIM

A module was developed with which topographic data that are required by numerical flood models can be extracted from the DTM. With this module the river network and cross-sections can be digitised on the screen. The user may choose any of the themes from the model to be displayed in the background while he is digitising. The module provides

functions to add, select or remove cross-sections. A profile of a selected cross section can also be displayed. A route system is used to define the different channels of the river network and each channel can be given a unique name.

The river is represented by a network configuration as a system of inter-connected branches. The network consists of centre lines representing the different channels. A centre line can be defined as a line connecting the points with maximum water speed in the cross-sections (Tchoukanski, 1996). The river network for floods with a five-year return period in the Lower Orange River is illustrated by Figure 6.1.

The following rules must be considered during the digitising of centre lines and cross-sections:

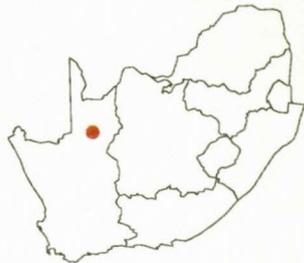
- Centre lines must be directed downstream.
- Cross-sections must be taken from left to right over a centre line when looking downstream.
- Cross-sections should be straight lines.
- Cross-sections are not allowed to cross each other.
- Cross-sections must cross a centre line, but are not allowed to cross more than one centre line.
- Cross-sections should be approximately perpendicular to the centre line.
- Cross-sections should extend far enough to cover the highest elevation expected to be reached by the flood.
- Cross-sections should not extend beyond the boundary of the DTM.

The graphical user interface of the module is described in detail in Chapter 3 of the user's manual in Appendix A. The exporting process is fully automatic and is activated by the click of a button.



Reference

- CHANNELS
- CROSS-SECTIONS



Projection: Gauss	Scale: 1:200000
Compiled by: H L Weepener	Date: 1998-11-14



Figure 6.1: Multiple channels for the Mike 11 simulation in the Lower Orange River

The output data is saved into two files. The first file describes the river network by giving the chainages where the different channels connect. The second file describes the cross-sections (see Figure 6.2). The following algorithm will describe the procedure with which the topographic information is extracted from the DTM and saved as text files.

Algorithm to export cross-sections and centre lines from FLODSIM:

1. Assumptions:
 - 1.1. Suppose the name of the cross-section coverage is *cross* and that all the cross-sections are straight lines (i.e. the cross-sections have no vertices and consist of only one segment defined by two nodes).
 - 1.2. Suppose the name of the centre line coverage is *cline* and that *cline* has a route system called *rl*. The route system will have a field named *channel* to identify the different channels in the river network. All the ids of the arcs in the *cline* coverage will be 9999 (This value is automatically allocated to the *cline-id* field while the user is digitising the centre lines).
2. Determine the position of points where centre lines and cross-sections intersect:
 - 2.1 Combine the *cline* and *cross* coverages with the 'append' command in ARC.
 - 2.2 Clean the combined coverage with the line option. This will create nodes where the centre lines and cross-sections intersect.
 - 2.3 Reselect all the cross sections of the combined coverage with the 'reselect' command in ARC by reselecting all the arcs that do not have an id of 9999. This will create a new coverage with the original cross-sections, but with additional nodes where the centre lines and cross-sections intersect. Call this coverage *cross_3nodes*.
 - 2.4 Build *cross_3nodes* with the 'node' option.
3. Calculate the chainages for the cross-sections:
 - 3.1 Use the 'addroutemeasure' command to measure the nodes of *cross_3nodes* to the route system in *cline*. This will create an info file containing three items namely the internal number of the node, the internal number of the route on which it falls and the measure location.

- 3.2 Merge the info file with *cline.ratr1* on the internal number of the route system (i.e. *r1#*) with the 'joinitem' command in ARC. The info file will now have two additional fields namely *r1-id* and *channel*.
- 3.3 Add two fields named *chainage* and *channel* to *cross_3nodes.aat*.
- 3.4 Establish two relates named *rel_fnode* and *rel_tnode* to the info file on the field containing the internal number of the nodes. Define the info item of the first relate as *fnode#* and the info item of the second relate as *tnode#*.
- 3.5 Assign the channel names and chainages in the info file to the corresponding cross-sections in *cross_3nodes* using the relate named *rel_fnode* (use the 'calculate' command in ARCPLOT).
- 3.6 Reselect all the arcs in *cross_3nodes* where the chainage is 0.
- 3.7 Assign the channel names and chainages in the info file to the corresponding cross-sections in *cross_3nodes* using the relate named *rel_tnode* (use the 'calculate' command in ARCPLOT).
- 3.8 Merge the arcs in *cross_3nodes* with the 'dissolve' command in ARC and save the new file as *cross_2nodes*.
4. Calculate the chainages for the connections of centre lines:
 - 4.1 Build *cline* with the node option.
 - 4.2 Use the 'addroutemeasure' command to measure the nodes of *cline* to the route system in *cline*. Save the info file as *connection_measures*. The chainages can now be found in the item named *measure* that was created for *connection_measures*.
 - 4.3 Add a field named *channel* to *connection_measures*.
 - 4.4 Establish a relate *rel_cline* to *cline.ratr1* on the internal number of the route system (i.e. *r1#*).
 - 4.5 Assign the channel names in *cline* to the corresponding centre lines in the *connection_measures* using the relate named *rel_cline* (use the 'calculate' command in ARCPLOT).
5. Extract the profile co-ordinates for the cross-sections from the DTM:
 - 5.1 Load the DTM as the current surface as the source of z values for surface analyses by using the 'surface' command in ARCPLOT.

5.2 Write surface profile co-ordinates for the cross-sections in *cross_2nodes* to an info file (named *profile_info*) with the 'surfacexsection' command. The 'surfacexsection' command attempts to interpolate z values for each point (ESRI, 1997). Only those portions of the cross sections that intersect the current surface extent will have z values interpolated. The 'surfacexsection' command will write the profile information to two output INFO tables named *profile_info* and *profile_info.sec*. The file named *profile_info* contains cross-section profile information with the samples recorded at the two nodes and one vertex of each cross-section as well as every interval of the specified sample distance. The file named *profile_info.sec* contains cross-section profile information with the samples recorded only at the two nodes and one vertex of each cross-section. The files contain six items namely:

- *px* - x-coordinate of the section line sample point in meters.
- *py* - y-coordinate of the section line sample point in meters.
- *section-id* - integer identifying the cross section line.
- *surface-id* - the specified surface id of the surface used to interpolate the section line profile.
- *distance* - cumulative planimetric distance along a section line.
- *spot* - the surface z value of the section line sample point. SPOT values are expressed in meters.

6. Add the heights of the levees to the spot heights of the cross-sections:

6.1 Use the 'linegrid' command in GRID to create a grid named *levee_grid* that represents the height of levees.

6.2 Load *levee_grid* as the current surface as the source of z values for surface analyses by using the 'surface' command in ARCPLOT.

6.3 Write surface profile co-ordinates for the cross-sections in *cross_2nodes* to an info file (named *profile_l_info*) with the 'surfacexsection' command. All sample points outside the SURFACEEXTENT or the interpolateable region of the surface are assigned the NODATA value.

6.4 Use the 'redefine' command in INFO to combine the *px* and *py* items as an item named *pxy* for the files named *profile_info*, *profile_info.sec*, *profile_l_info*,

- profile_l_info.sec*. Redefine the item as PXY,16,16,C with a starting column of one.
- 6.5 Use the 'alter' command in INFO to rename the item named *spot* to *l_spot* for the *profile_l_info* and *profile_l_info.sec* files.
 - 6.6 Reselect all the records in *profile_l_info* where *l_spot* = -9999 (the NODATA value). Use the calculate command to assign the value 0 to these records.
 - 6.7 Reselect all the records in *profile_l_info.sec* where *l_spot* = -9999. Use the calculate command to assign the value 0 to these records.
 - 6.8 Merge *profile_info* with *profile_l_info* with the 'joinitem' command in ARC. Use *pxy* as the relate item. Save the new file as *profile_info*.
 - 6.9 Merge *profile_info.sec* with *profile_l_info.sec* with the 'joinitem' command in ARC. Use *pxy* as the relate item. Save the new file as *profile_info.sec*.
 - 6.10 Use the calculate command in INFO to add *spot* to *l_spot* in the files named *profile_info* and *profile_info.sec*. Assign the answer to *spot*.
7. Write the text files:
- 7.1 Use the 'print' command in INFO to write the file that describes the river network. The channel names and chainages where the different channels connect can both be found in the info file named *connection_measures*.
 - 7.2 The 'print' command in INFO can also be used to write the text file that is illustrated in Figure 6.2. The section id, chainage and the channel name of each cross section can be found in *cross_2nodes*. The section id, surface id, the distance in meters from the starting point of the section and the x-, y-, and z- co-ordinates of each point of the cross section can be found in *profile_info*, *profile_info.sec*. *Profile_info.sec* is used to give the information of the two nodes and one vertex (that indicates the position where the centre line and cross-section intersects) for each cross-section.

The file describing the cross-sections that is illustrated in Figure 6.2 consists of three parts. The different parts are delimited with a line that contains a '0'. The first part gives the section id, chainage of the section on the centre line of a channel in meters, and the channel name of each cross section. The second part gives the section id, surface id, the distance in

meters from the starting point of the section and the x-, y-, and z co-ordinates of three points for each cross section. These three points include the starting point and ending point of the cross section as well as the point on which the section intersects the centre line of a channel. The last part of the file describes the profile of each cross section. The x-, y-, and z co-ordinates are given for regular points along the line. The user determines the intervals between the points, and for this example a distance of 33m was taken. The cross-sections in the output file will be in the same order in which they were digitised.

Mfolozi						
	1,	26452.950,	MAIN			
	2,	25678.560,	MAIN			
	3,	25051.370,	MAIN			
0						
	1,	1,	0.000,	-60480.41009,	-42760.42602,	10.194
	1,	1,	3334.375,	-57359.47412,	-43934.22909,	3.629
	1,	1,	3922.329,	-56809.15573,	-44141.20719,	24.641
	2,	1,	0.000,	-60537.26579,	-42914.74836,	15.304
	2,	1,	3352.527,	-57665.97439,	-44645.38992,	4.278
	2,	1,	3461.496,	-57572.64692,	-44701.64210,	12.054
	3,	1,	0.000,	-60585.99918,	-43085.31545,	15.613
	3,	1,	3420.693,	-57914.20798,	-45221.35680,	3.742
	3,	1,	3993.179,	-57467.05759,	-45578.84421,	9.549
0						
	1,	1,	0.000,	-60480.41009,	-42760.42602,	10.194
	1,	1,	33.000,	-60449.52247,	-42772.04304,	9.873
	1,	1,	66.000,	-60418.63486,	-42783.66006,	7.591
	1,	1,	99.000,	-60387.74724,	-42795.27708,	7.218
	1,	1,	132.000,	-60356.85962,	-42806.89410,	7.530
	...					
	1,	1,	3922.329,	-56809.15573,	-44141.20719,	24.641
	2,	1,	0.000,	-60537.26579,	-42914.74836,	15.304
	2,	1,	33.000,	-60509.00274,	-42931.78362,	10.215
	2,	1,	66.000,	-60480.73969,	-42948.81888,	8.746
	2,	1,	99.000,	-60452.47664,	-42965.85414,	8.312
	2,	1,	132.000,	-60424.21360,	-42982.88941,	9.605
	...					
	2,	1,	3461.496,	-57572.64692,	-44701.64210,	12.054
	3,	1,	0.000,	-60585.99918,	-43085.31545,	15.613
	3,	1,	33.000,	-60560.22397,	-43105.92220,	13.051
	3,	1,	66.000,	-60534.44875,	-43126.52895,	13.059
	3,	1,	99.000,	-60508.67353,	-43147.13570,	11.517
	3,	1,	132.000,	-60482.89831,	-43167.74245,	8.988
	...					
	3,	1,	3993.179,	-57467.05759,	-45578.84421,	9.549

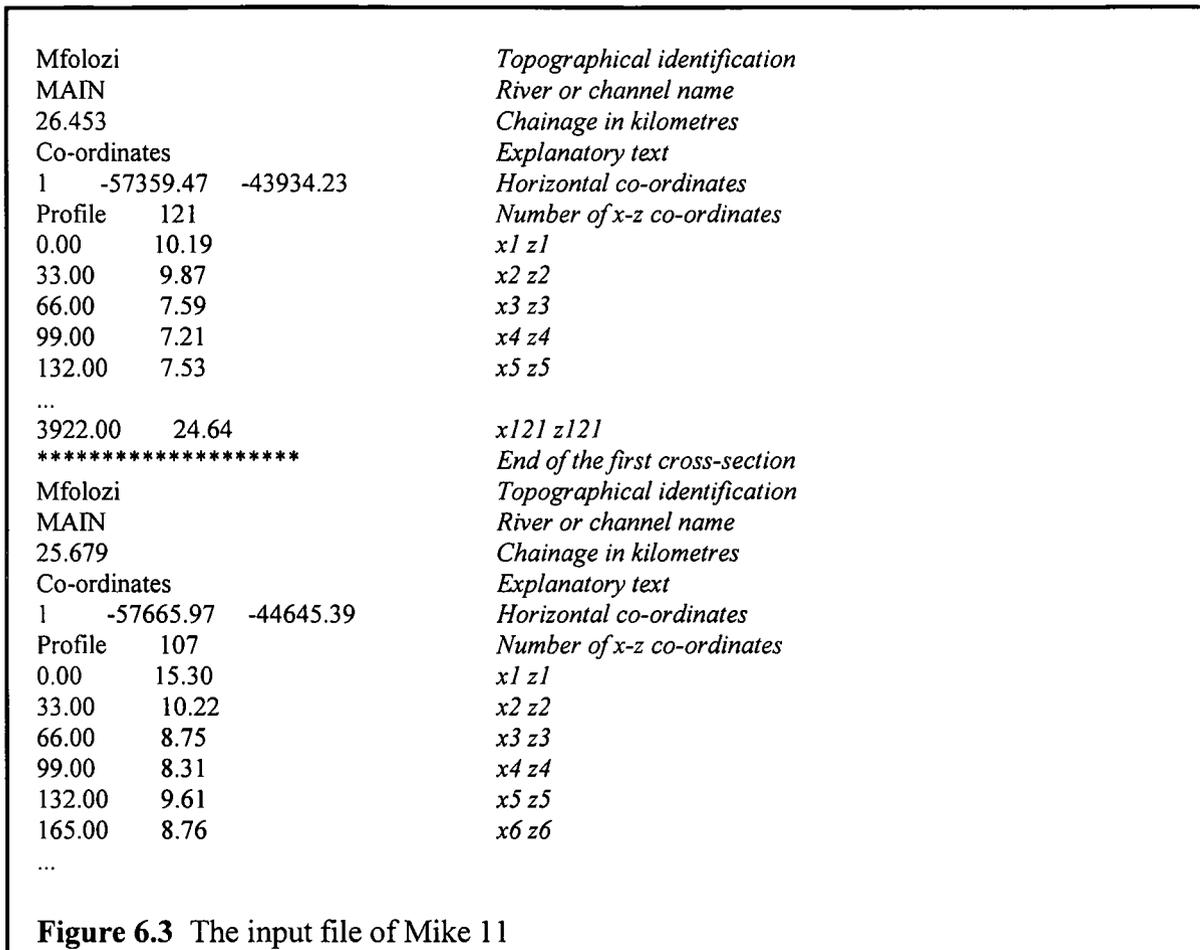
Figure 6.2 The output file of FLODSIM that describes the river network

6.4.2 The interface between FLODSIM and Mike 11

Mike 11 is a professional engineering software package, developed by the Danish Hydraulic Institute (DHI, 1992). It consists of several modules and can be used for the simulation of flows, sediment transport and water quality in estuaries, rivers, irrigation systems and similar water bodies. The core of the Mike 11 system is the hydrodynamic module, which is an implicit, finite difference model for the computation of unsteady flows. The hydrodynamic module is often applied as a flood management tool to simulate flooding behaviour of rivers and floodplains.

Two programs were written for the interface between FLODSIM and Mike 11. The first program, Arc2Mike, does the conversion from the output file of FLODSIM (see Figure 6.2) into a format supported by Mike 11 (see Figure 6.3). The second program, Mike2Arc, converts the Mike 11 output file (see Figure 6.4) into the format of FLODSIM's input file (Figure 6.6). The input and output files of Mike 11 will be described in the remainder of this paragraph.

Cross-sectional data can be read from a text file into the database of Mike 11 (DHI, 1995:2.14). The text files may be in several formats. The format used for the interface is described in Figure 6.3. The cross-sections are specified by a number of x-z co-ordinates where x is the distance from the beginning of the section and z is the corresponding bed elevation. A maximum number of 300 points is allowed for each cross-section (DHI, 1995:2.9). The cross-sections of the input file may be in any order and will be sorted in Mike 11 by channel name and chainage.



Mike 11 can write the results of the simulation to a text file (DHI, 1995:2.14). Mike 11 gives two options for the format of the output file (a summary or time series can be given). The summary file only gives the minimum and maximum water level of the flood for each cross-section. This file can be used when duration of inundation is unimportant as in the case with the Orange River. A file containing a time series is illustrated by Figure 6.4. With this file water levels are given over time-intervals, for example every hour during the total duration of the simulation. The interval can be defined in Mike 11. The channel name and chainage (in kilometres) identify the cross-sections. The first cross-section in Figure 6.4 is for example 51 metres from the beginning of the main channel. The minimum distance allowed between two cross-sections can be defined in Mike 11 (DHI, 1995:2.22). If the distance between two cross-sections is longer than the defined distance Mike 11 will generate a cross-section at the required position. Hydraulic parameters at these additional cross-sections will be calculated

by interpolating between the specified cross-sections. The results of the new cross-sections that were generated by Mike 11 will also be shown in the output file.

```

+-----+
! DATA FILE: MFOLOZI.RDF   BOUNDARY FILE: 10.BSF   !
! PARAMETER: 10-1.RRF      CALCULATED : 12-JAN-1998, 16:10 !
+-----+
!           ! MAIN   MAIN   MAIN   MAIN   MAIN   !
!HOURS:MIN ! 0.051 0.231 0.411 0.566 0.721 !
+-----+
1998 1 1 0 0      12.83 12.67 12.46 12.16 11.77
1998 1 1 1 0      13.05 12.88 12.63 12.28 11.84
1998 1 1 2 0      13.21 13.04 12.79 12.40 11.91
1998 1 1 3 0      13.35 13.18 12.89 12.47 11.97
1998 1 1 4 0      13.47 13.29 12.98 12.53 12.02
1998 1 1 5 0      13.58 13.39 13.06 12.58 12.07

```

Figure 6.4 The output file of Mike 11

Mike2Arc (see Figure 6.5) will also determine the elevation where the water will be for longer than a critical period for each cross-section. This is done by determining the duration of the water at levels from the flood peak downward with an interval declared by the user. Suppose the interval is 0.01 m and the flood peak is at 14 m above sea level then the duration of the water has to be computed for 13.99, 13.98, 13.97 ... until the duration is longer than the critical period. To determine the duration at 13.99 the first timestamp where the elevation-time graph crosses 13.99 has to be subtracted from the second timestamp where the elevation-time graph crosses 13.99. The required elevation will then be the first elevation at which the duration is equal to or longer than the critical period. In the case of sugarcane the critical periods would be the periods (for winter and summer) that the plant could be inundated before it is destroyed.

Two input files are required by Mike2Arc namely the output file from FLODSIM and the output file from Mike 11. The output file from FLODSIM is necessary to identify the original cross-sections. Only the original cross-sections will be included in the input file of FLODSIM.

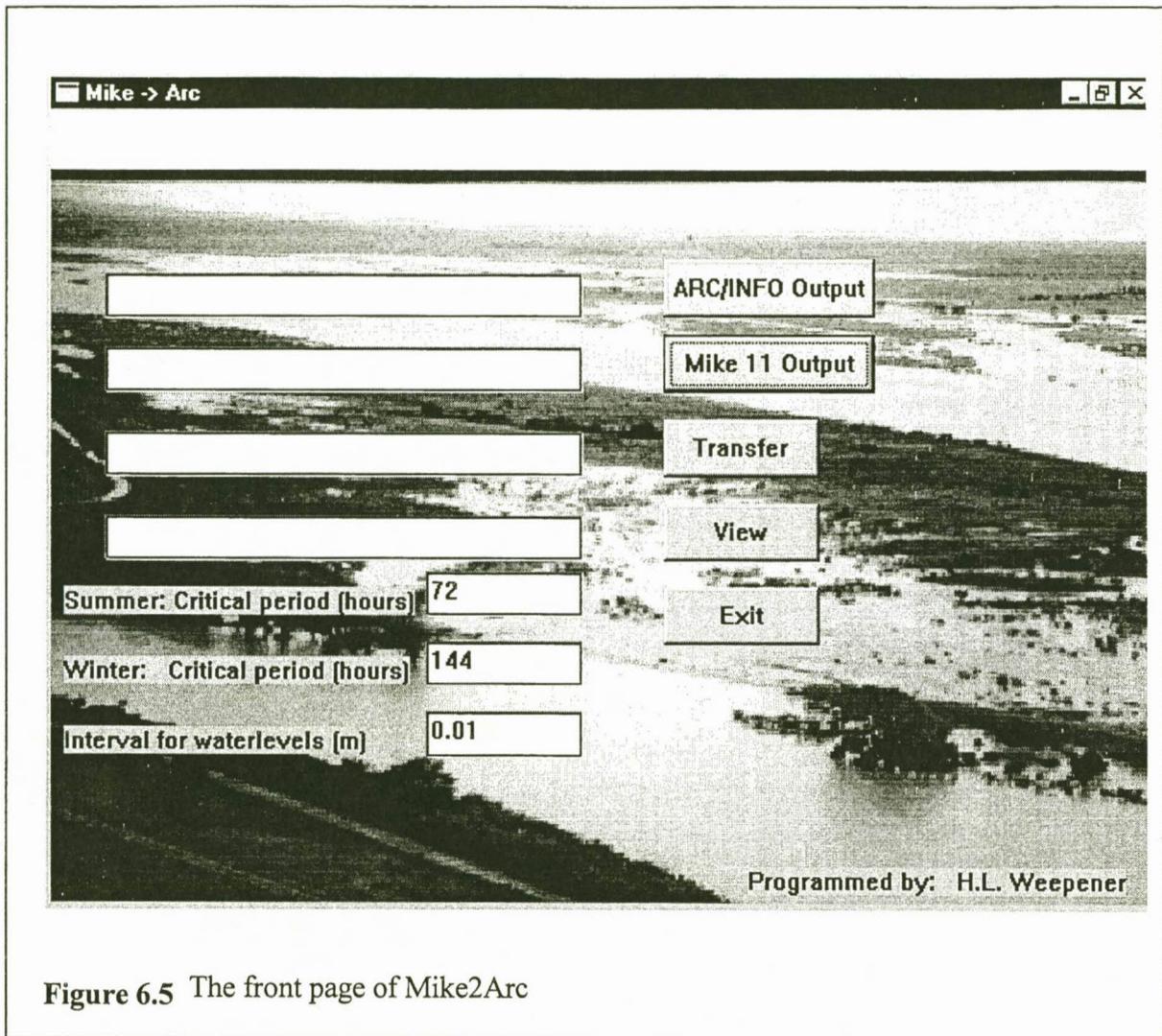


Figure 6.5 The front page of Mike2Arc

6.4.3 Importing hydraulic data into FLODSIM

FLODSIM contains a module with which a water grid can be generated from the hydraulic data that was computed by the numerical flood model for each cross-section. For the purposes of this thesis a water grid will be defined as a grid representing the elevation of water over the floodplain. The values in the cells of the water grid are calculated by interpolating between the water levels of adjacent cross-sections. The linear interpolation method (see Paragraph 4.5.3.2) of the 'tinlattice' command is used. Extra vertices are inserted into the cross-sections in order to optimise the triangulation process of the 'createtin'

command. The average distance between cross-sections is used as the interval at which the points should be inserted.

The input file required by FLODSIM must consist of at least three columns namely the channel name, chainage and flood peak of each cross-section (see Figure 6.6). Any number of additional fields may be added after the flood peak to provide for loss functions that are based on other flood characteristics. The same calculations, which are done for the flood peak, will also be done for the additional fields. Two additional fields were for example used for the Mfolozi River. Sugarcane may only be inundated for a certain period before it would be damaged. This period differs between winter and summer. The two fields that were added for the Mfolozi River represent respectively the elevation at which the water would stay for the critical periods (for the winter and summer) or longer.

The average depth of inundation for cultivated fields and for buildings are calculated by subtracting the elevation of the water grid from the elevation of the DEM. Only the length of infrastructure that is inundated is computed for infrastructure.

<i>Channel name</i>	<i>Chainage</i>	<i>Flood peak</i>	<i>Summer</i>	<i>Winter</i>
MAIN,	51.00,	15.36,	14.23,	13.22
MAIN,	411.00,	14.56,	13.57,	12.81
MAIN,	721.00,	13.58,	12.50,	11.93
MAIN,	1196.00,	13.02,	11.80,	11.03
MAIN,	1682.00,	12.83,	11.72,	11.01
MAIN,	2196.00,	12.70,	11.68,	10.99
MAIN,	2665.00,	12.55,	11.62,	10.98
MAIN,	3144.00,	12.08,	11.35,	10.86

Figure 6.6 Input file for FLODSIM

Sometimes there are areas that are lower than the water level, but cannot be reached by the water. An example would be when a levee lies between the area and the water. Programs were therefore written to find the flooded areas. The following algorithm illustrates the importation of hydraulic information.

Algorithm to import hydraulic data

1. Three input files are used namely the cross-section coverage named *cross*, the centre line coverage named *cline* and the text file containing the hydraulic information. The algorithm takes one argument namely the flood frequency of the simulation that was done on the numerical flood model. Call this variable *ff*. When *ff* is used in output file names or variable names it should be read as the argument that was taken by the algorithm to indicate the flood frequency. The different flood frequencies that can be used in the model are numbered by the Setup program and *ff* will therefore be a number between 1 and the number of flood frequencies that are used.
2. Find the area that are covered by the cross-sections:
 - 2.1 Use the 'nodepoint' command in ARC to create a point coverage named *points* from *cross*.
 - 2.2 Use the 'alter' command in ARC to assign *arc#* as alternative name for the *cross#* field in *cross.aat*.
 - 2.3 Use the 'alter' command in ARC to assign *points-id* as alternative name for the *cross-id* field in *cross.nat*.
 - 2.4 Establish a relate *rel_arc* to *cross.aat* on *arc#*.
 - 2.5 Establish a relate *rel_point-id* to *cross.nat* on *point-id*.
 - 2.6 Assign *rel_point//rel_arc//chainage* to *chainage* in *points* with the 'calculate' command in ARCPLOT.
 - 2.7 Assign *rel_point//rel_arc//channel* to *channel* in *points* with the 'calculate' command.
 - 2.8 Define an info file named *tmp_point* with items *px*, *py*, *channel* and *chainage*.
 - 2.9 Define a cursor to edit *tmp_point*.
 - 2.10 For each point in *points*: Write the x- and y- co-ordinates and the values in *points-id*, *channel* and *chainage* respectively to *px*, *py*, *value*, *channel* and *chainage* in *tmp_point*. The 'show' function in ARCPLOT can be used with the 'select' parameter to get the different values.
 - 2.11 Sort the records in *tmp_point* according to *channel* and *chainage*.

2.12 Create an AML file named *lines.aml* that can be used with the 'generate' command in ARC. All the possible line segments that can be formed with the four points of any two adjacent cross-sections will be written to this file. The first and last cross-sections of each centre line will also be connected with the starting and ending nodes respectively of the centre line on which it falls. Assign an id of '1' to all line segments that are written.

Repeat for all the channels:

2.12.1 Select all the records in *tmp_point* with channel names that correspond with the name of the current channel.

2.12.2 Get the co-ordinates of the first two points in the selection. Write the two line segments that can be formed with the starting point of the channel to *lines.aml*. (The first two points will automatically be the two points of the first cross section because *tmp_point* is ordered on chainage.)

2.12.3 For (the selected points / 2) - 1 do:

2.12.3.1 Get the co-ordinates of the next two points in the selection. Write the four line segments that can be formed with the previous two points to *lines.aml*.

2.12.4 Use the last two points in the selection to write the two line segments that can be formed with the ending point of the channel to *lines.aml*.

2.13 Use the 'generate' command in ARC with the line option to create a coverage from *lines.aml*. Call this coverage *cross_polygon_lines*.

2.14 Clean *cross_polygon_lines* with the polygon option. Call the new coverage *cross_polygons*.

2.15 Create a grid named *cross_area* from *cross_polygons* (use the 'polygrid' command in GRID). All the cells that falls within the area covered by the cross-sections will have grid cell codes of 1.

3. Read the hydraulic information from the text file:

3.1 Check the number of columns in the text file.

- 3.2 Define an info file named *hydraulic_info* with items *channel*, *chainage*, *spot* and additional items named *spot_i* (for $i = 1$ to number of columns - 3).
- 3.3 Use the 'add' command in TABLES to write the information in the text file to *hydraulic_info*.
- 3.4 Sort the records in *hydraulic_info* according to *channel* and *chainage*.
- 3.5 Sort the records in *cross* according to *channel* and *chainage*.
- 3.6 Add an item named *recordnr* to *cross*.
- 3.7 Assign the record number for each record in *cross* to *recordnr*.
- 3.8 Use the 'joinitem' command in ARC with the link option to add the fields in *hydraulic_info* to *cross*. Use *recordnr* as the relate item.
- 3.9 Sort *cross* on *cross#* to restore the order of the records to their original positions.
4. Create a water grid for each of the hydraulic characteristics (i.e. *spot*, *spot_1*, *spot_2* ... etc.):
 - 4.1 Calculate the total length of the centre lines.
 - 4.2 Find the number of cross-sections.
 - 4.3 Divide the total length of the centre lines by the number of cross-sections and assign the answer to *vertice_interval*.
 - 4.4 Use the 'densifyarc' command in ARC to add vertices to *cross* at the interval specified by *vertice_interval*.
 - 4.5 Create a tin named *water_tin* from *cross*. Use the 'createtin' command in ARC with *spot* as the source of z values.
 - 4.6 Create a grid named *water_ff* from *water_tin* (use the 'tinlattice' command in ARC).
 - 4.7 For all the other items in *cross* that contains hydraulic information:
 - 4.7.1 Create a tin named *water_tin_i* from *cross*. Use the 'createtin' command in ARC with *spot_i* as the source of z values.
 - 4.7.2 Use the tinlattice command in ARC to create a grid named *water_ff_i* from *water_tin_i*.
5. Determine the flooded area:
 - 5.1 Use the 'linegrid' command in GRID to create a grid named *levee_grid* that represents the height of levees.

- 5.2 Create a grid called *lower_area*. Assign a value of -1 to all cells that falls inside *cross_area* and where the $\text{DTM} + \text{levee_grid} - \text{water}$ is less than 0. Assign a value of 1 to all the other cells. Only lower areas that are covered by the cross-sections are considered. This is done to ensure consistency between the numerical flood model and FLODSIM. To enlarge the area the cross sections have to be lengthened and the whole process has to be repeated.
- 5.3 Create a polygon coverage named *lower_area_polys* from *lower_area* (use the 'gridpoly' command in GRID). The coverage will have an item named *grid-code* that represents the value of the grid cells at the corresponding area of each polygon in *lower_area*.
- 5.4 Reselect all the polygons in *lower_area_polys* where *grid-code* = -1.
- 5.5 Reselect all the polygons in *lower_area_polys* that are touched by the arcs in *cline*.
- 5.6 Use the 'nselect' command in ARCPLOT to switch the selected set of polygons in *lower_area_polys*.
- 5.7 Assign a value of 1 to *grid-code* for all the selected polygons in *lower_area_polys*.
- 5.8 Use the 'polygrid' command in GRID to create a grid named *flooded_area* from *lower_area_poly* (use *grid-code* to assign codes to the grid). All the cells that are flooded will have a value of -1.
6. Subtract the water surfaces from the DTM. This is done for each field that contains hydraulic information. This grid will not make sense for certain hydraulic attributes such as momentum flux and should then be ignored. The grid named *water_i* will provide adequate information in such cases:
 - 6.1 Create a grid called *diff_ff*. Assign a value of 0.01 to all the cells where the $\text{DTM} + \text{levee_grid} - \text{water} < 0$ and where *flooded_area* = 1. $\text{DTM} + \text{levee_grid} - \text{water}$ can be assigned to all the other cells.
 - 6.2 Create a difference grid for each of the remaining fields that contain hydraulic information. Call these grids *diff_ff_i*. Assign a value of 0.01 to all the cells where the $\text{DTM} + \text{levee_grid} - \text{water}_i < 0$ and where *flooded_area* = 1. $\text{DTM} + \text{levee_grid} - \text{water}_i$ can be assigned to all the other cells.

7. Calculate the average depth of each cultivated field:
 - 7.1 Use the 'polygrid' command in GRID to create a grid from the cultivated fields coverage. Use the internal number of the coverage to assign codes to the grid cells. Call this grid *land_grid*.
 - 7.2 Use *diff_ff* to calculate the mean depth of inundation for each cultivated field. Use the 'zonalstats' command in GRID with *land_grid* as input zone grid. Call the output info file *land_ff*. The info file will have items called *value*, *count*, *area* and *mean*. The internal number of the cultivated fields coverage can be related to *value* in *land* in order to find the mean depth of each cultivated field.
 - 7.3 Use *diff_ff_i* to calculate the mean difference for each of the other hydraulic characteristics for each cultivated field. Use the 'zonalstats' command in GRID with *land_grid* as input zone grid. Call the output info file *land_ff_i*.
8. Calculate the average depth of each building:
 - 8.1 Use the 'pointgrid' command in GRID to create a grid from the buildings coverage. Use the internal number of the coverage to assign codes to the grid cells. Call this grid *building_grid*.
 - 8.2 Use *diff_ff* to calculate the depth of inundation for each building. Use the 'zonalstats' command in GRID with *building_grid* as input zone grid. Call the output info file *building_ff*. The info file will have items called *value*, *count*, *area* and *mean*. The internal number of the buildings coverage can be related to *value* in order to find the depth of each building.
 - 8.3 Use *diff_ff_i* to calculate the difference for each of the other hydraulic characteristics for each building. Use the 'zonalstats' command in GRID with *building_grid* as input zone grid. Call the output info file *building_ff_i*.
9. Create a polygon coverage that represents the flooded areas:
 - 9.1 Reselect all the arcs in *lower_area_polys* that are part of the polygons with a grid-code of -1 in ARCPLOT.
 - 9.2 Use the 'selectget' command in ARCEDIT to get the same selection in ARCEDIT.
 - 9.3 Use the 'nselect' command in ARCEDIT to switch the selected set.
 - 9.4 Delete all the selected arcs.
 - 9.5 Build *lower_area_polys* with the poly option. Save the file as *floodline_ff*.

10. Determine the length of infrastructure that are inundated:
 - 10.1 Create a route for each arc in the infrastructure coverage (Use the 'measureroute' command in ARC).
 - 10.2 Create events where the polygons of *floodline_ff* intersect with the infrastructure (use the 'polygonevents' command in ARC). Three attributes are given to each event. The first two attributes are the 'from' and 'to' measurements to indicate the position where an infrastructure entered the polygon and where the infrastructure left it again. The third attribute indicates whether the segment is inundated (Negative values are inundated).
 - 10.3 Select all the inundated segments.
 - 10.4 Calculate the length of each segment by subtracting the 'to' measurement from the 'from' measurement.
 - 10.5 Use the 'statistics' command in ARCPLOT with the 'sum' option to determine the total length of each infrastructure category that is inundated. Allocate the distances to variables named *.i_inundation_length_ff_infra* (where *infra* indicates the symbol that is associated with the specific infrastructure category).
 - 10.6 Write the variables named *.i_inundation_ff_length_infra* to an AML file with which the values can be assigned to the variables when the program is run the next time.

A relate environment are automatically established by the system. The AML program files that determine the flood damage for buildings and cultivated fields use these relates to find the hydraulic properties of a specific entity in the corresponding table. The relates are respectively *rel_p_c* and *rel_p_b* for cultivated fields and buildings (*p* indicates the hydraulic property). The relates are automatically updated when the flood frequency changes. The same names can therefore be used for all the flood frequencies. The distance of infrastructure that are inundated can be read from variables named *.i_inundation_length_ff_infra* (where *infra* indicates the symbol that are associated with the specific infrastructure category and *ff* the flood frequency).

6.5 TESTING OF THE INTERFACE BETWEEN FLODSIM AND MIKE 11

The interface with Mike 11 was tested by comparing the results from Mike 11 with floodline calculations, which were done by an engineering firm, Chunnet, Fourie and Partners (1993) for the Orange River. Chunnet, Fourie and Partners (1993) used a steady state model that only provided for one channel. The cross-sections that were used by Chunnet, Fourie and Partners were created with a stereoplotter. These cross-sections were available and could therefore be compared with the cross-sections extracted from the DTM. The Hydraulic Studies Sub directorate from the Department of Water Affairs and Forestry did the flood line calculations on Mike 11 (Stemmet *et al.*, 1997).

The following scenarios were done:

- Use the cross-sections from Chunnet, Fourie and Partners, with one channel.
- Manipulate the cross-sections from Chunnet, Fourie and Partners to include all the channels.
- Use FLODSIM to create the same cross-sections as in the previous scenario from the DTM.
- Construct two new levees at Rouxville West and Top House.
- Remove the levees at Keidebees and Jooste eiland.
- Increase the height of the levees at Straussburg and Swartkop eiland.

The results of the study are described in detail by Stemmet *et al.* (1997). A difference was found between the cross-sections from the DTM and the cross-sections created with a stereoplotter. The DTM was created from contour maps of 1979 when the river flow was relatively low while the cross-sections that were used by Chunnet, Fourie and Partners (1993) were acquired from aerial photography that was done in May 1988. This was shortly after the floods and the river flow was therefore relatively high. The river bottom of the cross-sections from the DTM was almost a meter lower than the cross-sections created with a stereoplotter.

In their report Stemmet *et al.* (1997) state that except for floods with a return period of five years, no significant differences could be found between the results of Mike 11 and the steady state model used by Chunnet, Fourie and Partners (1993). Eleven channels were used for floods with a return period of five years in Mike 11, while only one channel could be used with the steady state model. Stemmet *et al.* (1997) also mentioned that the hypothetical manipulation of levees could be of great value in the future but that it should be done in co-operation with well-informed local people.

As a matter of interest the expected flood damage at the Orange River between Gifkloof weir and the Manie Conradie Bridge is given in Table 6.1. Du Plessis *et al.* (1998) describes the economic analyses of the different scenarios.

Table 6.1 Expected flood damage between the Gifkloof Weir and the Manie Conradie Bridge at Kanon Eiland, 1997

Return period	Flood damage (R)
5 years	3 033 339
10 years	37 256 153
20 years	69 576 939
50 years	96 963 338
100 years	100 044 518
200 years	110 040 052
1000 years (regional maximum flood)	136 363 913
Mean annual damage (MAD)	9 398 662

6.6 DETERMINATION OF FLOOD DAMAGE IN FLODSIM

FLODSIM calculates primary damage as well as secondary damage for the region and nationally. Loss functions are used to calculate the primary flood damage and then multipliers are used to get the secondary damage for the region and nationally.

The flood characteristics for each cultivated field and building can respectively be acquired from the info tables *land_ff* and *building_ff* (*ff* indicates the flood frequency of the data). The

length of each infrastructure type that is inundated is assigned to a variable that can be used by the loss function of the infrastructure type.

The following is a simplified portrayal of the procedure used to derive flood damage to cultivated fields. The same method is used for buildings and infrastructure and it will therefore not be repeated. Hydraulic characteristics for example the average depth of each cultivated field is used to acquire the corresponding damage from the loss functions. Different loss functions for each crop type is used to determine direct damage to the harvest, crop and soil. The damage in the loss-functions is given per hectare. By multiplying the damage with the area of the cultivated field the damage to the field can be estimated. The sum of the damage to all the cultivated fields will give the total damage to cultivated fields for the whole area.

The sum of the total damage to cultivated fields, infrastructure and buildings give the total damage for the area.

This process is repeated for floods of different probabilities in order to calculate the MAD. The MAD is represented by the area beneath the graph when the total damage is plotted against the flood probability (du Plessis 1994).

The secondary damage is calculated by multiplying the primary damage with the corresponding multipliers. The mean annual secondary damage is calculated in the same way as the primary damage.

FLODSIM provides the mean annual damage to the user and draws a graph that represents the damage-frequency relationship on the screen. Detailed information of the results of the simulation is written to a text file. The text file is illustrated by Figure 6.7. Results are given for each flood line in the form of a table. Information that can be read from the tables includes the harvest-, crop- and soil damage to each crop type; the total flood damage to buildings and the flood damage to each infrastructure category. The total flood damage for

the area as well as the flood damage to each crop type can be read from the last line in the table.

MAD R 3122840

FLOOD DAMAGE FOR THE 10 YEAR FLOOD LINE

DAMAGE	SUGARCANE	TOTAL
HARVEST	5918567	5918567
CROP	7045678	7045678
SOIL	0	0
BUILDINGS		0
ROADS		67926
TRAMLINES		11213
DRAINS		175769
SPILOWAYS		57086
BRIDGES		17452
LEVEES		28107
TOTAL	12964245	13321801

...
...
...

FLOOD DAMAGE FOR THE REGIONAL MAXIMUM FLOOD LINE

DAMAGE	SUGARCANE	TOTAL
HARVEST	14488502	14488502
CROP	11156299	11156299
SOIL	0	0
BUILDINGS	0	0
ROADS		5970029
TRAMLINES		9254681
DRAINS		3818684
SPILOWAYS		7074989
BRIDGES		2896203
LEVEES		13760673
TOTAL	25644801	68420063

Figure 6.7 An example of a text file that contains information on the results of a simulation that was done on FLODSIM

6.7 IMPLEMENTATION OF FLODSIM ON THE MFOLOZI FLOODPLAIN

6.7.1 The acquisition of topographic data

The cultivated fields, roads, tramways, levees, drainage systems and rivers were digitised from 1:10 000 orthophotos (see Figure 6.8 & Figure 6.9). Unfortunately the most recent available orthophotos were created from old (1979) photography. The digitised data was therefore updated with information derived from 1996 air photos and digital data that was kindly made available by Bosch & Associates.

Two methods were applied to obtain a DEM for the Mfolozi floodplain. With the first method digital photogrammetry was used (see Paragraph 4.5.2). The results from this method were unreliable due to the dense vegetation. A second DEM was created with an analogue stereoplotter. With this method points within cultivated fields could be ignored. The points obtained from each stereoscopic model were saved in a DXF file and then converted to an ARC/INFO coverage with the 'dxfarc' command. The different coverages of the stereoscopic models were combined before the combined coverage could be converted to a grid with the 'topogrid' command.

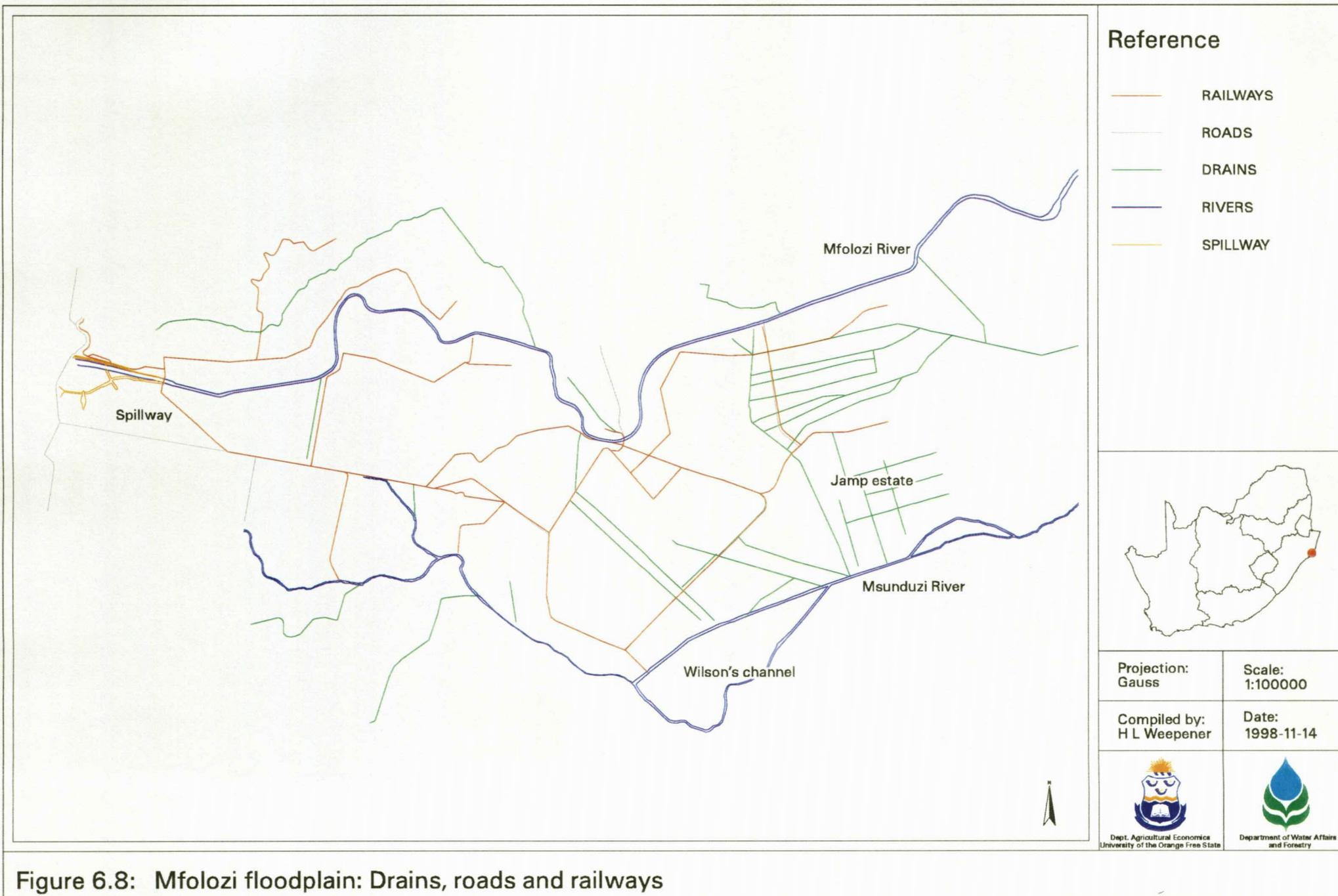


Figure 6.8: Mfolozi floodplain: Drains, roads and railways

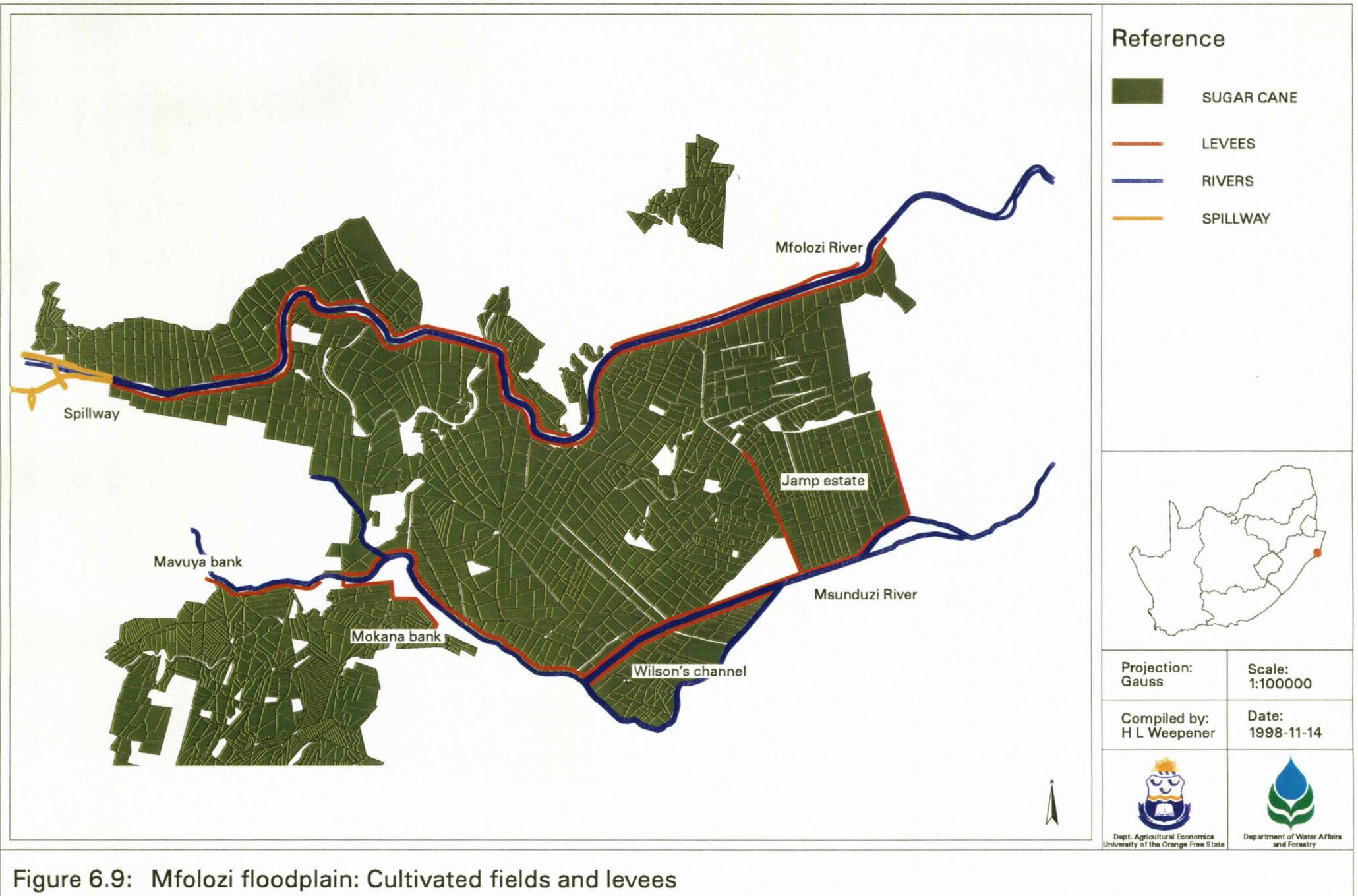


Figure 6.9: Mfolozi floodplain: Cultivated fields and levees

6.7.2 The acquisition of hydraulic data for the Mfolozi floodplain

The Hydraulic Studies Sub directorate from the Department of Water Affairs and Forestry did the floodline calculations (Cai & Myburgh, 1998). Mike 11 was used to develop the dynamic floodline model for the Mfolozi floodplain. The cross-sections and river network, needed by Mike 11 to describe the floodplain topography, were defined in FLODSIM (see Paragraph 6.4.1).

The part of the floodplain to the north of the Mfolozi was disregarded, as it is very small in comparison with the rest and it was assumed that it could be protected at quite low costs. The Mfolozi River's right side embankment was therefore taken as the model's northern boundary. The volume water that would go down the Mfolozi River was handled as a constant and subtracted from the water that would go over the spillway.

6.7.3 Implementation of loss functions for the Mfolozi floodplain

This paragraph should be read together with Paragraph 5.6 where the loss functions are described in more detail.

6.7.3.1 Determination of flood damage to sugarcane

The only crop that is planted in the Mfolozi floodplain is sugarcane. The sugarcane plant is only damaged after it was inundated for a certain period. Hydraulic data required by the loss functions for sugarcane includes the average depth of the flood peak, the average depth after the critical period for the summer expired and the average depth after the critical period for the winter expired. It is almost impossible to keep track of the heights of sugarcane on different cultivated fields. The sugarcane is cut several times a year and all the cultivated fields are not cut simultaneously. The average percentages of the area under sugarcane with different heights were therefore determined for each month.

Algorithm to determine harvest damage to sugarcane

1. For sugarcane heights from 0.1 meter to the maximum height of sugarcane in steps of 0.1 meter do:
 - 1.1 Select all the cultivated fields where the depth of the water is between the current height and the following height for sugarcane.
 - 1.2 Calculate the decrease in income, because of destroyed sugarcane, for the selected cultivated fields (see Paragraph 5.6.2.3).
 - 1.3 Calculate the decrease in costs, because of partially damaged sugarcane, for the selected cultivated fields (see Paragraph 5.6.2.3).
 - 1.4 Calculate the decrease in income, because of partially damaged sugarcane, for the selected cultivated fields (see Paragraph 5.6.2.3).
 - 1.5 The harvest damage for the selected cultivated fields is the value calculated in steps 1.2 - 1.3 + 1.4 (see Paragraph 5.6.2.3).
2. The total harvest damage of sugarcane for the whole area is the sum of the harvest damages to all the cultivated fields.

Algorithm to determine crop damage to sugarcane

1. Calculate the damage to the crop when the farmer re-establish sugarcane (see Paragraph 5.6.2.4).
2. Calculate the damage to the crop when the farmer does not re-establish sugarcane (see Paragraph 5.6.2.4).
3. Select all the cultivated fields where more than 30 percent of sugarcane is destroyed.
4. The crop damage for the selected cultivated fields is the area of each field multiplied by the damage to the crop when the farmer re-establish sugarcane.
5. Select all the cultivated fields where less than 30 percent of sugarcane is destroyed.
6. The crop damage for the selected cultivated fields is the area of each field multiplied by the damage to the crop when the farmer does not re-establish sugarcane.
7. The total crop damage of sugarcane for the whole area is the sum of the crop damages to all the cultivated fields.

The percentage destroyed sugarcane mentioned in steps two and four is determined by the sum of the percentages of sugarcane that is lower than the elevation of the waterlevel after the critical period expired.

6.7.3.2 Determination of flood damage to infrastructure

Loss functions were constructed to estimate the flood damage to levees, drains, roads and tramways for the Mfolozi floodplain. The loss function of each category of infrastructure depicts the damage per meter depending on the return period and flood peak of the flood (see Paragraph 5.6.3). The loss functions were developed from actual damage that occurred with previously floods at the Mfolozi floodplains and the loss functions can therefore not be used for other areas.

The flood damage of each category of infrastructure is the length inundated by water multiplied by the damage per meter for the specific flood line.

6.7.4 Flood damage mitigation measures that were investigated for the MFOLOZI floodplain

Flood damage mitigation measures were chosen that would shorten the time of inundation as flood damage to sugar cane depends mainly on the duration of inundation. The study area can be roughly divided into three areas based on vegetation. The first area is the state-expropriated land that begins at the upstream boundary of the study area, immediately downstream of the spillway. This area is totally covered by wild weed, reeds and shrubs. The second area is the sugarcane fields. The last area is very densely vegetated and can be found around the river mouth. Manning's roughness coefficient will differ for each of these areas. The coefficient was taken as 0.055, 0.065 and 0.1 respectively for each area (Cai & Myburgh, 1998).

The four flood damage mitigation measures that were investigated are:

- The *status quo*.
- Controlled vegetation. Plant lucerne on the expropriated land so that Manning's roughness coefficient can be lowered to 0.035 for this area.
- Removal of dense vegetation around the river mouth. Manning's roughness coefficient was taken as 0.045.
- Controlled vegetation combined with removed dense vegetation around the river mouth.

According to Cai and Myburgh (1998) the single most significant positive change can be effected by the removal of the extremely dense vegetation around the river mouth. Up to 1.5 meters of water level draw down and 24 hours decrease in duration of inundation for the regional maximum flood conditions can be achieved at the centre of the study area. This is also reflected in the mean annual damage for the different scenarios (see Table 6.2).

Table 6.2 The mean annual flood damage for the different scenarios that were investigated for the Mfolozi floodplain, 1995

Description of scenario	Mean annual flood damage (R)
<i>Status quo</i>	3 122 000
Controlled vegetation	3 633 000
Removal of dense vegetation	2 593 000
Controlled vegetation combined with removed dense vegetation	2 430 000

According to Du Plessis *et al.* (1998) an average annual gross margin of R2 914 million can be expected with the additional 1 639 ha lucerne. This is the net benefit that is obtained when lucerne is replaced every ten years. When lucerne has to be replaced every seven or three years respectively, due to floods, average annual gross margins of R2 57 and R1 05 million are obtained. This is still larger than the additional damage (R508 000) that occurs. To put this into practice, other factors such as the utilisation and marketing of lucerne in the Mfolozi floodplain should also be investigated.

According to Du Plessis *et al.* (1998) deforestation can only be of economic benefit if the costs of deforestation does not exceed the average amount of R529 000 per annum (1995). Although this option may look economically beneficial, ecologically it can be a very sensitive alternative. A comprehensive ecological impact study should be undertaken before any recommendation can be made.

6.8 CONCLUSION

With the changes that were made to FLODSIM it should be relative easy to apply it to other flood prone areas as well. The Setup program guides the user through the different variables that should be defined and the program can adapt itself according to the different situations at flood plains. FLODSIM was restructured to simplify the inclusion of loss functions for new crop- and infrastructure types.

The acquisition of hydraulic data was made easier by the interface that was developed with Mike 11. The acquisition of topographic and economic data will however still require a lot of time and money. Over time more loss functions will be developed with the result that a time will be reached when the required loss functions exist for all the crop types in a new area.

CONCLUSION

7.1 INTRODUCTION

After FLODSIM was adapted to be generally applicable in flood prone areas it was tested on the Mfolozi floodplain. The model can be of great value in floodplain management studies and can be applied to agricultural- and/or urban areas. Detailed topographic, hydraulic and economic data, of the area on which it is applied, are however required by the model.

FLODSIM can estimate flood damage for three land use categories namely area-, linear- and location categories. An example of a land use type where the area is important, is cultivated fields. The damage to a field is calculated per hectare and then multiplied with the area of the field to determine the damage to the entire field. The linear category includes infrastructures such as roads, power lines, tramlines, drainage systems, etc. The damage to these structures is calculated per meter and then multiplied with the length. Residential-, commercial- and industrial structures belong to the location category. These structures are classified according to size and content and the same loss function is used for structures of the same class.

7.2 THE PROGRAMMING ENVIRONMENT

FLODSIM was developed with ARC/INFO for workstations. Currently there is a trend in GIS technology towards PC based systems, but the software that are available for PCs does not yet have the full functionality that is required by FLODSIM. Software vendors are continuously improving their products and it might be possible in the near future to extend

FLODISM to be used on PCs as well. Some information on the leading GIS software vendors is given in Chapter 2.

7.3 ACQUISITION OF INPUT DATA THAT ARE REQUIRED BY FLODSIM

7.3.1 Topographic data

In a literature study that was conducted to investigate different methods for obtaining topographic data it was found that data can either be acquired in digital form from another institution, or it has to be digitised from analogue map documents (see Chapter 3). When data are obtained from another department or agency, the people who were responsible for the data should be interviewed to make sure that the data are suitable for the envisaged purposes. Aspects essential to your project might not have been important to them.

When no data are available for the area it may be collected *in situ* or by means of remote sensing. Remote sensing can also be of great value in updating data such as land use patterns that change over time.

Special attention was given in Chapter 4 to the generation of DEMs. DEMs are usually constructed from contour lines and spot heights with the aid of an interpolation method. Other sources used to derive elevation data vary from ground surveys and photogrammetry to radar or laser altimetry. The different sources vary in cost, production time and quality of the product and these characteristics should be considered when the data source is chosen.

7.3.2 Hydraulic data

Programs were developed to speed up the process of acquiring new hydraulic information after levees were added or removed. Topographic data required by numerical flood models usually consists of a river network and cross section profiles of the floodplain. Previously the cross-sections were acquired by means of ground surveys or aerial photography. Both these procedures are tedious and time consuming. The river network and cross section profiles can

now easily be extracted from the DTM in FLODSIM and saved as a text file. After the hydraulic data were computed with the numerical flood model they are re-imported into FLODSIM by means of a text file.

An interface with Mike 11 was developed as an example system to illustrate the coupling between FLODSIM and numerical flood models. The interface can be categorised as an isolated system. The software that converts the input and output data is independent of both models. It is therefore possible to create interfaces between FLODSIM and other numerical flood models as well. Examples of other numerical flood models that use cross-sections to describe the topography are HEC-RAS (US Army Corps of Engineers, 1997:B.12- B.14), CFP (ECC, 1987:5-6), XP-SWMM and WSPRO (Van Bladeren, 1998).

7.3.3 Economic data

Economic data are required for the determination of primary damage as well as for secondary damage for the region and nationally and should be provided by an economist. The data that are required to determine primary damage will depend on the different loss functions that are used. Regional and national multipliers have to be calculated to determine secondary damage for the region and nationally.

FLODSIM was restructured to simplify the inclusion of loss functions for new crop types. It is difficult to quantify the amount of work that will have to be done to construct new loss functions and it will differ for different crop types. The most time will however go into the research work that has to be done by an economist. The programming of additional loss functions after it was constructed will not take long.

7.4 IMPLEMENTATION OF FLODSIM ON THE MFOLOZI FLOODPLAIN

The cultivated fields, roads, tramways, levees, drainage systems and rivers in the Mfolozi floodplain were digitised from 1:10 000 orthophotos. Unfortunately the most recent available orthophotos were created from old (1979) photography. The digitised data was therefore

updated with information derived from 1996 air photos and digital data that was kindly made available by Bosch & Associates.

Two methods were applied to obtain a DEM for the Mfolozi floodplain. With the first method digital photogrammetry was used (see Paragraph 4.5.2). The results from this method were unreliable due to the dense vegetation. A second DEM was therefore created with an analogue stereoplotter.

The Hydraulic Studies Sub Directorate from the Department of Water Affairs and Forestry did the floodline calculations on Mike 11 (Cai & Myburgh, 1998). Flood damage mitigation measures were chosen that would shorten the time of inundation because flood damage to sugar cane depends mainly on the duration of inundation. The different scenarios were all changes in land use which caused Manning's roughness coefficient to change as well.

Loss functions had to be constructed to estimate the flood damage to sugar cane, levees, drains, roads and tramways for the Mfolozi floodplain. Only sugarcane is cultivated in the Mfolozi floodplain and a budget was drawn up for that (Du Plessis *et al.*, 1998). Besides this budget, regional and national multipliers were calculated in order to calculate regional secondary effects of the floods. The national secondary effects were not calculated.

7.5 RECOMMENDATIONS

The model still has some shortcomings. Cross-sections that are used in numerical flood models sometimes have to be curved in order to be perpendicular to contour lines. Unfortunately, the cross-sections that are taken from the DTM in FLODSIM must be straight lines. FLODSIM would be more useful if the algorithm for extracting cross-sections can be changed to incorporate cross-sections that have more than two points. It would also be better if the cross-sections could be described at different levels of resolution.

More research should be done on the risk that is associated with floods. Flood hydrographs differ significantly and a probability that the hydrograph of real floods will be the same as the

hydrograph that was used as input to the numerical flood model should be determined. The mean annual damage (MAD) can then be given as the probability that it will be within the range of two values.

7.6 MARKETING OF FLODSIM

After a model was developed the next challenge is to move the product from the research labs into the market place. The acceptance and use of FLODSIM will be determined by the marketing strategy that is followed. According to Dent (1997) a marketing strategy must be aimed at satisfying the customers needs. To do that the marketer has four basic ingredients that can be used in what is termed the marketing mix. These are often termed the four P's of marketing i.e. product, price, place and promotion.

FLODSIM was developed for the purpose of creating informed decisions about flood plain management. The model do not make the decisions, the model output simply informs the decision makers. The customers/users of FLODSIM will therefore be organisations that are concerned with flood plain management. The segments of FLODSIM's market might include national departments such as the Department of Water Affairs and Forestry and the Department of Agriculture; provincial governments; city councils; consultants; insurance companies; academics etc. The needs of these segments might differ slightly and should be considered in the marketing strategy.

7.7 CONCLUSION

The development of FLODSIM should be followed up with a good marketing strategy in order to ensure the product is used in the wider South Africa. As was mentioned in Paragraph 7.5, there are still some improvements that can be made to the model. The main focus of future developments will probably be in the construction of loss functions for additional land use types.

With the changes that were made to FLODSIM it should be relative easy to apply it to other flood prone areas as well. The real value of FLODSIM will be ascertained after it has been applied to a few more areas.

FLODSIM
USER'S MANUAL

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CHAPTER 5

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APPENDIX I

LOSS FUNCTIONS IMPLEMENTED IN FLODSIM

INTRODUCTION

1.1 BACKGROUND

The Flood Damage Simulation Model (FLODSIM) estimates flood damage in a flood plain and can be used to evaluate flood damage mitigation measures. The model is of great value in floodplain management studies and can be applied to agricultural- and/or urban areas. Detailed topographic data of the area on which it is applied, are however required by the model. These data include an altitude grid (DTM), levee coverage, and at least one coverage representing land use. Other data such as a contour coverage and spot height coverage are optional.

The benefits of several different combinations of flood damage control measures can be identified by comparing the mean annual flood damage for the different combinations with each other. Flood damage control measures are aimed at the minimisation of the physical extent of floods, to lighten the influence of floods on the community and to lower the probability of flood damage in different areas. Flood damage control measures can be grouped into structural and non-structural measures. Structural measures are implemented to change the physical nature and extent of floods. The volume of water running down, the flood peak, the form of the flood hydrograph, the extent of the area inundated and the speed and height of the water can for example be affected by these measures. Structural measures mainly include engineering works such as drainage networks, levees, dams and spillways. Examples of non-structural measures are effective warning systems, evacuation plans, flood awareness programs, insurance and training.

FLODSIM provides for three land use categories namely area-, linear- and location categories. An example of a land use type where the area is important, is cultivated fields. The damage to a field is calculated per hectare and then multiplied with the area of the field to determine the damage to the entire field. The linear category includes

infrastructures such as roads, power lines, tramlines, drainage systems, etc. The damage to these structures is calculated per meter and then multiplied with the length. Residential-, commercial- and industrial structures belong to the location category. These structures are classified according to size and content and the same loss function is used for structures of the same class.

The terms cultivated fields, infrastructure and buildings are more readily understood than area-, linear- and location categories. The above-mentioned terms are therefore used in the model to describe the three categories. The user should, however, be aware of the fact that the model can also be applied to other fields for example environmental studies, as long as loss functions can be developed for it. Note that the damage to cultivated fields are divided into harvest-, crop- and soil damage in FLODSIM.

Loss functions are used to determine the flood damage for each land use type. According to Smith *et al.* (1981:19) a loss function defines the relationship between flood damage and certain flood characteristics such as depth of inundation, duration of inundation, area inundated, momentum flux and silt content of floodwaters for a specific damage category. These relationships can be expressed algebraically, graphically or in tabular form. Loss functions for several land use types are included in the model and additional loss functions can be added when necessary.

Hydraulic and hydrologic information are calculated outside FLODSIM. Water surface profiles can be read from a file into FLODSIM while flood return periods are typed in manually. Topographic information, required by numerical flood models¹ on which the hydraulic information is calculated, can be exported from FLODSIM.

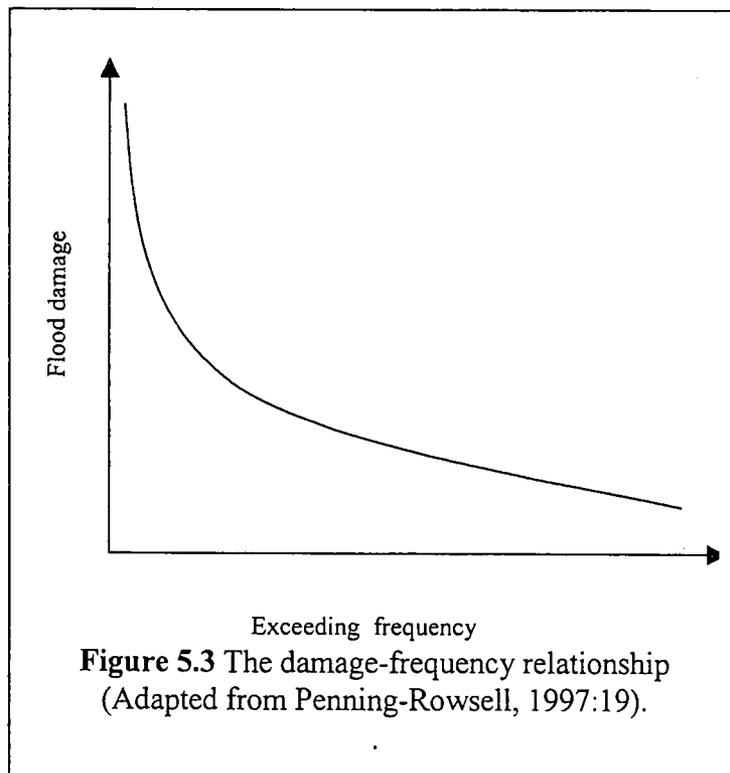
Normally a team consisting of hydrologists, hydraulic experts, economists, civil engineers, sociologists, geographers and urban and regional planners would work together in flood management studies that are done with FLODSIM. The hydrologist would determine the flood hydrographs and flood probabilities of different floods while the hydraulic expert would do the simulations on numerical flood models. Economists would usually develop the loss functions for different land use types. Civil engineers would

¹ Also known as backwater packages

suggest the different structural flood damage control measures that can be used and they might also determine the risks associated with these structures. Sociologists, geographers and urban and regional planners would be concerned with non-structural flood damage control measures.

1.2 THE ESTIMATION OF THE MEAN ANNUAL FLOOD DAMAGE

According to the US Army Corps of Engineers (1988:3) the mean annual flood damage computations may be computed by determining the potential for damage from specific flood events and then weighing the damage values with the probability that these events might be exceeded. The simplest way to develop the final frequency-damage relationship is to relate stage of flow to damage and then to relate stage of flow to frequency. The first relationship (between stage and damage) is known as stage damage curves, but the relation can actually be between flood damage and any other flood characteristic and therefore the term loss function is preferred.



The damage-frequency relationship is illustrated by Figure 5.3. The area under the curve gives the mean annual flood damage (Ramirez and Adamowicz, 1988, as quoted by Du Plessis, 1994:140; Viljoen, 1979:152).

Different loss functions are usually developed for different land use types. The loss function used for vineyard will for example

differ from the loss function for sugarcane.

INSTALLATION

2.1 HARDWARE AND SOFTWARE REQUIREMENTS

The following hardware and software are required by FLODSIM

- SUN Ultra 5 Workstation or better
- 64 Mbytes of available Random Access Memory (RAM)
- 4 Gbytes (or greater) available hard disk space
- Solaris 2.6 or higher
- ARC/INFO version 7.1.1 or higher
- GRID version 7.1.1 or higher
- TIN version 7.1.1 or higher

2.2 DATA REQUIREMENTS

Data such as the altitude grid (DTM), levee coverage, and at least one coverage representing land use should be prepared before FLODSIM can be installed. All the data files must be copied to the same directory for the model to have easy access to it. The different coverages that can be included in the model will be described in this paragraph. The model automatically adds coverage items that are used for calculation purposes and only the items that are required from the user will be listed for each coverage. The different item names are only suggestions and the user might want to choose his own item names.

2.2.1 Altitude grid

The altitude grid plays a mayor role when the depth of inundation is calculated and FLODSIM can therefore not function without it. The altitude grid is usually constructed from contour lines and spot heights by using the 'topogrid' command in ARC/INFO. Other sources used to derive elevation data vary from ground surveys and photogrammetry to radar or laser altimetry. The different sources vary in cost, production time and quality of the product and these characteristics should be considered when the data source is chosen.

2.2.2 Levee coverage

The levee coverage represents existing flood mitigation structures. The coverage will be duplicated by FLODSIM in order to have a coverage that can be edited to represent different flood mitigation measures. In the absence of an original levee coverage an empty coverage will be created for the different flood mitigation measures. The levee coverage should have items for the average height and material of the structures (see Table 2.1). The height of the structures will be taken into account with cross section extraction for numerical flood models to recognise flood mitigation measures. The height of the levee should be measured from the ground and one must be careful not to allocate the elevation of the levee to this item. The height should be given in metres.

Table 2.1 Items that should be added to the levee coverage

Item name	Width	Output	Type	N.dec
Height	4	4	F	2
Material	5	5	C	-

2.2.3 Contour and spot height coverages

The contour and spot height coverages are only used for display purposes in FLODSIM and are optional. The user may, however, want to use it to create an altitude grid by means of interpolation (the 'topogrid' command is suggested). Both coverages should contain an item representing the elevation (see Table 2.2 and Table 2.3). The elevation should be given in metres.

Table 2.2 Items that should be added to the spot height coverage

Item name	Width	Output	Type	N.dec
Elevation	6	6	N	2

Table 2.3 Items that should be added to the contour coverage

Item name	Width	Output	Type
Elevation	4	5	B

2.2.4 River coverage

As with the contour and spot height coverages, the river coverage is only used for display purposes in FLODSIM and is also optional. If the river coverage represents the centre of the river it can be used in the streams option with the 'topogrid' command. This will improve the drainage enforcement procedure with the result of a better altitude grid.

2.2.5 Cultivated fields coverage

This coverage usually contains cultivated fields, but any risk type that depends on the area may be included into this coverage. The coverage should have a symbol field that will represent the different crop types (see Table 2.4). The two letters that are used to distinguish between the different crop types are also used in the naming convention for the AML files that contain the programs for the different loss functions.

Table 2.4 Items that should be added to the cultivated fields coverage

Item name	Width	Output	Type
Crop_symbol	2	2	C

2.2.6 Infrastructure coverage

This coverage contains infrastructures such as roads, power lines, tramlines, drainage systems, etc. The coverage should have a symbol field that will represent the different infrastructure types (see Table 2.5). The two letters that are used to distinguish between the different infrastructures are also used in the naming convention for the AML files that contain the programs for the different loss functions.

Table 2.5 Items that should be added to the infrastructure coverage

Item name	Width	Output	Type
Infra_symbol	2	2	C

2.2.7 Building coverage

Residential-, commercial- and industrial structures can be included into the building coverage. Unlike cultivated fields and infrastructure a class number is used to distinguish between the different building classes. The class numbers should follow chronologically on each other, starting from one. Damage to these structures usually only depends on depth of inundation and the same program is therefore used for all the classes. It is important to note that the user cannot add his own programs as in the case of cultivated fields or infrastructure.

The coverage should have items for the damage class, indication if the structure is raised and the height raised. The item indicating whether the structure is raised or not should contain a '1' when it is raised and a '0' otherwise. The height that the structure is raised should be given in metres.

Table 2.6 Items that should be added to the building coverage

Item name	Width	Output	Type	N.dec
Dam_class	3	3	I	-
Raised	2	2	I	-
Ht_raised	5	5	N	2

2.3 INSTALLING FLODSIM

A program called 'Setup' is used to prepare FLODSIM for the study area on which it is to be applied. An example of the graphical user interface will be given in this paragraph but the user should note that it might differ for each individual area. The setup program will automatically adapt the menus according to the situation in the study area.

2.3.1 Copy the files from the CD to a hard disk

Copy all the files in the directory called 'system' from the CD to the hard disk. Make sure that the data files described in Paragraph 2.2 are all in the same directory.

2.3.2 Start the setup program

Change the directory to `.../system/setup`

Start ARC/INFO

Run the *setup* AML

Example:

```
unix_prompt> cd /system/setup
```

```
unix_prompt> arc
```

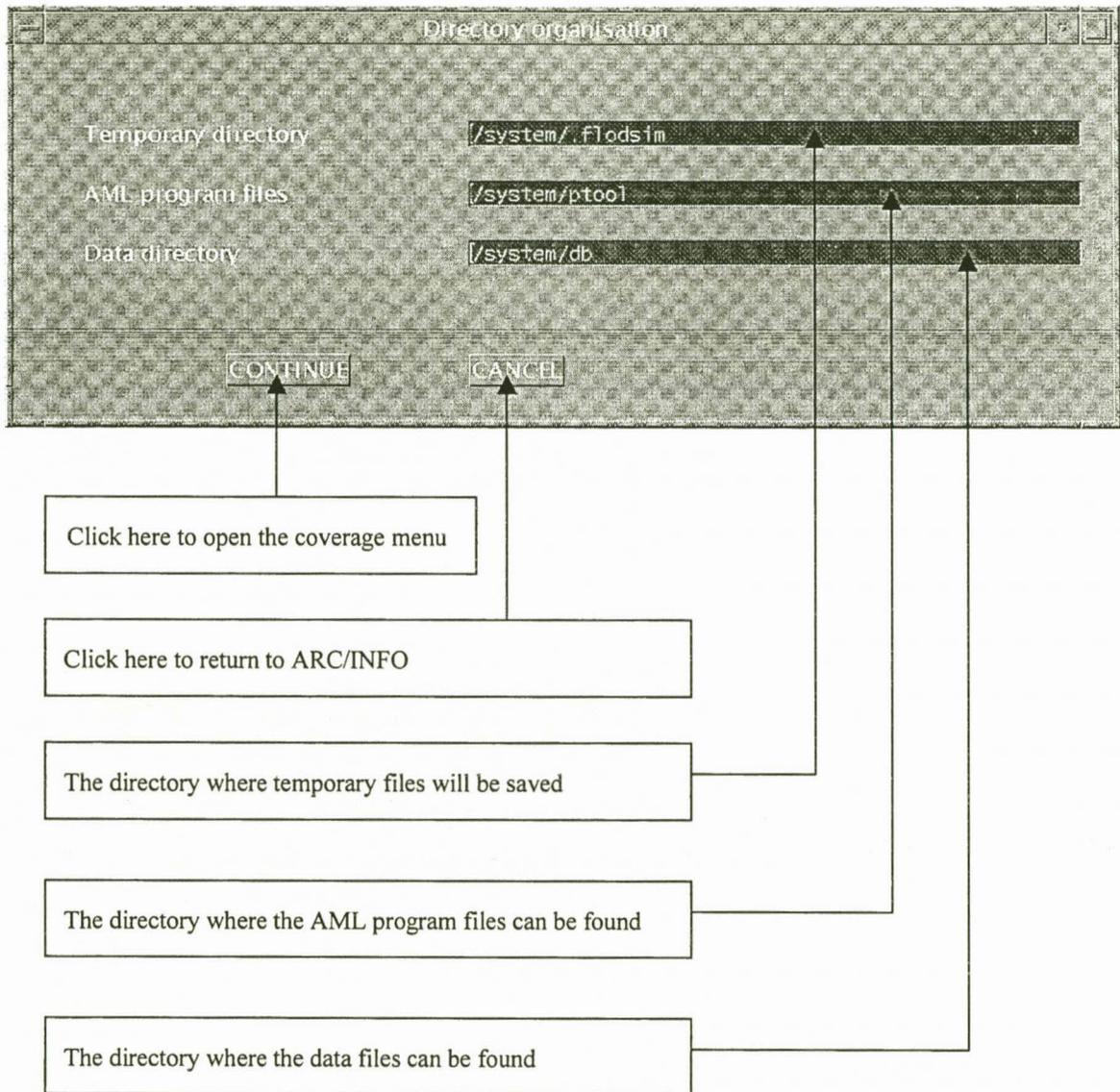
Copyright (C) 1982-1997 Environmental Systems Research Institute, Inc.

All rights reserved.

ARC Version 7.1.1 (Thu Feb 6 23:26:50 PST 1997)

```
Arc: &r setup
```

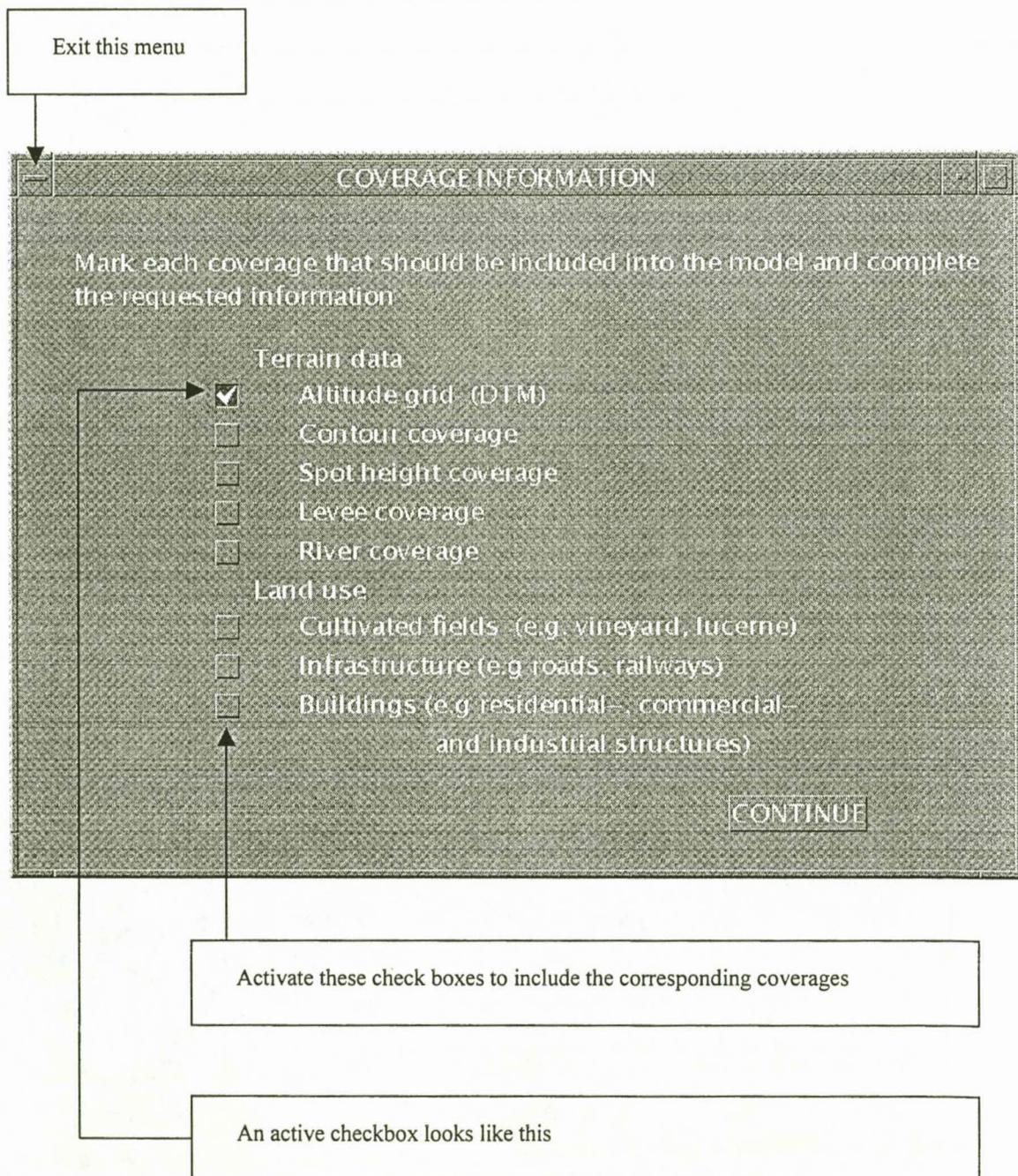
The following menu will now be displayed:



2.3.2.1 The coverage information menu

This menu gives the user the opportunity to indicate the coverages that should be included in the model. There is a checkbox next to each coverage that can be activated when it should be included into the model. When the checkbox is activated a menu will appear that will prompt the user to give more detail of the coverage.

The coverage information menu looks like this:



2.3.2.1.1 Information menu for the altitude grid

The screenshot shows a window titled "COVERAGE INFORMATION". Inside, there is a section "Altitude grid:" followed by a list box containing "altgrid". Below this is a "GENERAL SETTINGS:" section with a "CELL SIZE:" field set to "20" and "m". At the bottom right is a "Return" button. Three callout boxes with arrows point to the list box, the "20" field, and the "Return" button.

All the available grids will be listed here. Highlight the one that you want to use

The cell size that should be used in FLODSIM when new grids are generated

Click here to return to the previous menu

2.3.2.1.2 Information menu for the contour coverage

The screenshot shows a window titled "COVERAGE INFORMATION". Inside, there is a section "CONTOUR COVERAGE:" followed by a list box containing "cline", "con tour", and "cross". Below this is an "ITEMS CONTOUR:" section with an empty text field. At the bottom right is a "Return" button. Three callout boxes with arrows point to the list box, the empty text field, and the "Return" button.

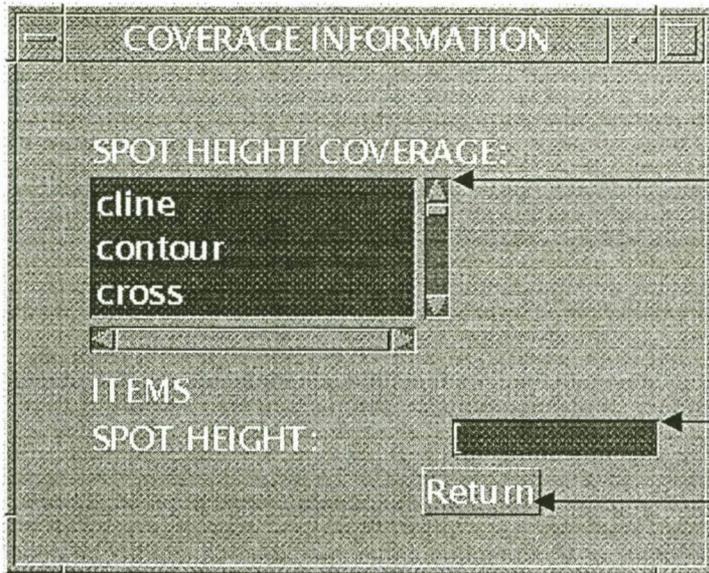
All the available coverages will be listed here. Highlight the one that you want to use

The item containing the elevation of contours

Click here to return to the previous menu

Note that items will only be accepted if it exists in the highlighted coverage. This will also apply to the following coverages.

2.3.2.1.3 Information menu for the spot height coverage

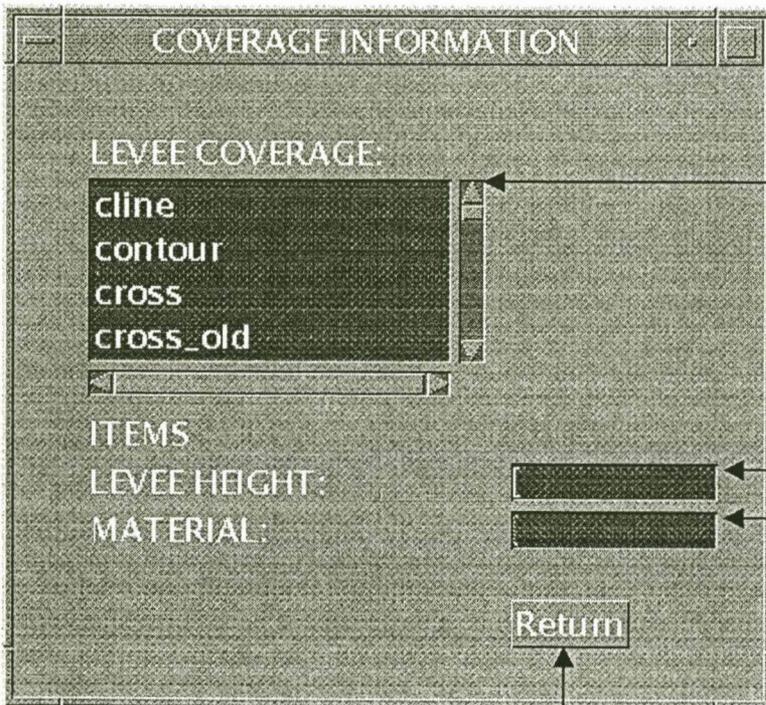


All the available coverages will be listed here. Highlight the one that you want to use

The item containing the elevation of the points

Click here to return to the previous menu

2.3.2.1.4 Information menu for the levee coverage



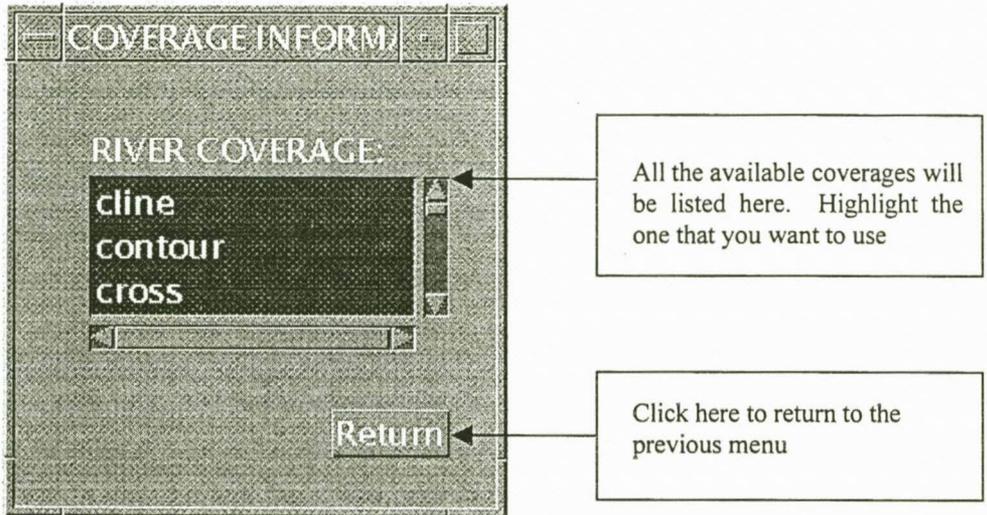
All the available coverages will be listed here. Highlight the one that you want to use

The item containing the height of the levees

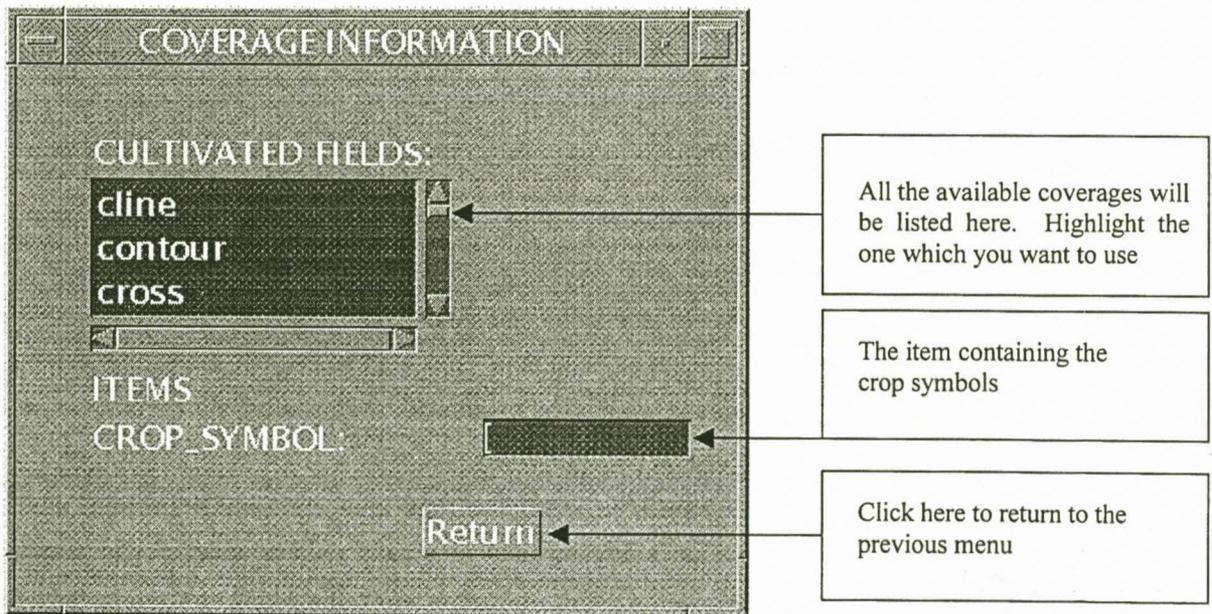
The item for the material of the levees

Click here to return to the previous menu

2.3.2.1.5 Information menu for the river coverage



2.3.2.1.6 Information menu for the cultivated fields coverage



2.3.2.1.7 Information menu for the infrastructure coverage

COVERAGE INFORMATION

INFRASTRUCTURE COVERAGE:

- cline
- contour
- cross

ITEMS

INFRA_SYMBOL :

Return

All the available coverages will be listed here. Highlight the one which you want to use

The item containing the infrastructure symbols

Click here to return to the previous menu

2.3.2.1.8 Information menu for the building coverage

COVERAGE INFORMATION

BUILDING COVERAGE

- cline
- contour
- cross

ITEMS

RAISED:

HEIGHT RAISED:

DAMAGE CLASS:

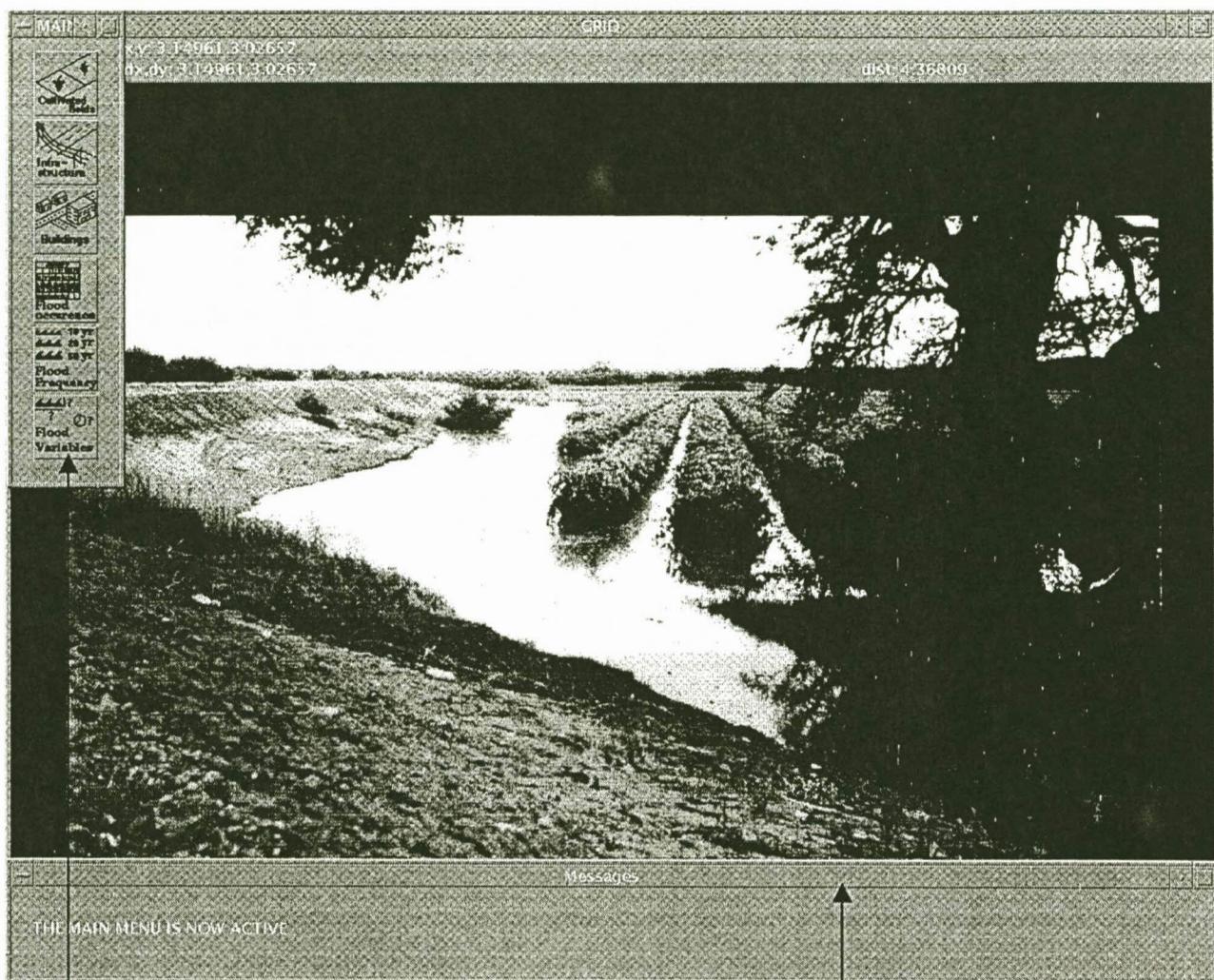
Return

All the available coverages will be listed here. Highlight the one which you want to use

The items for the damage class, whether it is raised and the height raised

Click here to return to the previous menu

2.3.3 The screen layout

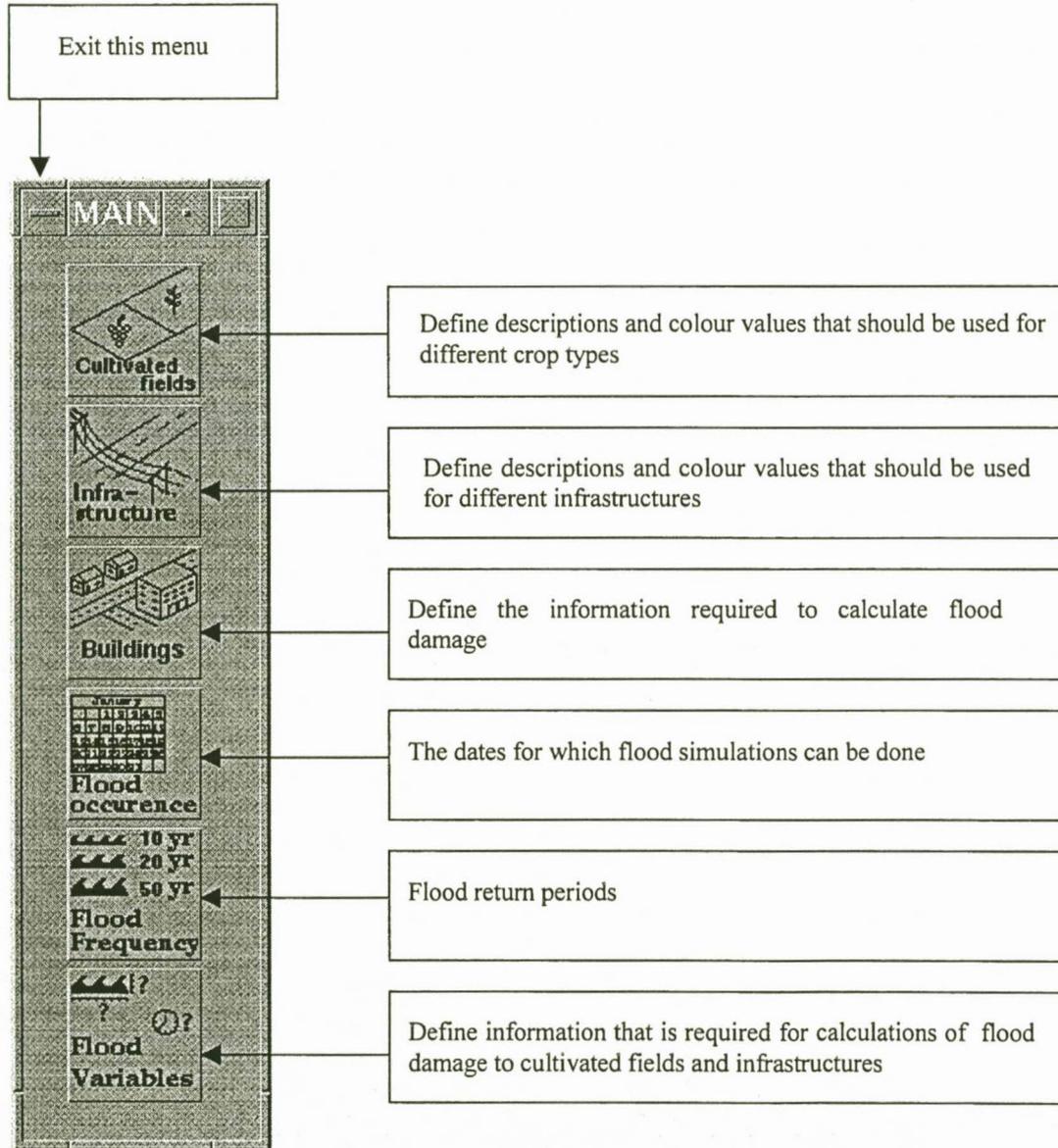


The main menu

The message window. Messages from the system will be displayed here.

2.3.4 The main menu

The layout of the main menu will depend on the coverages that have to be included in the model. Options that were not marked in the previous menu will not be shown on the main menu.



2.3.5 The cultivated fields menu

All the symbols (in the *crop_symbol* field of the cultivated fields coverage) that were detected by the setup program will be displayed in this menu.

The screenshot shows a window titled "CULTIVATED FIELDS" with a table of crop options. Callouts provide instructions for each part of the interface:

- Exit this menu:** Points to the top-left corner of the window.
- The description of the crop type. This can be any name without spaces.**: Points to the "Crop Description" column.
- Click here to pick the shade symbol that should be used to draw this crop.**: Points to the "Pick colour" buttons.

Symbol	Crop Description	Colour	
f	FALLOW	[Shaded Box]	Pick colour
l	LUCERNE	[Shaded Box]	Pick colour
rc	ROTATIONAL_CROPS	[White Box]	Pick colour
v	VINEYARD	[Shaded Box]	Pick colour

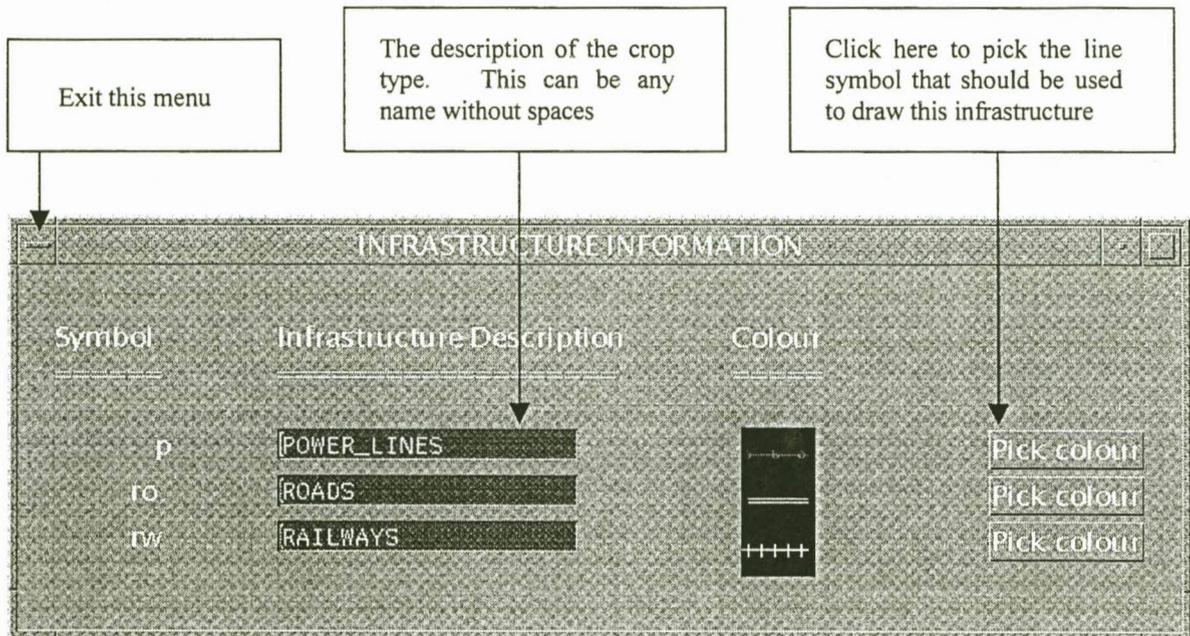
The shade symbol menu:

The screenshot shows a smaller window titled "VINEYARD" containing a list of horizontal bars representing different shades. Callouts explain its function:

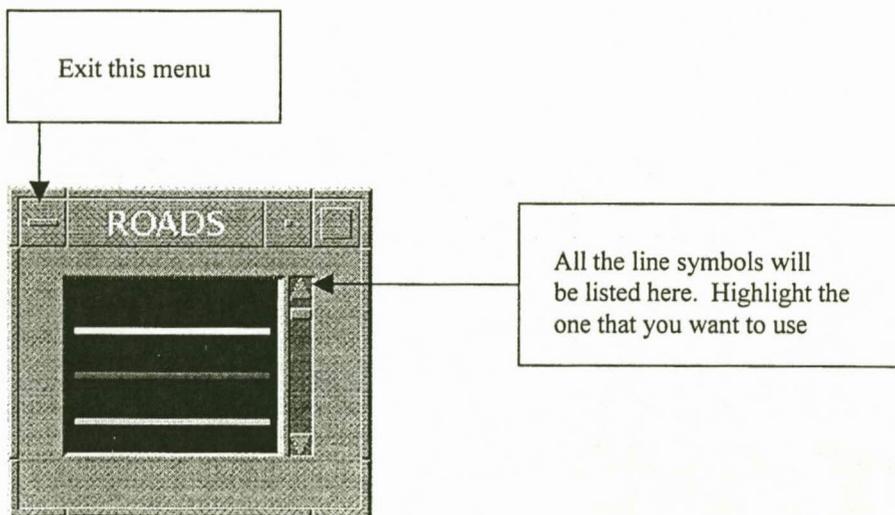
- Exit this menu:** Points to the top-left corner of the window.
- All the shade symbols will be listed here. Highlight the one that you want to use**: Points to the list of shade symbols.

2.3.6 The infrastructure menu

All the symbols (in the *infra_symbol* field of the infrastructure coverage) that were detected by the setup program will be displayed in this menu.

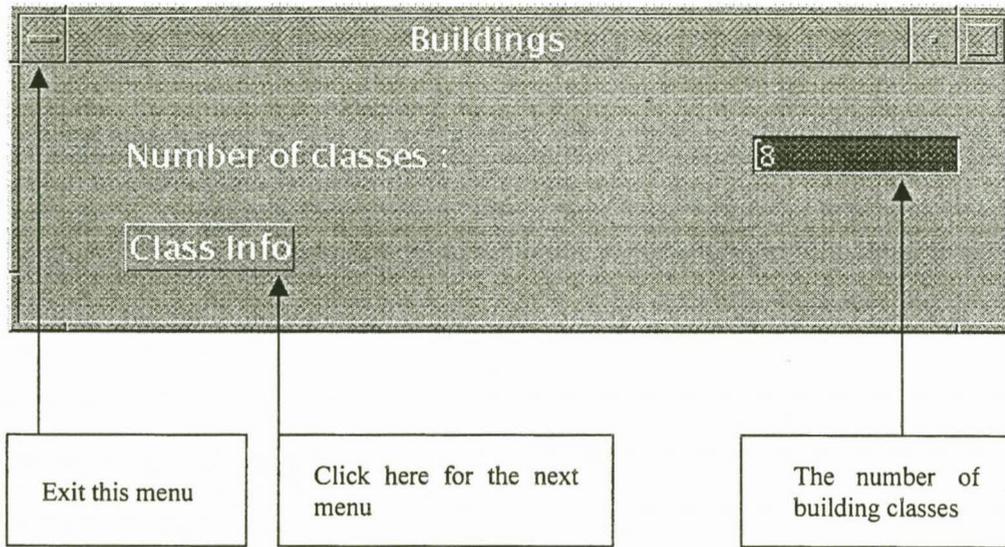


The line symbol menu:

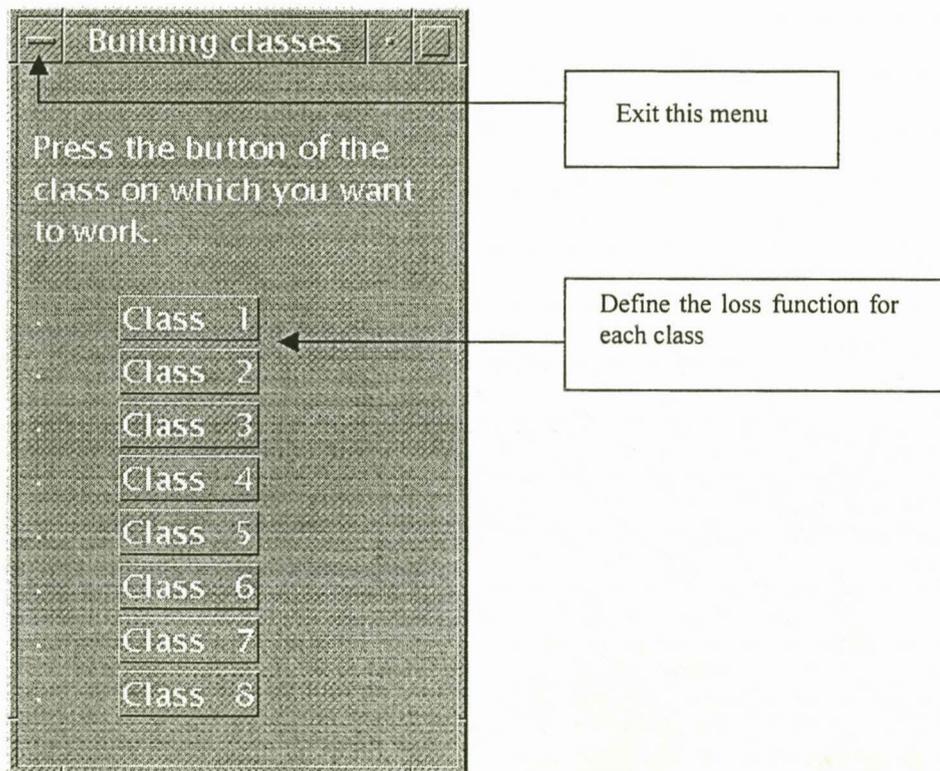


2.3.7 The buildings menu

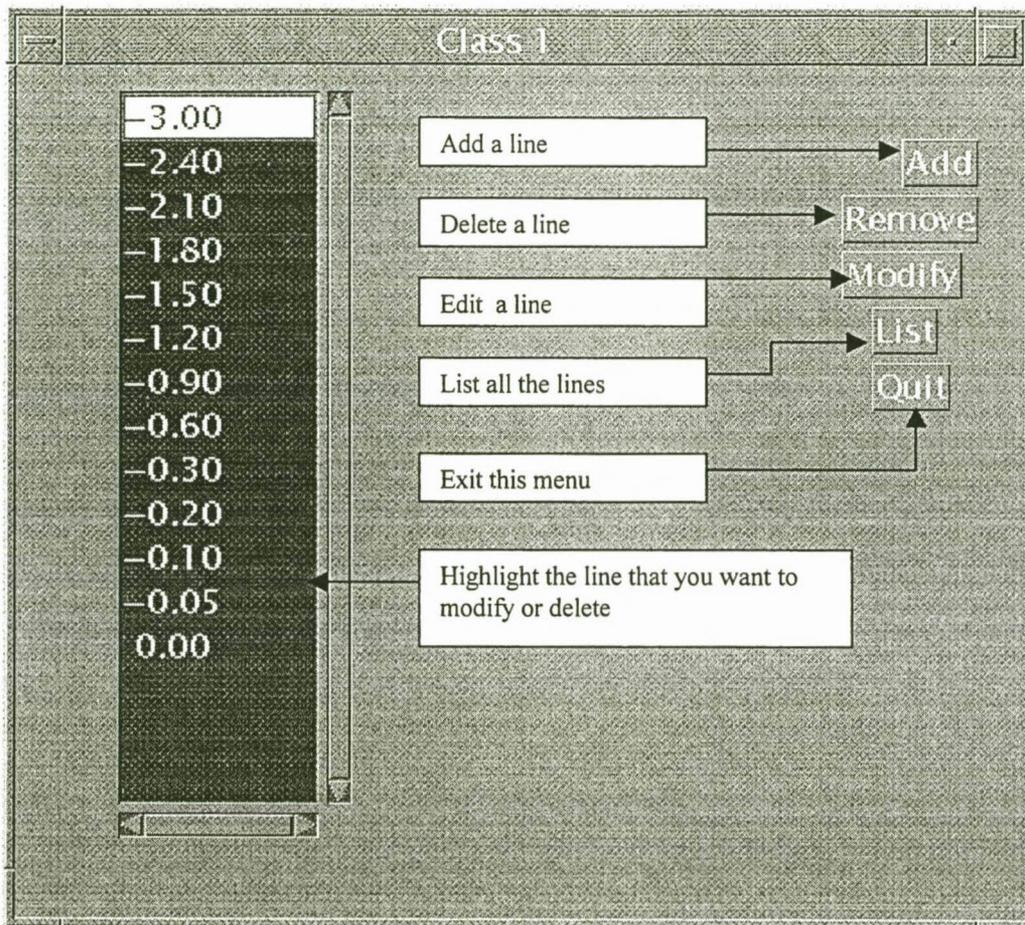
The buildings menu together with its sub-menus supply an graphical user interface with which loss functions can be prepared for the different building classes. The first menu prompts the user to give the number of classes that should be used. The program will automatically adapt the sub-menus according to the number that is given.



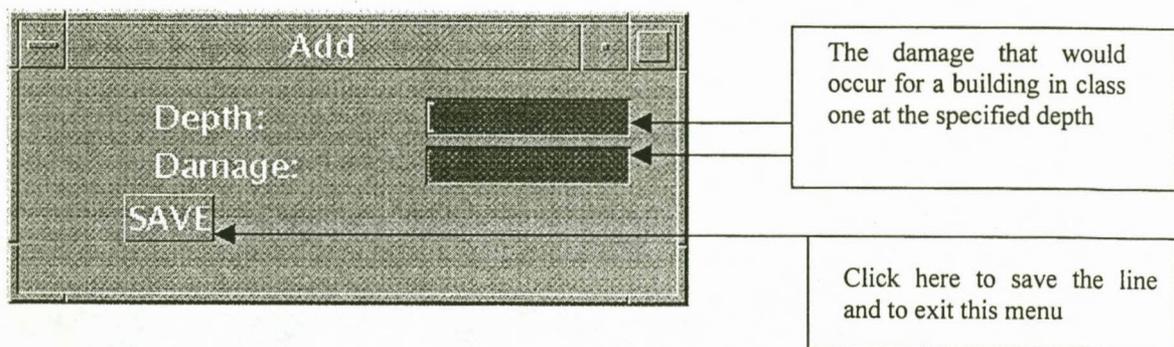
2.3.7.1 The class info menu



2.3.7.1.1 The menu for class 1 as example



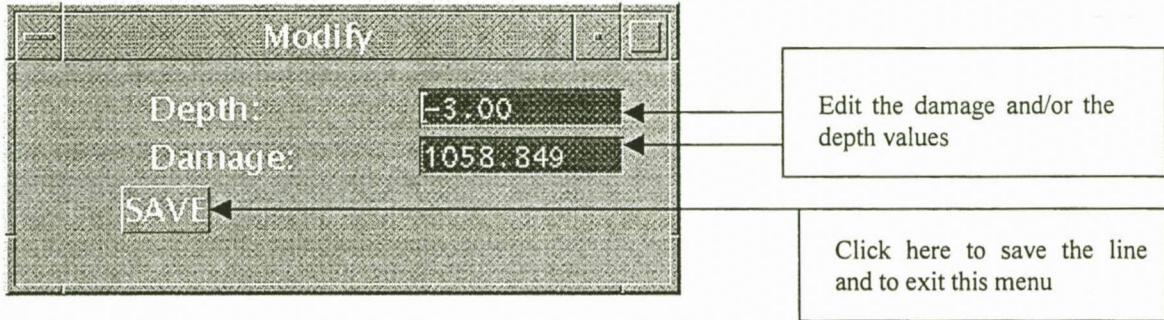
When you click on the Add button the following menu will appear:



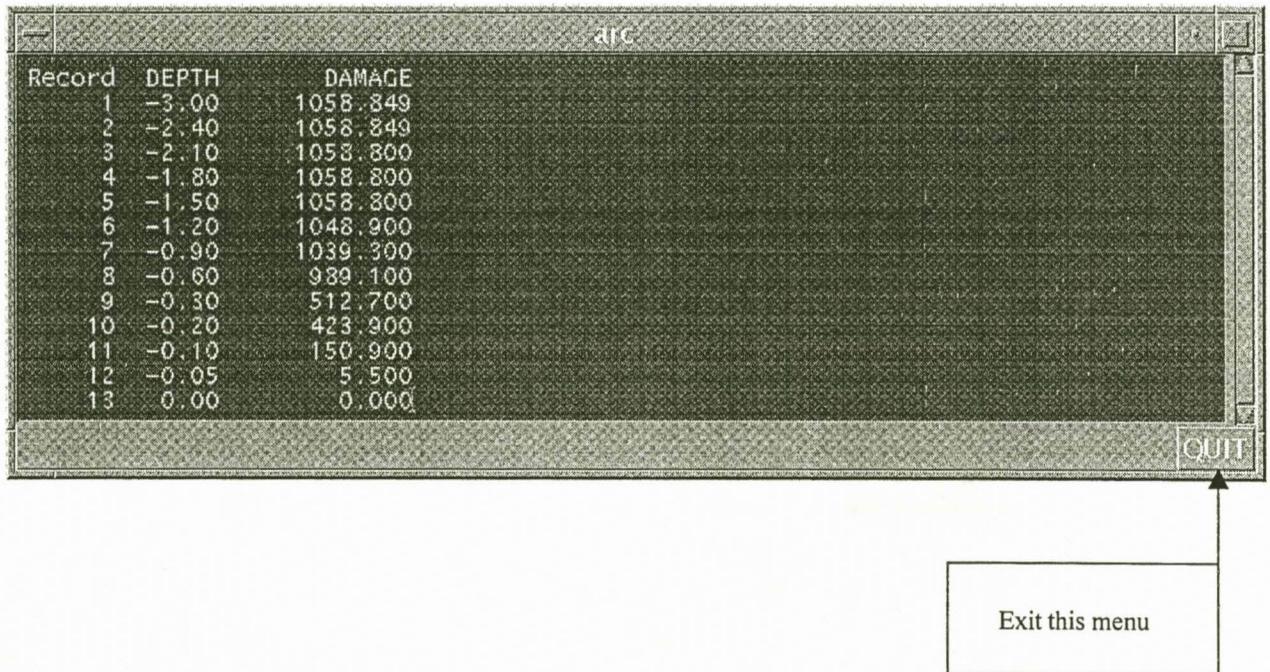
Note that the inundation depth should be indicated with a negative number.

When you click on the Remove button the highlighted line will be removed

When you click on the Modify button the following menu will appear for the highlighted line:



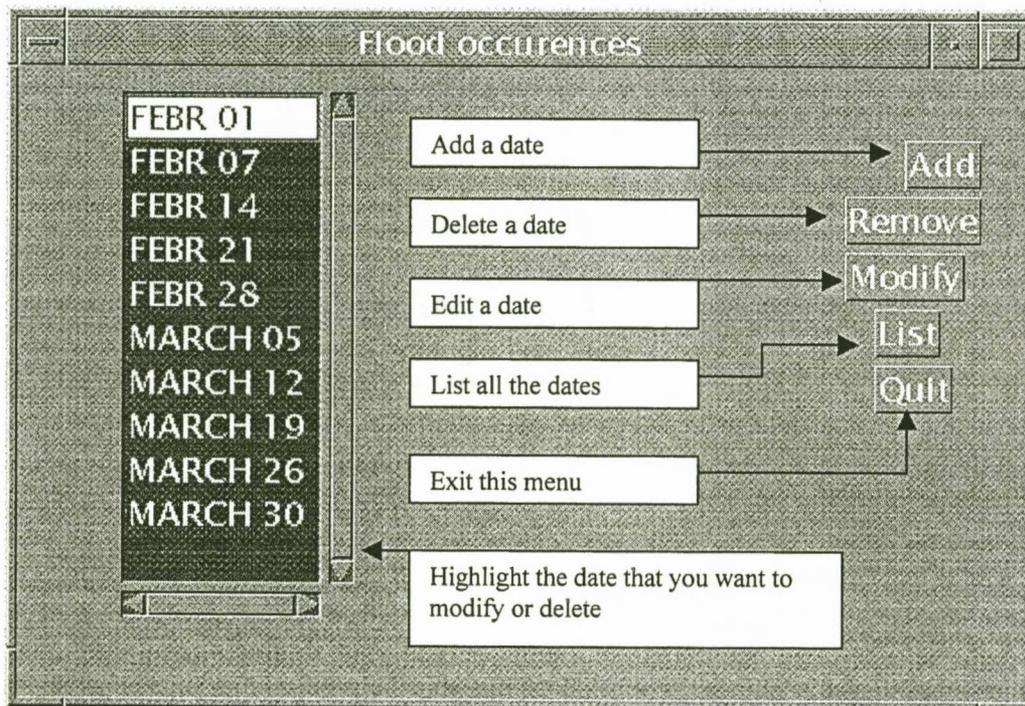
When you click on the List button the following menu will appear:



2.3.8 The flood occurrence menu

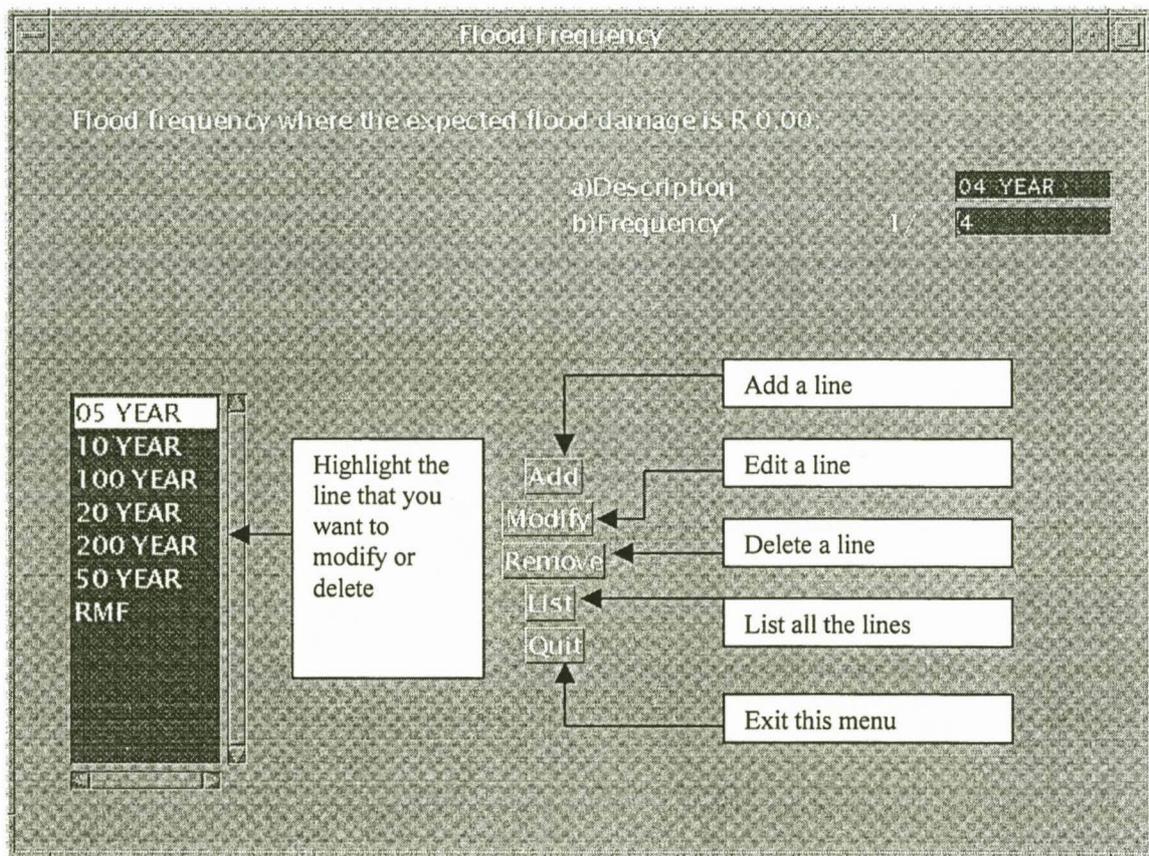
This menu is used to define the dates for which simulations can be done. The date of a flood occurrence is important as it will determine the percentage of cultivated fields that are harvested. The temperature of the flood water might also differ in different times of the year.

The sub-menus function the same way as that of the buildings menu and it will therefore not be repeated.



2.3.9 The flood frequency menu

This menu is used to define the frequency of floods with different sizes. The menu layout is the same as that of the Buildings- and Flood occurrence menus. Three fields, namely the description, frequency and cumecs have to be defined for each flood. At the top of the menu the description and frequency is asked for the flood at which no damage will occur. This is needed for the calculation of the mean annual damage.

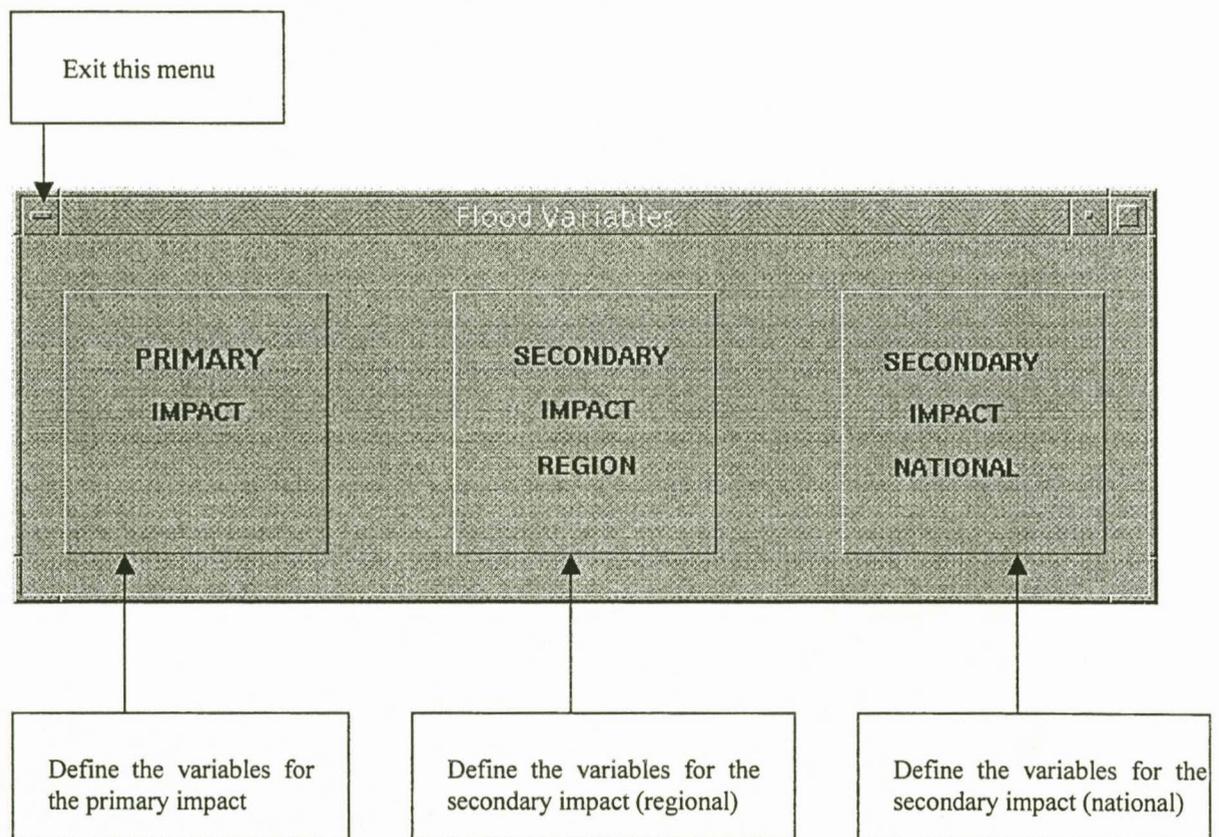


Here is an example of the values that can be used for the Orange River:

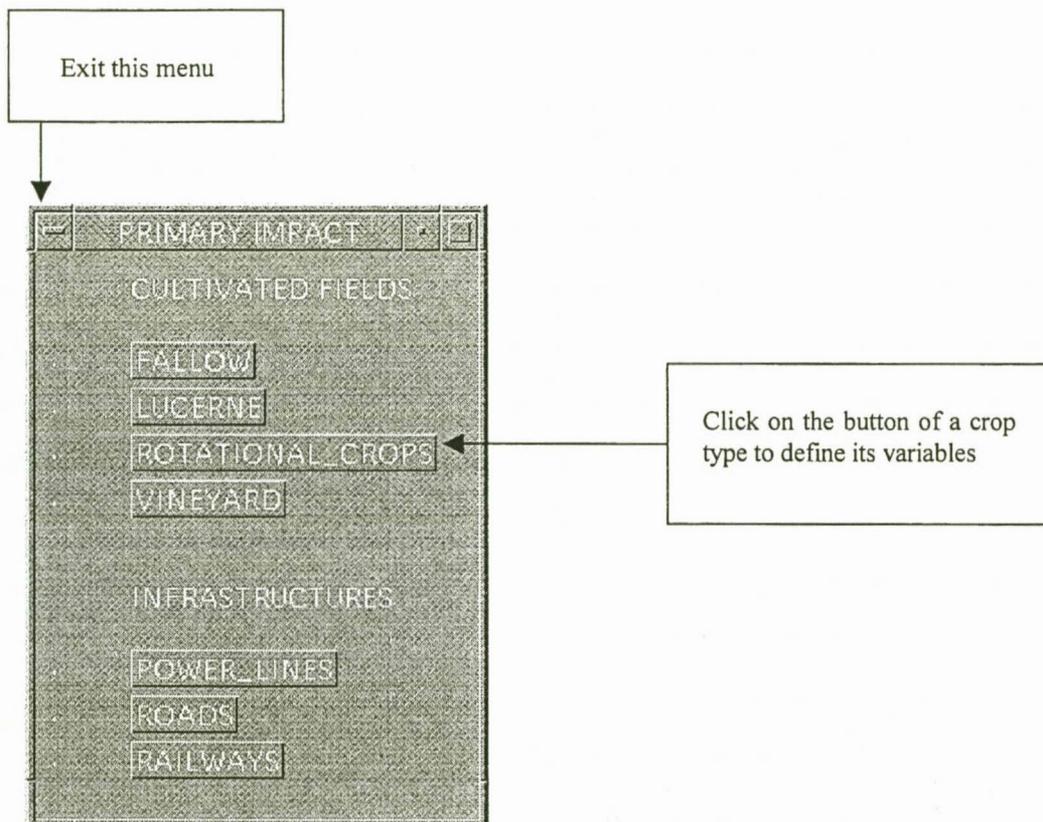
Record	FLOOD_LINE	FREQUENCY	CUMECs
1	05 YEAR	5	4300
2	10 YEAR	10	6000
3	20 YEAR	20	8300
4	50 YEAR	50	11800
5	100 YEAR	100	12200
6	200 YEAR	200	14400
7	RMF	1000	24500

2.3.10 The flood variables menu

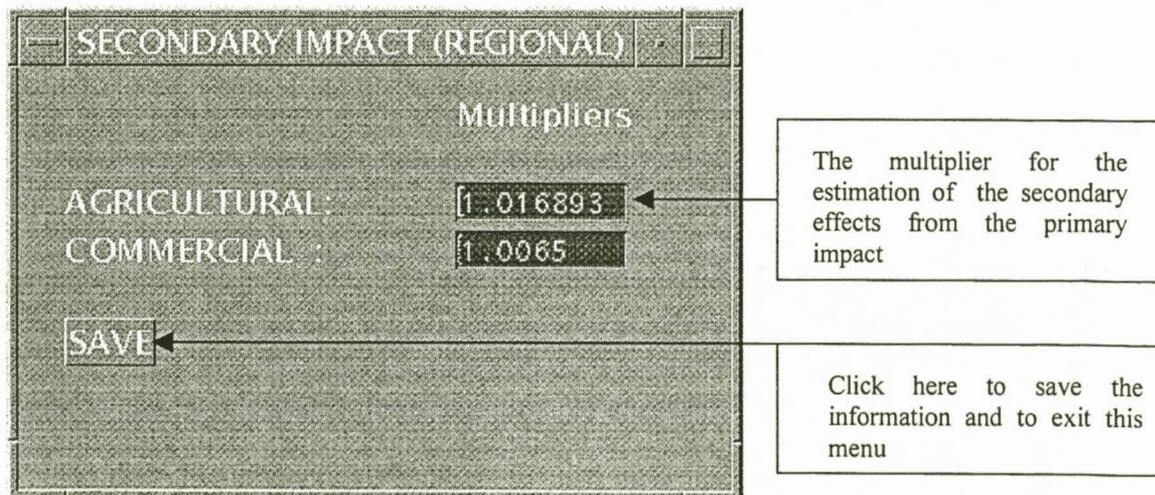
This menu is used to define the variables for the primary impact, secondary impact (regional) and secondary impact (national). The items in the primary impact menu will depend on the crop and infrastructure types that are included into the corresponding coverages. When you click on a button in the primary impact menu, the program will display the menu for the specific crop or infrastructure type if it can be found. When the menu does not exist, a message will be given in the message window. Refer to Appendix I for a list of available land use types.



2.3.10.1 The primary impact menu



2.3.10.2 The secondary impact (regional) menu



2.3.10.3 The secondary impact (national) menu

The screenshot shows a window titled "SECONDARY IMPACT (NATIONAL)". Inside the window, there is a list of crop types on the left and their corresponding multipliers on the right. The multipliers are displayed in a column of input fields. At the bottom left of the window, there is a "SAVE" button.

	Multipliers
FALLOW	0
LUCERNE	2.1758
ROTATIONAL_CROPS	1.8337
VINEYARD	2.2333
COMMERCIAL	1.1241

SAVE

The multiplier for the estimation of the secondary effects from the primary impact

Click here to save the information and to exit this menu

WORKING WITH FLODSIM

3.1 START THE GRAPHICAL USER INTERFACE

The program that is used to export cross-sections uses Inter Application Communication (IAC). This requires the use of two Arc/Info sessions. The one session will be the client (this is the main program) while the other session will be the server. A server session must therefore first be started when you want to export cross sections. Note that the server session is not required by any of the other functions that are provided in FLODSIM. The program that is used to export cross-sections is activated by the last button in the main menu (see Paragraph 3.3).

To start FLODSIM do the following:

Change the directory to .../system/ptool

Start ARC/INFO

Run the *startup* AML

Start the server session in a different window (only when you want to export cross-sections):

Change the directory to .../system/ptool

Start ARC/INFO

Run the *start_server* AML

Example:

The server session:

```
unix_prompt> cd /system/ptool
```

```
unix_prompt> arc
```

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All rights reserved.

ARC Version 7.1.1 (Thu Feb 6 23:26:50 PST 1997)

Arc: *&r start_server*

The main program (client session):

```
unix_prompt> cd /system/ptool
```

```
unix_prompt> arc
```

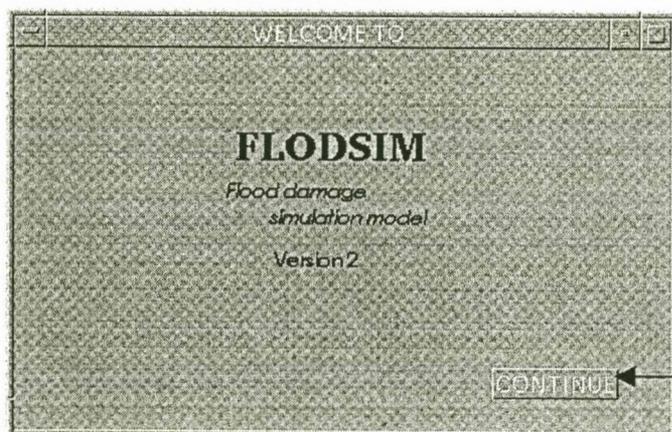
Copyright (C) 1982-1997 Environmental Systems Research Institute, Inc.

All rights reserved.

ARC Version 7.1.1 (Thu Feb 6 23:26:50 PST 1997)

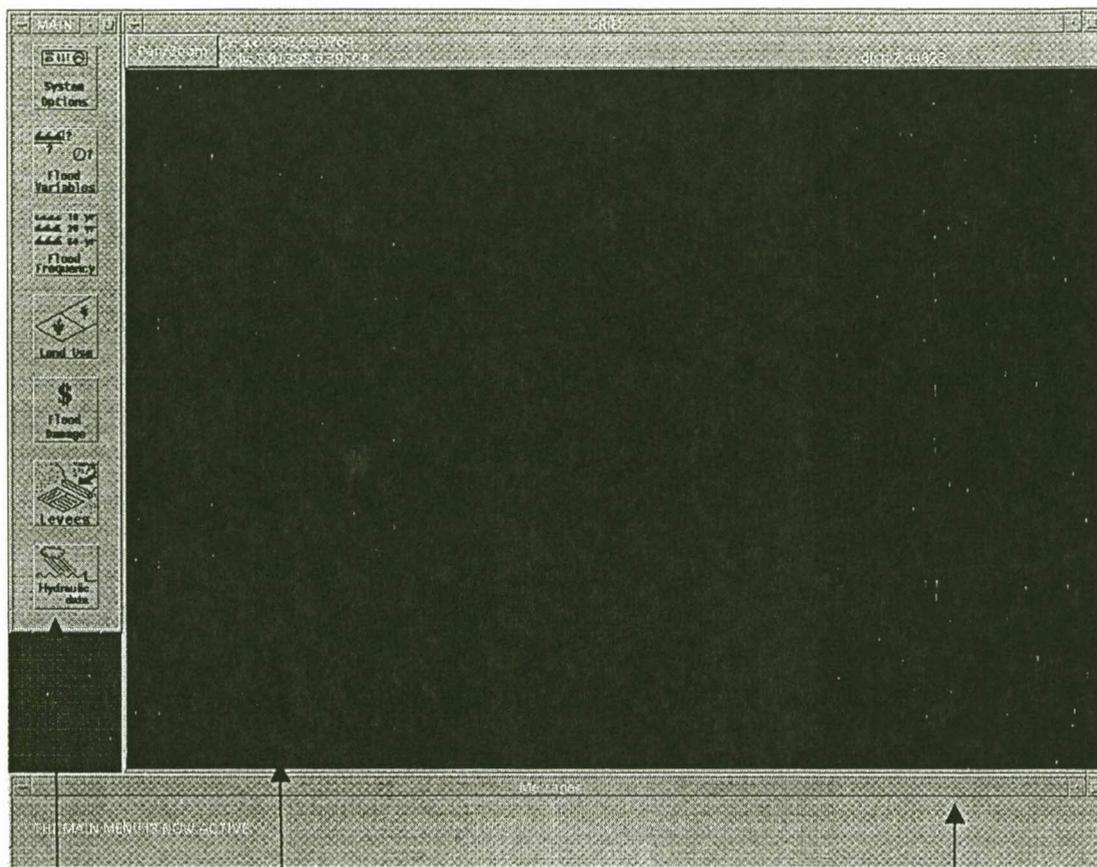
Arc: *&r startup*

The following menu will now be displayed:



Click here to enter the system

3.2 THE SCREEN LAYOUT

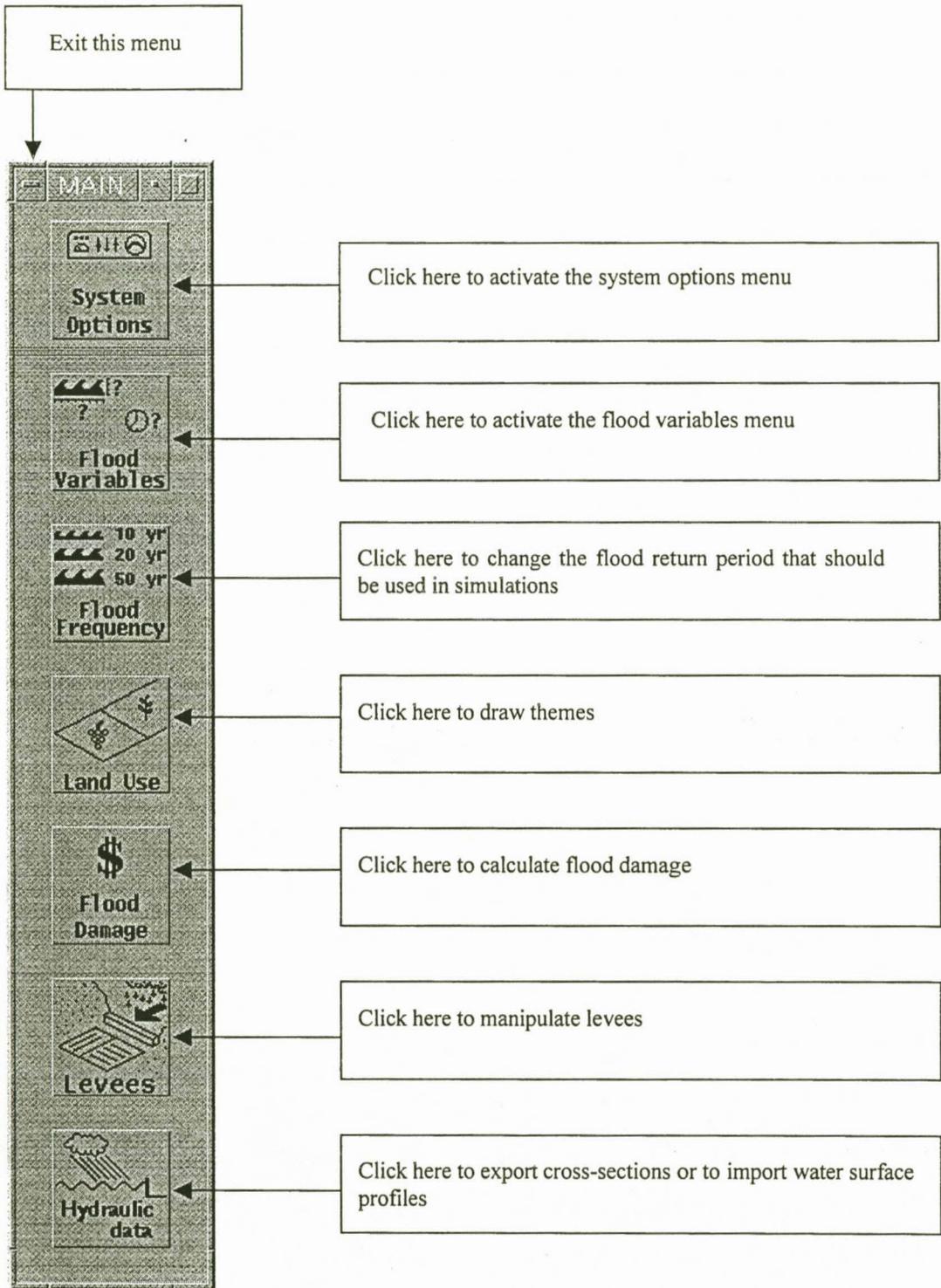


The main menu

The display area

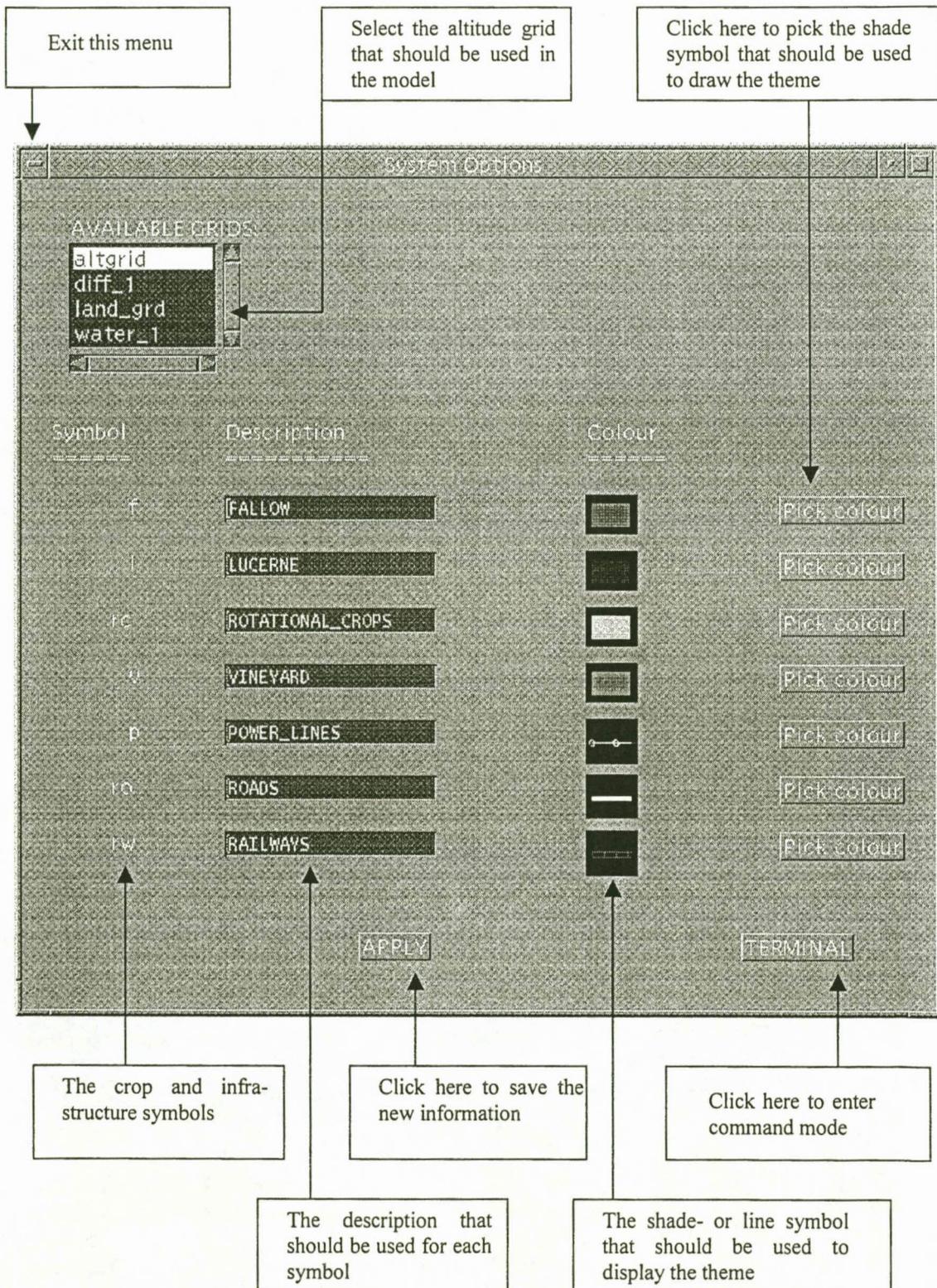
The message window. Messages from the system will be displayed here

3.3 THE MAIN MENU

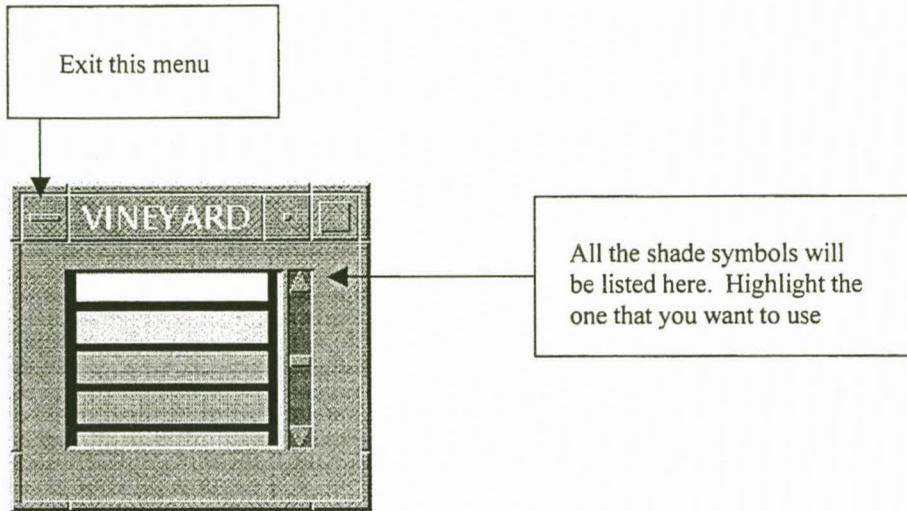


3.3.1 The system options menu

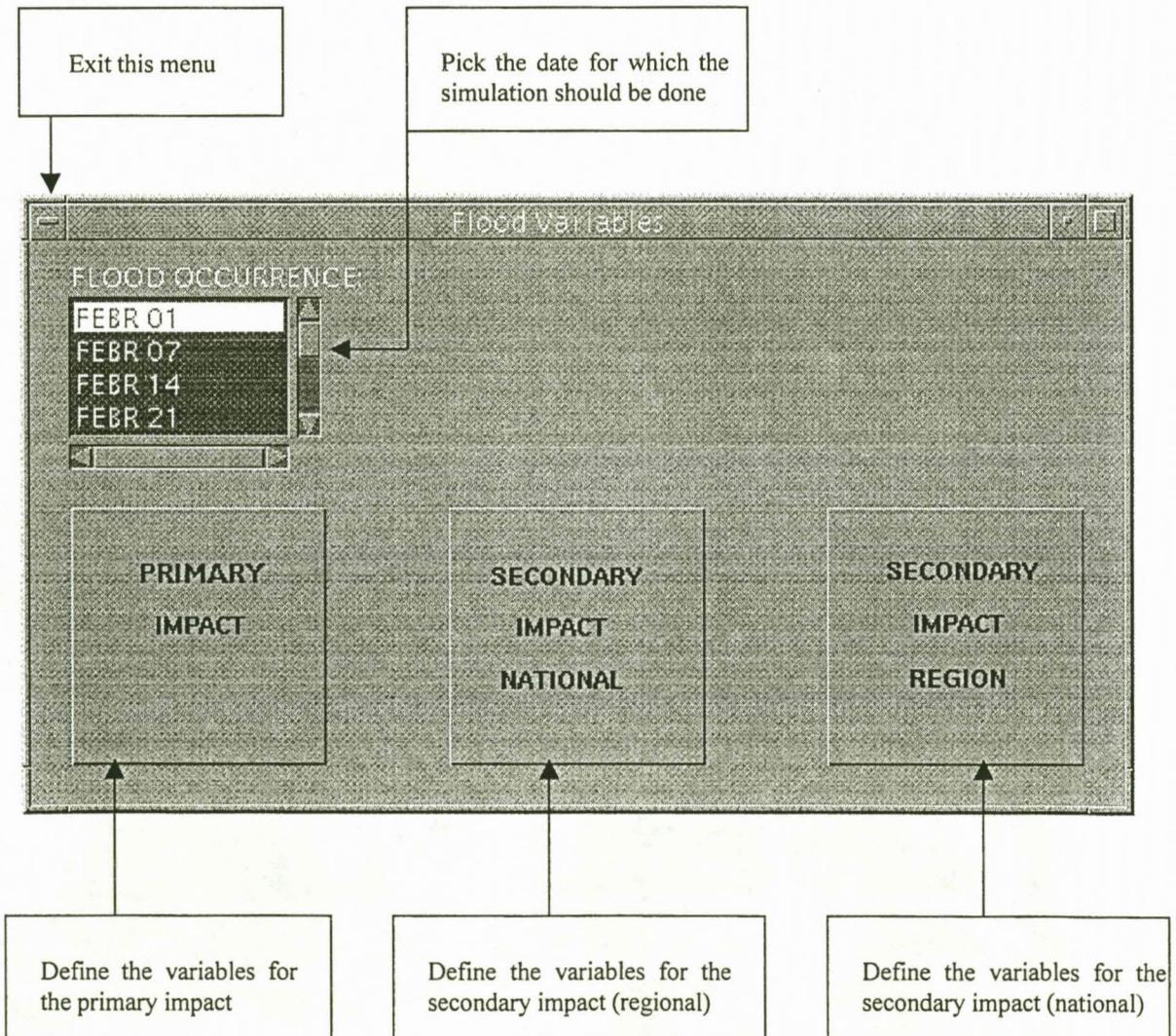
This menu is used to select the shade symbols that should be used to display the different crop- and infrastructure types. Another altitude grid can also be selected in this menu.



3.3.1.1 The shade symbol menu:

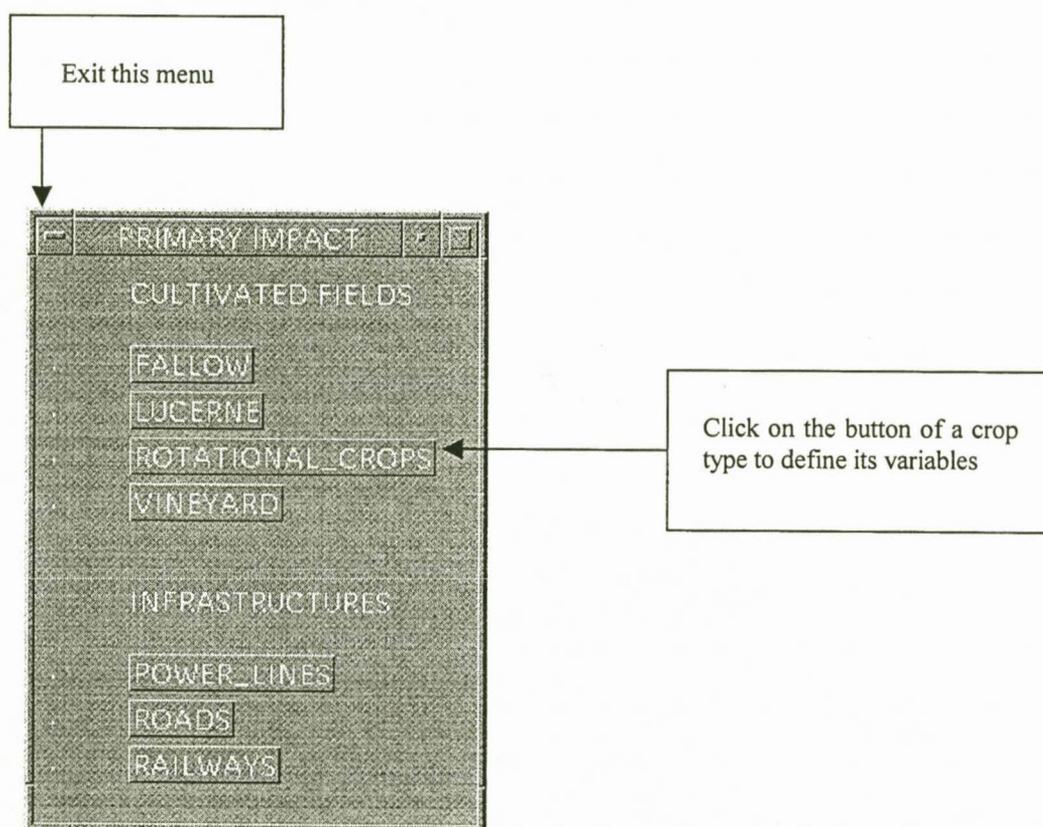


3.3.2 The flood variables menu



This menu is used to define the variables for the primary impact, secondary impact for the regional and secondary national impact. The items in the primary impact menu will depend on the crop and infrastructure types that are included in the corresponding coverages. When you click on a button in the primary impact menu, the program will display the menu for the specific crop or infrastructure type if it can be found. When the menu does not exist, a message will be given in the message window. Refer to Appendix I for a list of available land use types.

3.3.2.1 *The primary impact menu:*



3.3.2.2 The secondary impact (regional) menu:

The screenshot shows a window titled "SECONDARY IMPACT (REGIONAL)". Inside, there is a section labeled "Multipliers" with two entries: "AGRICULTURAL" with a value of 1.016893 and "COMMERCIAL" with a value of 1.0065. A "SAVE" button is located at the bottom left. Two callout boxes are present: one pointing to the agricultural multiplier value with the text "The multiplier for the estimation of the secondary effects from the primary impact", and another pointing to the "SAVE" button with the text "Click here to save the information and to exit this menu".

Category	Multiplier
AGRICULTURAL	1.016893
COMMERCIAL	1.0065

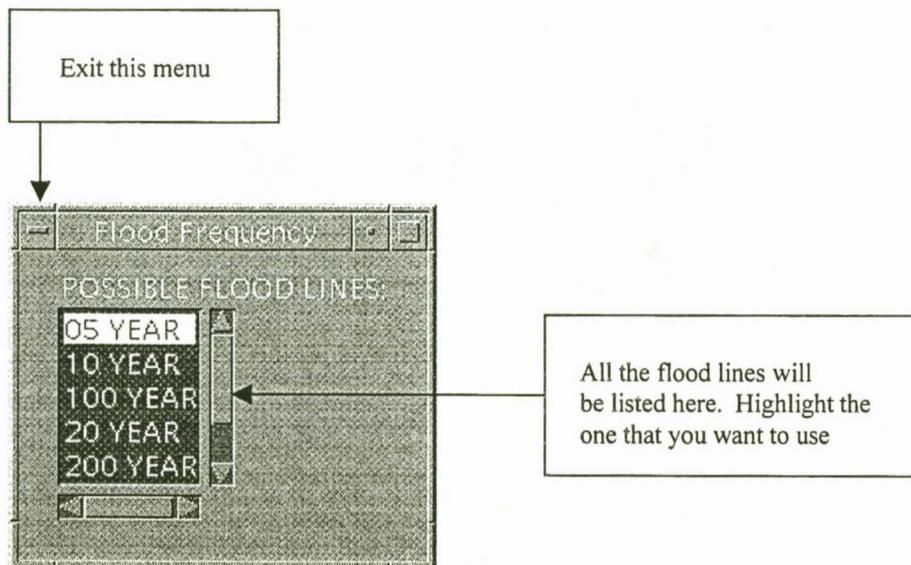
3.3.2.3 The secondary impact (national) menu:

The screenshot shows a window titled "SECONDARY IMPACT (NATIONAL)". Inside, there is a section labeled "Multipliers" with five entries: "FALLOW" (0), "LUCERNE" (2.1758), "ROTATIONAL_CROPS" (1.8337), "VINEYARD" (2.2333), and "COMMERCIAL" (1.1241). A "SAVE" button is located at the bottom left. Two callout boxes are present: one pointing to the "FALLOW" multiplier value with the text "The multiplier for the estimation of the secondary effects from the primary impact", and another pointing to the "SAVE" button with the text "Click here to save the information and to exit this menu".

Category	Multiplier
FALLOW	0
LUCERNE	2.1758
ROTATIONAL_CROPS	1.8337
VINEYARD	2.2333
COMMERCIAL	1.1241

3.3.3 The flood frequency menu

The flood line that should be used in the model is selected with this menu. The flooded areas will be displayed for this flood line and it will be used when the flood damage has to be calculated for only one flood line.

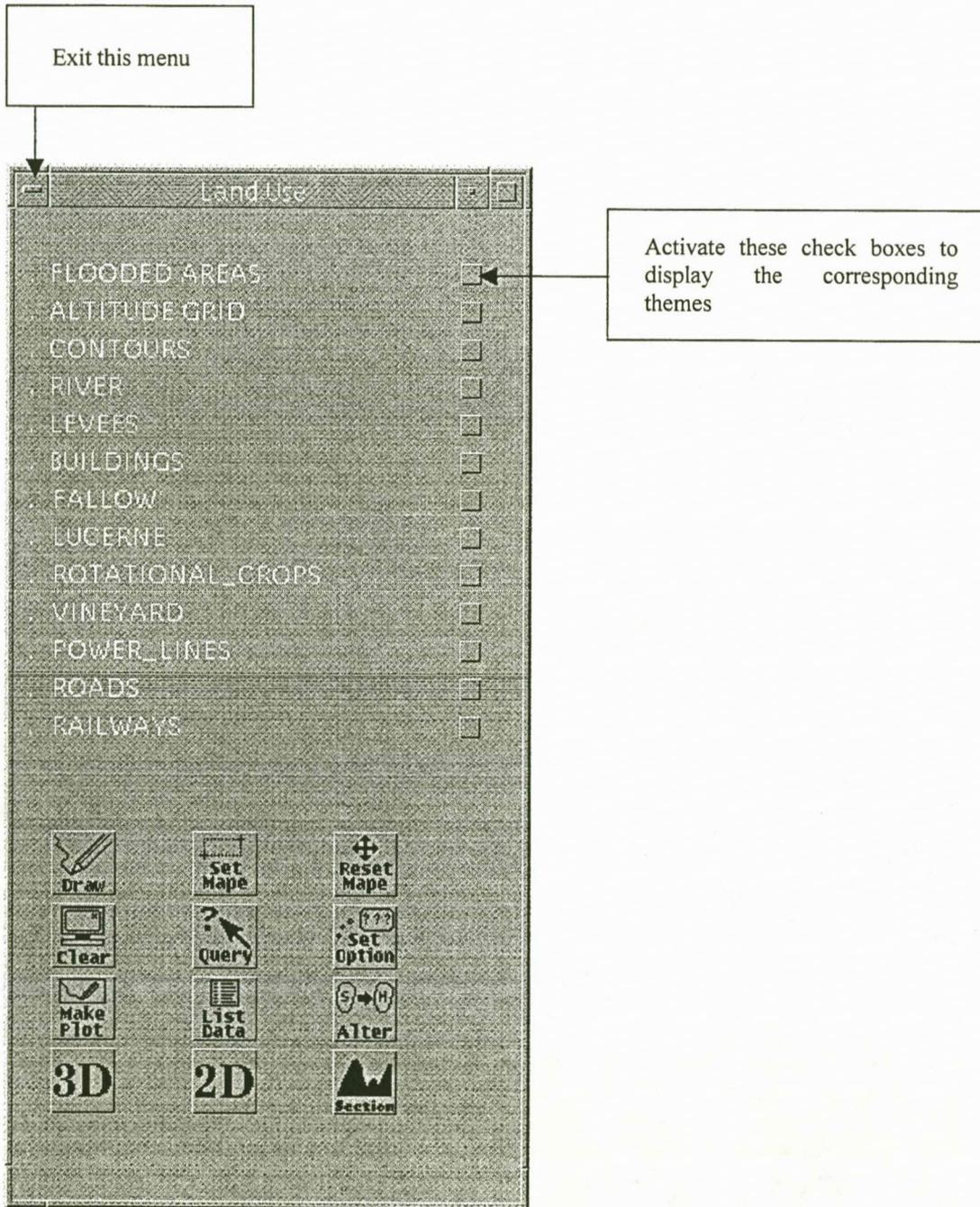


3.3.4 The land use menu

This menu is used to display the different themes. The crop types of cultivated fields can also be changed temporarily with this menu. Flood damage can then be calculated for the temporary crop types (see Paragraph 3.3.6). Other functions that are supplied by this menu include three-dimensional displays, queries of cultivated fields, data listing of cultivated fields and the creation of plot files. The model still has to be expanded to supply additional functions for infrastructures and buildings. The menu contains the following buttons:

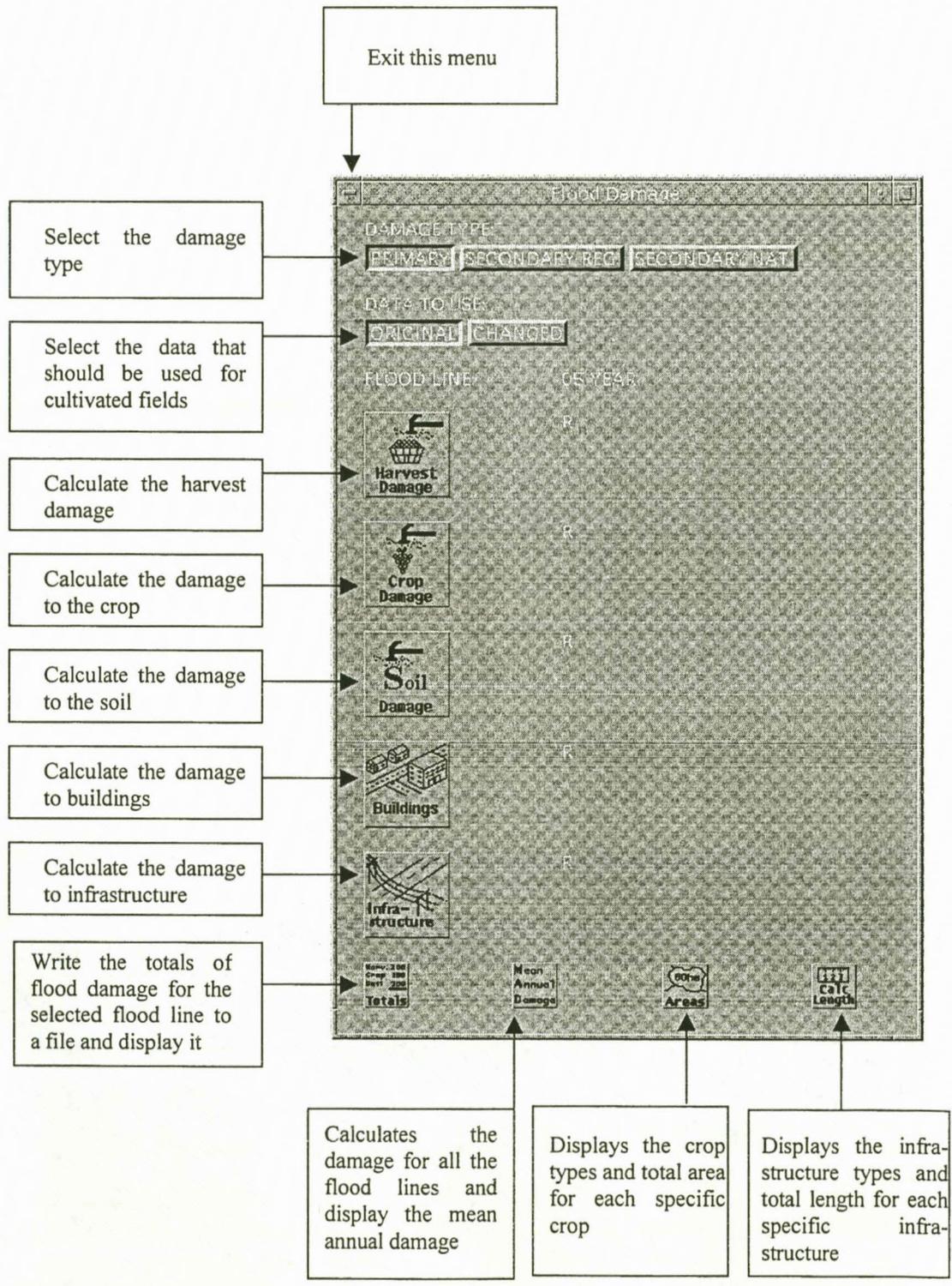
Button	Description
Draw	Draw the selected themes in the display area.
Set mape	Set the new map extent.
Reset mape	Reset the map extent.
Clear	Clear the current screen display.
Query	Query one cultivated field at a time.

Button	Description
Set option	Set display and data to display options.
Make plot	Creates a plot file of what is currently displayed on the screen.
List data	Lists information of all the cultivated fields on the screen.
Alter	Change the attributes of the cultivated fields temporarily.
3D	Activates the 3D view.
2D	Return to normal 2D view.
Section	Define a cross section and display its profile on the screen.



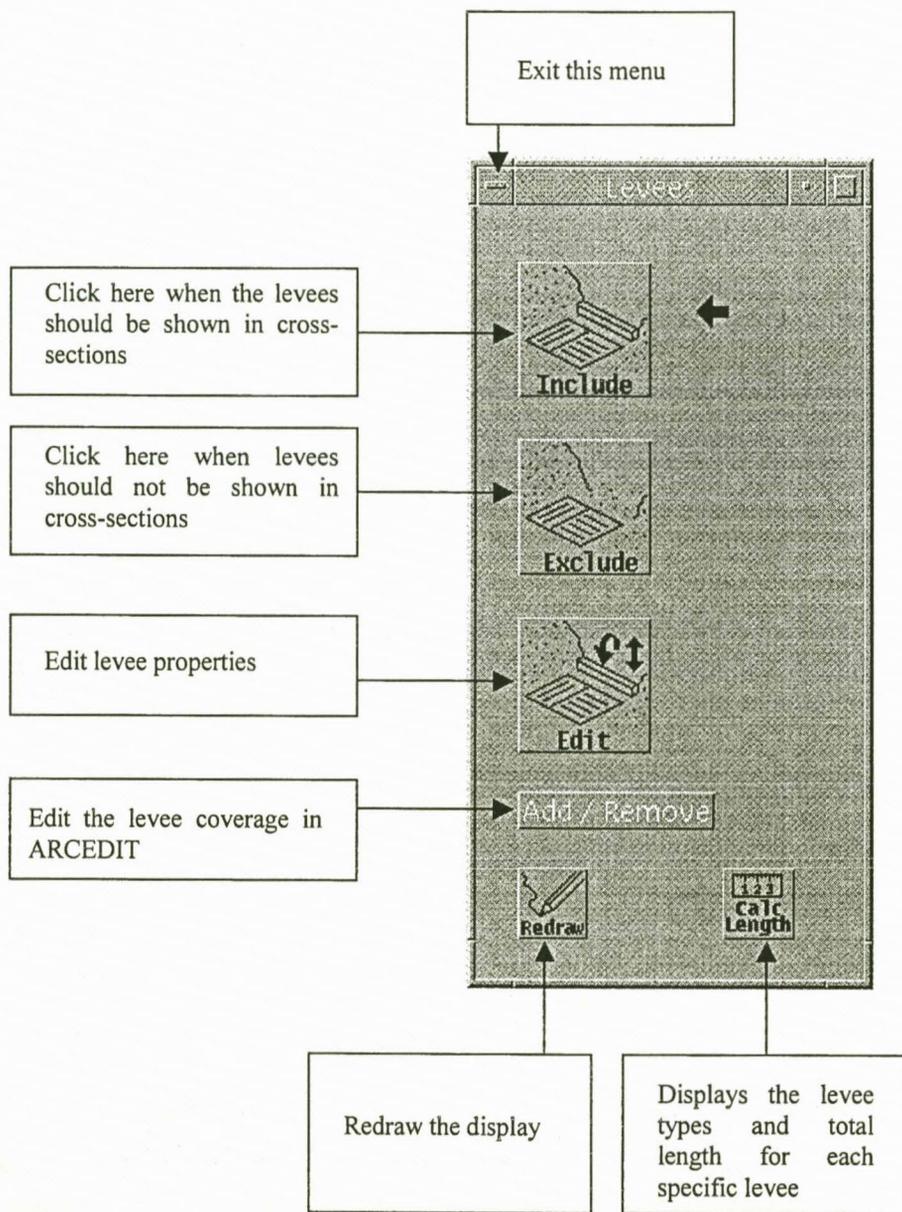
3.3.5 The flood damage menu

This menu calculates the primary damage, secondary damage for the region and secondary national damage. When the mean annual damage button is clicked the total damage for all the flood lines will be calculated and the mean annual damage (MAD) as well as the graph that represents the MAD will be displayed in the display area.



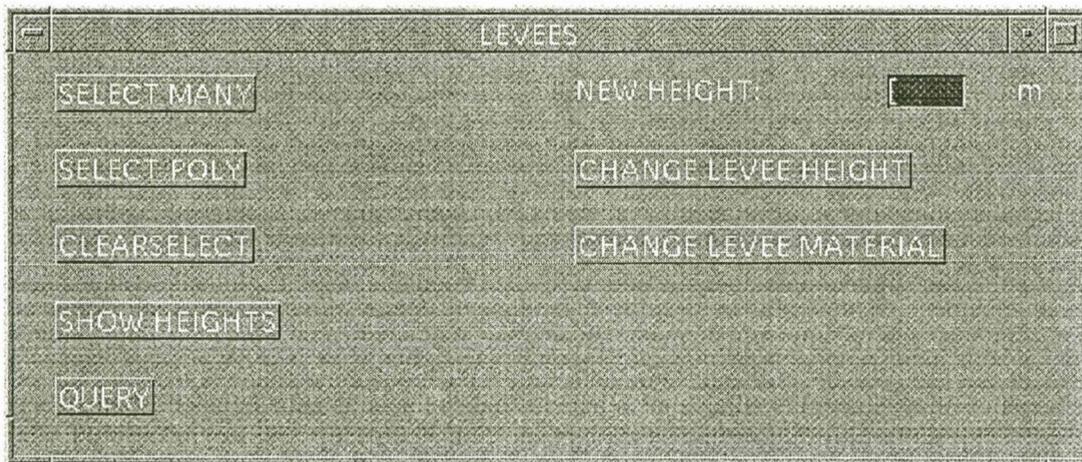
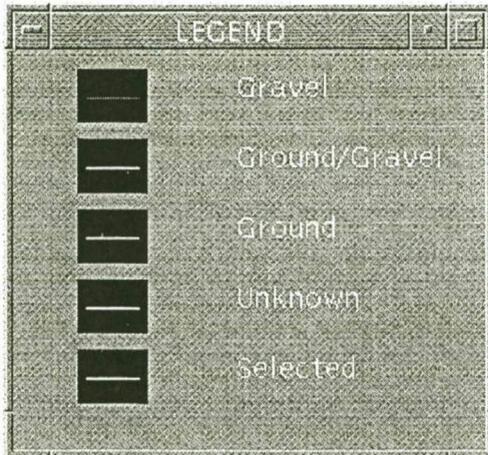
3.3.6 The levees menu

This menu is used to set levee calculation options, to edit levee properties and to create new levee scenarios.



3.3.6.1 The edit menu

Levee properties are edited with this menu. The levees are displayed in the display area. Different line symbols are used to draw the levees according to the material used. The selected levees are displayed in yellow. The legend looks like this:

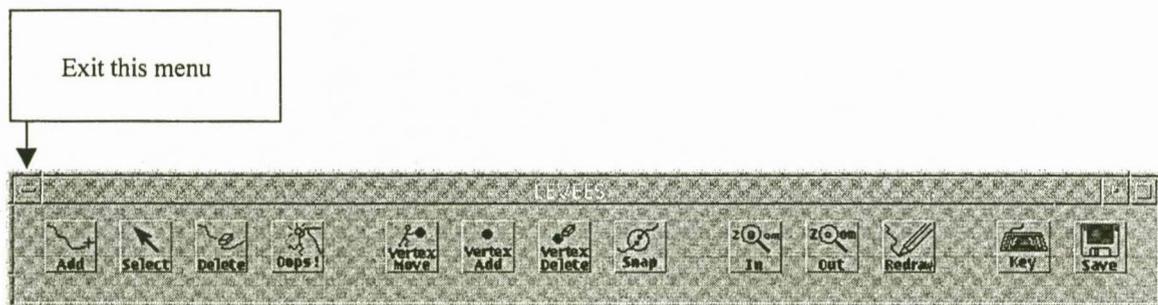


Button	Description
Select many	Click this button to select a subset of levees. Select the levees with the left mouse button. Press the 9 key on the keyboard to stop selecting.
Select poly	Click this button to select a subset of levees that falls within the boundary of a digitised polygon. Use the left mouse button to add the vertices of the selection polygon. Press the 9 key to close the polygon.

Button	Description
Clearselect	Clears the selected set of levees.
Show heights	Display the height of each levee.
Query	Query an individual levee
Change levee height	Change the height of the selected levees. The value in <i>new height</i> will be assigned to the levees.
Change levee material	Change the material of the selected levees. A menu will be displayed with the available material types. Highlight the material that should be allocated to the selected set of levees.

3.3.6.2 The add / remove menu

This menu can be used to edit the levee coverage in ARCEDIT.

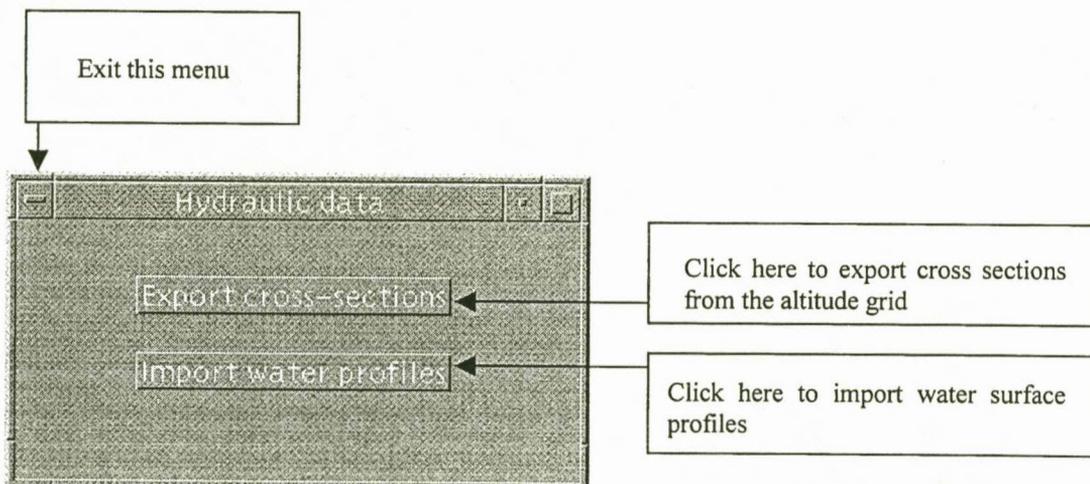


Button	Description
Add	Add a levee. You must start and end the line with a node (middle mouse button). Define the actual line (vertices) with the left mouse button. Press the 9 key on the keyboard to stop adding lines.
Select	Select one or more levees. Selected lines will turn yellow.
Delete	Deletes the current selection of lines. If no lines are selected the system will prompt you to select something.
Oops	Will undo your last action. Click this button if you want to undelete something which you deleted.
Vertex move	Allows you to move any of the vertices of the levee.
Vertex add	Allows you to add vertices to the levee.
Vertex delete	Allows you to delete any of the vertices of the levee.

Button	Description
Snap	Allows you to snap two or more vertices together.
Zoom in	Zoom in on the display.
Zoom out	Zoom to the previous level.
Redraw	Redraw the screen.
Key	Enters command mode. In command mode you can use any ARCEDIT commands. Type &return to return to menu mode.
Save	Saves your work.

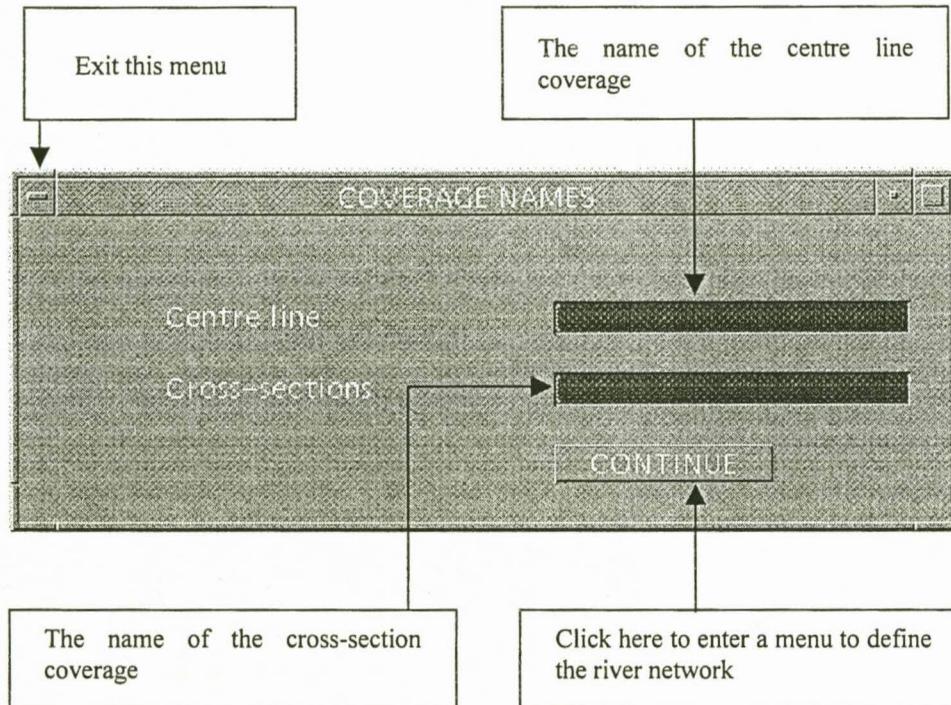
3.3.7 The hydraulic data menu

Use this menu to export cross-sections or to import water surface profiles. The server session should be started before cross-sections can be exported (see Paragraph 3.1)



3.3.7.1 The export cross-sections menu

The names of the coverages for centre lines and cross-sections are requested by this menu. The system will create new coverages if the specified coverages do not exist in the temporary directory.

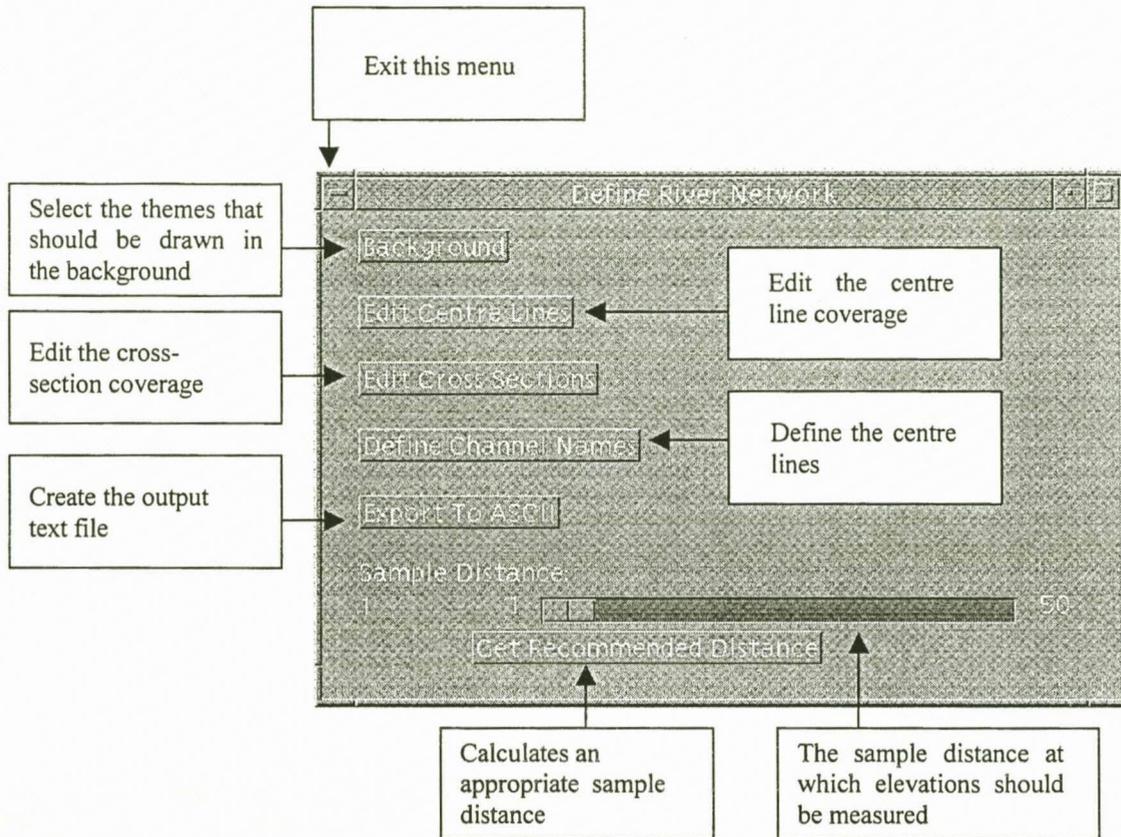


3.3.7.1.1 The define river network menu

Use this menu to export the river network and cross-sections to a text file. The format of the text file that is exported will be described in Chapter 4.

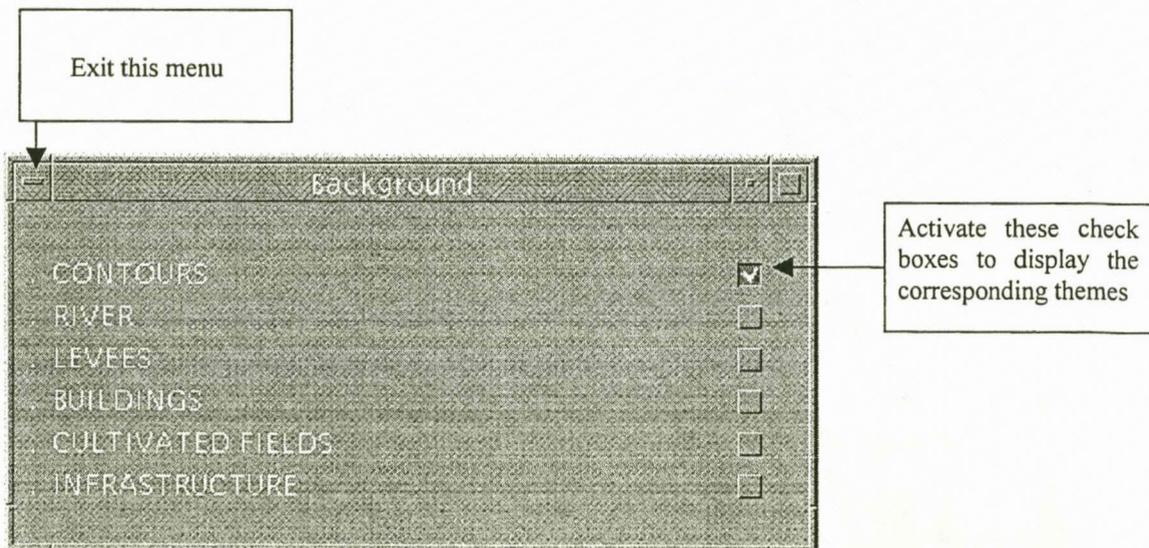
The river network and cross-sections can be digitised on the screen. The elevations of points in the cross-sections are automatically calculated by the system. The user may choose any of the themes to be displayed in the background while he is digitising.

The river is represented by a network configuration as a system of inter-connected branches. The network consists of centre lines representing the different channels. A centre line can be defined as a line connecting the points with maximum water speed in the cross-sections (Tchoukanski, 1995).



3.3.7.1.2 The background menu

Use this menu to select the themes that should be displayed in the background while the cross-sections and centre lines are digitised.



3.3.7.1.3 The edit centre lines menu

Use this menu to edit the centre line coverage. Note that the centre lines must be directed downstream.



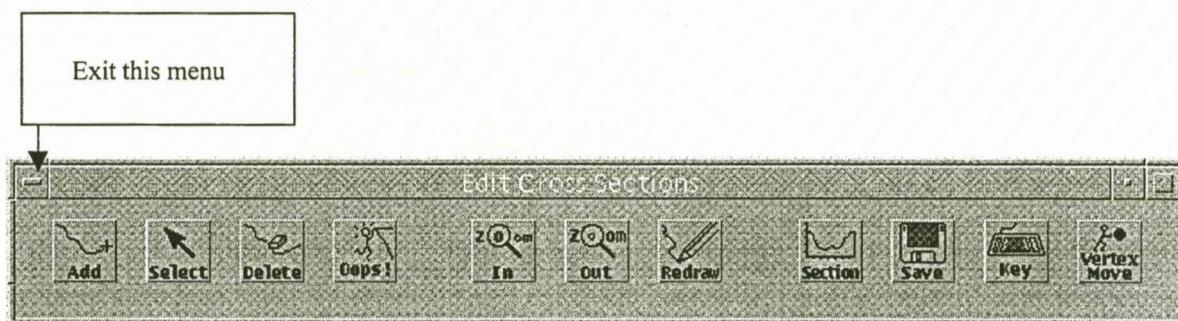
Button	Description
Add	Add a centre line. You must start and end the line with a node (middle mouse button). Define the actual line (vertices) with the left mouse button. Press the 9 key on the keyboard to stop adding lines.
Select	Select one or more centre lines. Selected lines will turn yellow.
Delete	Deletes the current selection of centre lines. If no lines are selected the system will prompt you to select something.
Oops	Will undo your last action. Click this button if you want to undelete something which you deleted.
Vertex move	Allows you to move any of the vertices of the centre line.
Vertex add	Allows you to add vertices to the centre line.
Vertex delete	Allows you to delete any of the vertices of the centre line.
Snap	Allows you to snap two or more vertices together.
Zoom in	Zoom in on the display.
Zoom out	Zoom to the previous level.
Redraw	Redraw the screen.
Key	Enters command mode. In command mode you can use any ARCEDIT commands. Type &return to return to menu mode.
Save	Saves your work.

3.3.7.1.4 The edit cross-sections menu

Use this menu to edit the cross-section coverage

The following rules must be considered during the digitising of cross-sections:

- Cross-sections must be taken from left to right over a centre line when looking downstream.
- Cross-sections should be straight lines.
- Cross-sections are not allowed to cross each other.
- Cross-sections must cross a centre line, but are not allowed to cross more than one centre line.
- Cross-sections should be approximately perpendicular to the centre line.
- Cross-sections should extend far enough to cover the highest elevation expected to be reached by the flood.
- Cross-sections should not extend beyond the boundary of the DTM.



Button	Description
Add	Add a cross-section. Use the middle mouse button to start and end the line. Press the 9 key on the keyboard to stop adding lines.
Select	Select one or more cross-sections. Selected lines will turn yellow.
Delete	Deletes the current selection of cross-sections. If no lines are selected the system will prompt you to select something.
Oops	Will undo your last action. Click this button if you want to undelete something which you deleted.
Zoom in	Zoom in on the display.
Zoom out	Zoom to the previous level.

Button	Description
Redraw	Redraw the screen.
Section	Allows you to select a cross-section. The profile of the cross-section will then be displayed in a separate window.
Key	Enters command mode. In command mode you can use any ARCEDIT commands. Type &return to return to menu mode.
Save	Saves your work.
Vertex move	Allows you to move any of the nodes of the cross-section.

3.3.7.1.5 The define channel names menu

Use this menu to define the channels in the river system. A route system is used to define the different channels of the river network. Each channel is defined as a separate route that consists of a subset of centre lines. The channels can be identified by name and the system will automatically calculate the chainages for each channel.

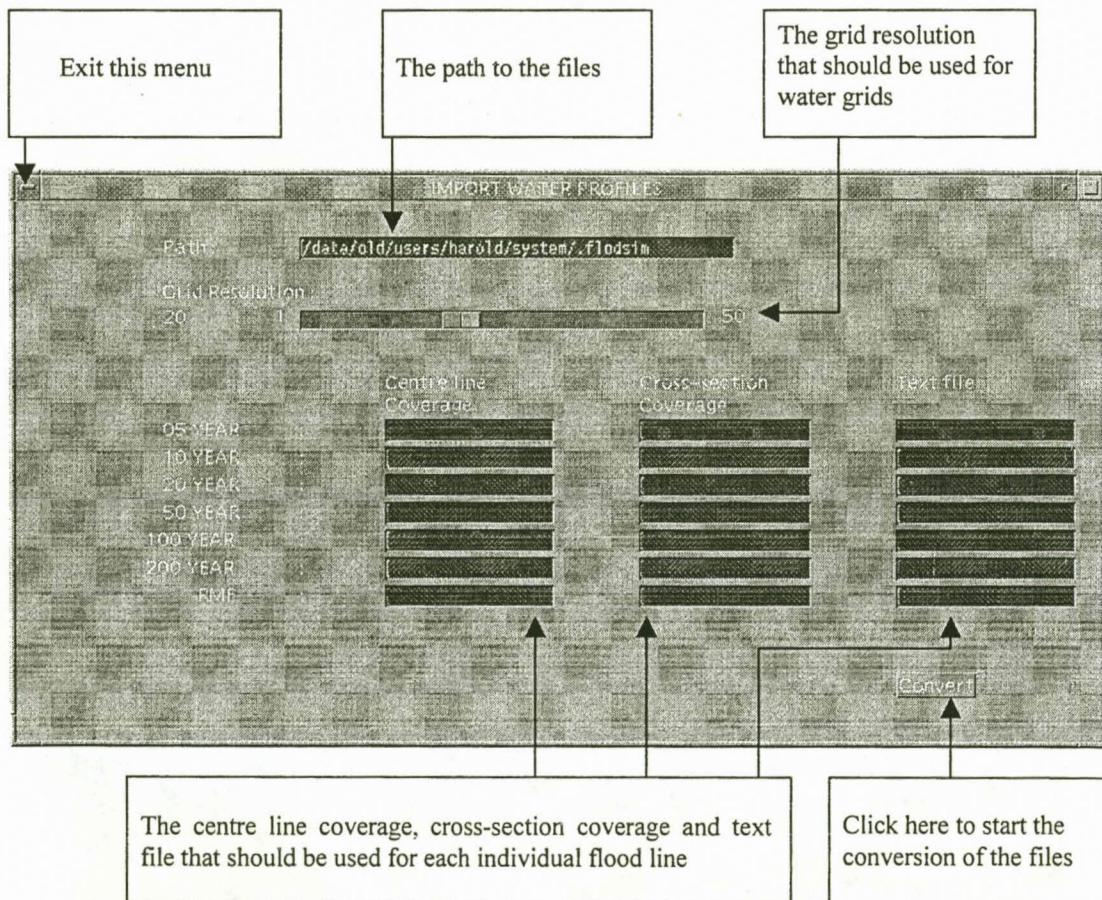


Button	Description
Create	Prompts you to give the name that should be used to identify the channel that is represented by current selection of centre lines. If no lines are selected the system will prompt you to select something.
Select	Select one or more centre lines. Selected lines will turn yellow.
Delete	Prompts you to give the name of the channel that should be removed from the river network.
Oops	Will undo your last action.
Name	Displays each channel with a unique line symbol. The names of the channels are also displayed.

Button	Description
Hatch	Draws hatch lines along the channels.
Redraw	Redraw the screen.
Zoom in	Zoom in on the display.
Zoom out	Zoom to the previous level.
Key	Enters command mode. In command mode you can use any ARCEDIT commands. Type &return to return to menu mode.
Save	Saves your work.

3.3.7.2 The import water profiles menu

Use this menu to import the water surface profiles. The centre line coverages and cross-section coverages that are required for each flood line were created with the exportation of the river network (see Paragraph 3.3.7.1). The format of the text files that are also required by this menu is described in Chapter 4.



ACQUISITION OF HYDRAULIC DATA

4.1 INTRODUCTION

Topographic data required by numerical flood models usually consists of a river network and cross section profiles of the floodplain. Previously the cross-sections were acquired by means of ground surveys or aerial photography. Both these procedures are tedious and time consuming. The river network and cross section profiles can now easily be extracted from the DTM in FLODSIM and saved as a text file. After the hydraulic data were computed with the numerical flood model they are re-imported into FLODSIM by means of a text file.

An interface with Mike 11 was developed as an example system to illustrate the coupling between FLODSIM and numerical flood models. The interface can be categorised as an isolated system. The software that converts the input and output data is independent of both models. It is therefore possible to create interfaces between FLODSIM and other numerical flood models as well. Examples of other numerical flood models that use cross-sections to describe the topography are HEC-RAS (US Army Corps of Engineers, 1997:B.12- B.14), CFP (ECC, 1987:5-6), XP-SWMM and WSPRO (van Bladeren, 1998).

4.2 DEFINING THE RIVER NETWORK AND CROSS-SECTIONS

The graphical user interface of this module is described in detail in Chapter 3. The exporting process is fully automatic and is activated by the click of a button.

The output data is saved into two files. The first file describes the river network by giving the chainages where the different channels connect. The second file describes the cross-sections (see Figure 4.1). The names of these files will respectively be *cline.chn* and *cline.aio*. Where *cline* should be read as the name of the centre line coverage. The file extensions respectively mean *chainage* and *ARC/INFO output*.

Mfolozi					
	1,26452.950,MAIN				
	2,25678.560,MAIN				
	3,25051.370,MAIN				
0					
	1,1, 0.000,	-60480.41009,	-42760.42602,		10.194
	1,1, 3334.375,	-57359.47412,	-43934.22909,		3.629
	1,1, 3922.329,	-56809.15573,	-44141.20719,		24.641
	2,1, 0.000,	-60537.26579,	-42914.74836,		15.304
	2,1, 3352.527,	-57665.97439,	-44645.38992,		4.278
	2,1, 3461.496,	-57572.64692,	-44701.64210,		12.054
	3,1, 0.000,	-60585.99918,	-43085.31545,		15.613
	3,1, 3420.693,	-57914.20798,	-45221.35680,		3.742
	3,1, 3993.179,	-57467.05759,	-45578.84421,		9.549
0					
	1,1, 0.000,	-60480.41009,	-42760.42602,		10.194
	1,1, 33.000,	-60449.52247,	-42772.04304,		9.873
	1,1, 66.000,	-60418.63486,	-42783.66006,		7.591
	1,1, 99.000,	-60387.74724,	-42795.27708,		7.218
	1,1, 132.000,	-60356.85962,	-42806.89410,		7.530
	...				
	1,1, 3922.329,	-56809.15573,	-44141.20719,		24.641
	2,1, 0.000,	-60537.26579,	-42914.74836,		15.304
	2,1, 33.000,	-60509.00274,	-42931.78362,		10.215
	2,1, 66.000,	-60480.73969,	-42948.81888,		8.746
	2,1, 99.000,	-60452.47664,	-42965.85414,		8.312
	2,1, 132.000,	-60424.21360,	-42982.88941,		9.605
	...				
	2,1, 3461.496,	-57572.64692,	-44701.64210,		12.054
	3,1, 0.000,	-60585.99918,	-43085.31545,		15.613
	3,1, 33.000,	-60560.22397,	-43105.92220,		13.051
	3,1, 66.000,	-60534.44875,	-43126.52895,		13.059
	3,1, 99.000,	-60508.67353,	-43147.13570,		11.517
	3,1, 132.000,	-60482.89831,	-43167.74245,		8.988
	...				
	3,1, 3993.179,	-57467.05759,	-45578.84421,		9.549

Figure 4.1 The output file of FLODSIM that describes the river network

The file describing the cross-sections that is illustrated in Figure 4.1 consists of three parts. The different parts are delimited with a line that contains a '0'. The first part gives the section id, chainage of the section on the centre line of a channel in meters, and the channel name of each cross section. The second part gives the section id, surface id, the distance in meters from the starting point of the section and the x-, y-, and z co-ordinates of three points for each cross section. These three points include the starting point and ending point of the cross section as well as the point on which the section intersects the centre line of a channel. The last part of the file describes the profile of each cross section. The x-, y-, and z co-ordinates are given for regular points along the line. The user determines the intervals between the points, and for this example a distance of 33m

was taken. The cross-sections in the output file will be in the same order in which they were digitised.

4.2.1 The interface between FLODSIM and Mike 11

Mike 11 is a professional engineering software package, developed by the Danish Hydraulic Institute (DHI, 1992). It consists of several modules and can be used for the simulation of flows, sediment transport and water quality in estuaries, rivers, irrigation systems and similar water bodies. The core of the Mike 11 system is the hydrodynamic module, which is an implicit, finite difference model for the computation of unsteady flows. The hydrodynamic module is often applied as a flood management tool to simulate flooding behaviour of rivers and floodplains.

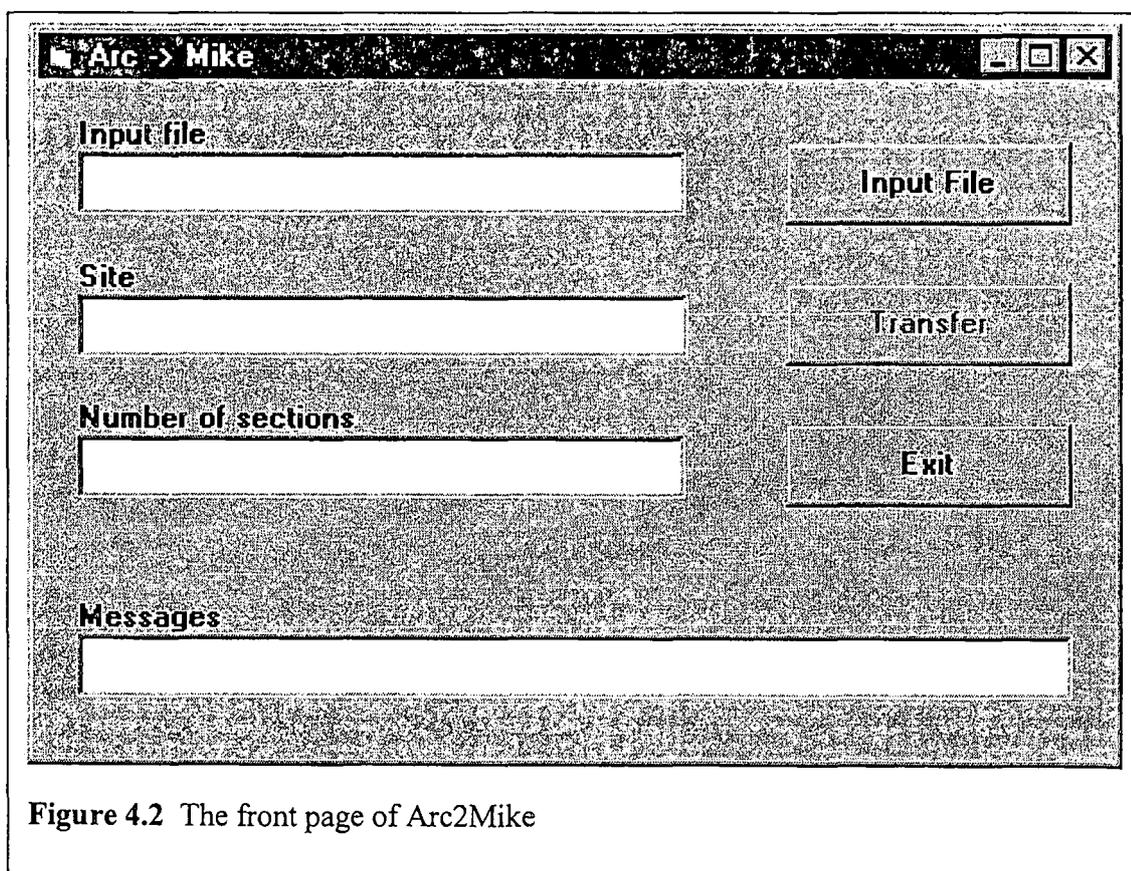


Figure 4.2 The front page of Arc2Mike

Two programs were written for the interface between FLODSIM and Mike 11. The first program, Arc2Mike (see Figure 4.2), does the conversion from the output file of FLODSIM (see Figure 4.1) into a format supported by Mike 11 (see Figure 4.3). The second program, Mike2Arc, converts the Mike 11 output file (see Figure 4.4) into the

format of FLODSIM's input file (Figure 4.6). The input and output files of Mike 11 will be described in the remainder of this paragraph.

Mfolozi			<i>Topographical identification</i>
MAIN			<i>River or channel name</i>
26.453			<i>Chainage in kilometres</i>
Co-ordinates			<i>Explanatory text</i>
1	-57359.47	-43934.23	<i>Horizontal co-ordinates</i>
Profile	121		<i>Number of x-z co-ordinates</i>
0.00	10.19		<i>x1 z1</i>
33.00	9.87		<i>x2 z2</i>
66.00	7.59		<i>x3 z3</i>
99.00	7.21		<i>x4 z4</i>
132.00	7.53		<i>x5 z5</i>
...			
3922.00	24.64		<i>x121 z121</i>
*****			<i>End of the first cross-section</i>
Mfolozi			<i>Topographical identification</i>
MAIN			<i>River or channel name</i>
25.679			<i>Chainage in kilometres</i>
Co-ordinates			<i>Explanatory text</i>
1	-57665.97	-44645.39	<i>Horizontal co-ordinates</i>
Profile	107		<i>Number of x-z co-ordinates</i>
0.00	15.30		<i>x1 z1</i>
33.00	10.22		<i>x2 z2</i>
66.00	8.75		<i>x3 z3</i>
99.00	8.31		<i>x4 z4</i>
132.00	9.61		<i>x5 z5</i>
165.00	8.76		<i>x6 z6</i>
...			

Figure 4.3 The input file of Mike 11

Cross-sectional data can be read from a text file into the database of Mike 11 (DHI, 1995:2.14). The text files may be in several formats. The format used for the interface is described in Figure 4.3. The cross-sections are specified by a number of x-z co-ordinates where x is the distance from the beginning of the section and z is the corresponding bed elevation. A maximum number of 300 points is allowed for each cross-section (DHI, 1995:2.9). The cross-sections of the input file may be in any order and will be sorted in Mike 11 by channel name and chainage.

Mike 11 can write the results of the simulation to a text file (DHI, 1995:2.14). Mike 11 gives two options for the format of the output file (a summary or time series can be given). The summary file only gives the minimum and maximum water level of the flood for each cross-section. This file can be used when duration of inundation is unimportant

as in the case with the Orange River. A file containing a time series is illustrated by Figure 4.4. With this file water levels are given over time-intervals, for example every hour during the total duration of the simulation. The interval can be defined in Mike 11. The channel name and chainage (in kilometres) identify the cross-sections. The first cross-section in figure 6.4 is for example 51 metres from the beginning of the main channel. The minimum distance allowed between two cross-sections can be defined in Mike 11 (DHI, 1995:2.22). If the distance between two cross-sections is longer than the defined distance Mike 11 will generate a cross-section at the required position. Hydraulic parameters at these additional cross-sections will be calculated by interpolating between the specified cross-sections. The results of the new cross-sections that were generated by Mike 11 will also be shown in the output file.

```

+-----+
! DATA FILE: MFOLOZI.RDF   BOUNDARY FILE: 10.BSF   !
! PARAMETER: 10-1.RRF     CALCULATED : 12-JAN-1998, 16:10 !
+-----+
!           ! MAIN   MAIN   MAIN   MAIN   MAIN   !
!HOURS:MIN ! 0.051 0.231 0.411 0.566 0.721 !
+-----+
1998 1 1 0 0      12.83 12.67 12.46 12.16 11.77
1998 1 1 1 0      13.05 12.88 12.63 12.28 11.84
1998 1 1 2 0      13.21 13.04 12.79 12.40 11.91
1998 1 1 3 0      13.35 13.18 12.89 12.47 11.97
1998 1 1 4 0      13.47 13.29 12.98 12.53 12.02
1998 1 1 5 0      13.58 13.39 13.06 12.58 12.07

```

Figure 4.4 The output file of Mike 11

Mike2Arc will also determine the elevation where the water will be for longer than a critical period for each cross-section (see Figure 4.5). This is done by determining the duration of the water at levels from the flood peak downward with an interval declared by the user. Suppose the interval is 0.01 m and the flood peak is at 14 m above sea level then the duration of the water has to be computed for 13.99, 13.98, 13.97 ... until the duration is longer than the critical period. To determine the duration at 13.99 the first timestamp where the elevation-time graph crosses 13.99 has to be subtracted from the second timestamp where the elevation-time graph crosses 13.99. The required elevation will then be the first elevation at which the duration is equal to or longer than the critical period. In the case of sugarcane the critical periods would be the periods (for winter and summer) that the plant could be inundated before it is destroyed.

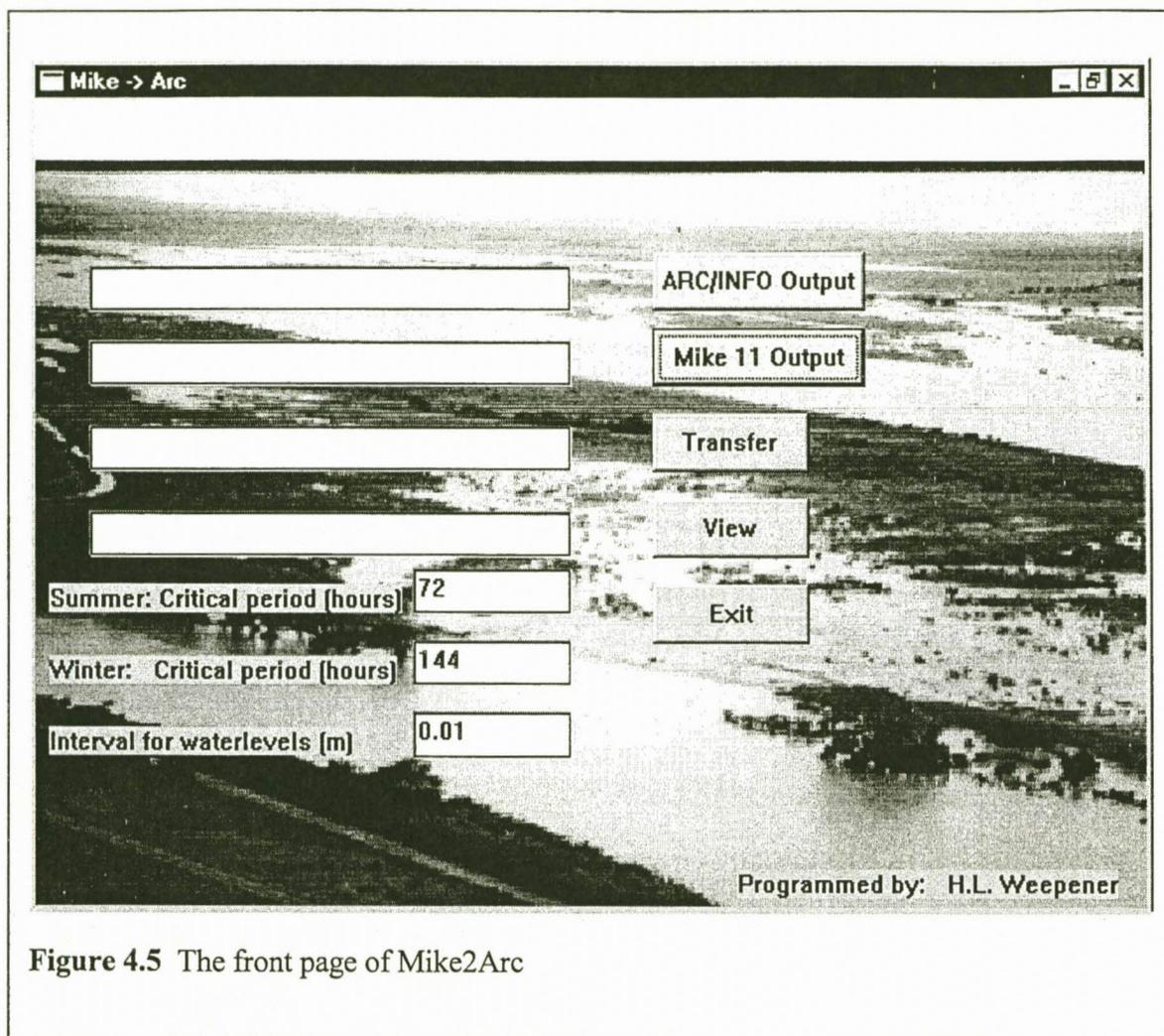


Figure 4.5 The front page of Mike2Arc

Two input files are required by Mike2Arc namely the output file from FLODSIM and the output file from Mike 11. The output file from FLODSIM is necessary to identify the original cross-sections. Only the original cross-sections will be included in the input file of FLODSIM.

4.2.2 Importing hydraulic data into FLODSIM

The input file required by FLODSIM must consist of at least three columns namely the channel name, chainage and flood peak of each cross-section (see Figure 4.6). Any number of additional fields may be added after the flood peak to provide for loss functions that are based on other flood characteristics. The same calculations, which are done for the flood peak, will also be done for the additional fields. Two additional fields were for example used for the Mfolozi River. Sugarcane may only be inundated for a

certain period before it would be damaged. This period differs between winter and summer. The two fields that were added for the Mfolozi River represent respectively the elevation at which the water would stay for the critical periods (for the winter and summer) or longer.

<i>Channel name</i>	<i>Chainage</i>	<i>Flood peak</i>	<i>Summer</i>	<i>Winter</i>
MAIN,	51.00,	15.36,	14.23,	13.22
MAIN,	411.00,	14.56,	13.57,	12.81
MAIN,	721.00,	13.58,	12.50,	11.93
MAIN,	1196.00,	13.02,	11.80,	11.03
MAIN,	1682.00,	12.83,	11.72,	11.01
MAIN,	2196.00,	12.70,	11.68,	10.99
MAIN,	2665.00,	12.55,	11.62,	10.98
MAIN,	3144.00,	12.08,	11.35,	10.86

Figure 4.6 Input file for FLODSIM

The hydraulic properties for cultivated fields and buildings are saved in info-files. Only the distance of infrastructures that are inundated is computed for infrastructures.

A relate environment is automatically established by the system. The AML program files that determines the flood damage for buildings and cultivated fields use these relates to find the hydraulic properties of a specific entity in the corresponding table. The relates are respectively *rel_p_c* and *rel_p_b* for cultivated fields and buildings (*p* indicates the hydraulic property). The relates are automatically updated when the flood frequency change. The same names can therefore be used for all the flood frequencies. The distance of infrastructures that are inundated can be read from variables named *.i_inundation_length_ff_infra* (where *infra* indicates the symbol that are associated with the specific infrastructure category and *ff* the flood frequency)

CONSTRUCTION OF NEW LOSS FUNCTIONS

5.1 INTRODUCTION

Loss functions are usually constructed by economists. Viljoen (1979:160-161) suggests that a combination of inductive- and deductive methods be used to develop loss functions. Reported damages of real floods are used with the inductive method, while flood damage is determined independently of real floods with the deductive method. The main advantage of the inductive method is that the relationships are based on real floods. With the deductive method relationships for different frequencies of floods can be determined in the absence of historical data.

It is difficult to quantify the amount of work that will have to be done to construct new loss functions and it will differ for different crop types. The most time will however go into the research work that has to be done by an economist. The programming of additional loss functions after it was constructed will not take long. The following paragraph will give some guidelines for the implementation of the loss-functions that were constructed by the economists. The access to hydraulic properties was already described in Paragraph 4.2.2 and will not be repeated in this paragraph.

5.2 HANDLING OF DIFFERENT CROP- AND INFRASTRUCTURE TYPES

A naming convention is used in FLODSIM to recognise the programs that calculate flood damage to different crops and infrastructures. Standard input and output variables are also used in these programs.

A symbol consisting of two letters is used to identify the crop- or infrastructure types. The AML program filenames for harvest-, crop- and soil damage should for example be *hd_crop.aml*, *cd_crop.aml* and *sd_crop.aml* (*crop* should be replaced with the two letters

of the crop symbol). The filenames for flood damage to infrastructure should be *fd_infra.aml* (*infra* should be replaced with the two letters of the infrastructure symbol).

A menu file with the name *impact_c_crop.menu* and *impact_i_infra.menu* can be used as interface with the user (*crop* and *infra* are again the symbols for the entities). This menu will be called from the primary impact menu (see Paragraph 2.3.10.1 and Paragraph 3.3.2.1). The values that are acquired can be written to a file with the name *defaults_c_crop.aml* or *defaults_i_infra.aml*. These files are called by *defaults.aml* if they exist.

A naming convention is also used for variable names. The Setup program will automatically check the cultivated fields and infrastructure coverages for the different symbols that are used. The number of crop symbols that are found is allocated to a variable called *.c_number*. The Setup program numbers the crop symbols and each individual crop symbol is allocated to *.c_symbol_i* (where *i* is the number that is assigned to the specific crop type). The user will be prompted to give a description and colour value for each crop type that will be saved as *.c_type_i* and *.c_value_i* respectively. The variable names for infrastructures are *.i_number*, *.i_symbol_i*, *.i_type_i* and *.i_value_i*.

Each AML program file (*hd_crop.aml*, *cd_crop.aml*, *sd_crop.aml* and *fd_infra.aml*) should have an argument for the number that was assigned to the crop or infrastructure type. This number should be used in the variable name for the expected total damage that was calculated by the program. The variables that are used to save the total harvest damage, total soil damage or total crop damage for the first crop type should respectively be named *.tot_hd_1*, *.tot_sd_1* and *.tot_cd_1*. The total damage for the first infrastructure type should be saved as *.tot_fd_i_1*.

FLODSIM will first check if the program exists before it will try to run it. If the program does not exist the damage will be considered as zero. This might be the case for annual crop types where there is no damage to the crop, but only damage to the harvest and the soil. At the moment programs exist to determine flood damage to vineyards, lucerne, rotational crops and sugarcane.

LOSS FUNCTIONS IMPLEMENTED IN FLODSIM

I.1 LOCATION SPECIFIC LOSS FUNCTIONS

Several loss functions were developed for the Lower Orange River area and for the Mfolozi floodplain that are location specific. Loss functions that were developed for the Lower Orange River area include loss functions for fallow lands, and loss functions to determine soil damage to cultivated fields (vineyard, lucerne and rotational crops). Loss functions for railways, roads, bridges, drains, levees, and spillways were developed for the Mfolozi floodplain.

I.2 SUGAR CANE

The symbol used for sugar cane is 's'. Sugarcane may only be inundated for a certain period before it would be damaged. This period differs between winter and summer. Two additional hydraulic characteristics are therefore required. The two characteristics represent respectively the elevation at which the water would stay for the critical periods (for the winter and summer) or longer. The menu looks like this:

The screenshot shows a menu titled "SUGAR CANE" with two main sections: "HARVEST DAMAGE" and "CROP DAMAGE". Each section contains several variables with their corresponding values in input fields. Callout boxes point to specific elements: "Exit this menu" points to the top-left corner; "Harvest damage variables" points to the list of variables in the "HARVEST DAMAGE" section; "Crop damage variables" points to the list of variables in the "CROP DAMAGE" section; and "Click here to save the changes" points to a "SAVE" button at the bottom left.

Section	Variable	Value
HARVEST DAMAGE	GROSS INCOME PER TON SUGARCANE:	915
	GROSS INCOME PER TON SUCROSE:	112
	TONS SUGARCANE PER HECTARE:	94
	HARVESTING COST PER TON SUGARCANE:	32.4
	NORMAL CONTENT SUCROSE PER TON SUGARCANE:	12.3
	LOWER CONTENT SUCROSE PER TON SUGARCANE: (AFTER FLOOD)	10.3
AVERAGE MAXIMUM HEIGHT OF SUGARCANE	2.4	
CROP DAMAGE	ESTABLISHING COST	4326
	ANNUAL INCOME PER HECTARE	10579
	ANNUAL COST PER HECTARE	8543
	DISCOUNT RATE	0.1
	LENGTH OF CROP CYCLE (YEAR)	10

SAVE

I.3 VINEYARD

The symbol used for vineyard is 'v'. The menu looks like this:

The screenshot shows a menu titled "VINEYARD" with the following sections and values:

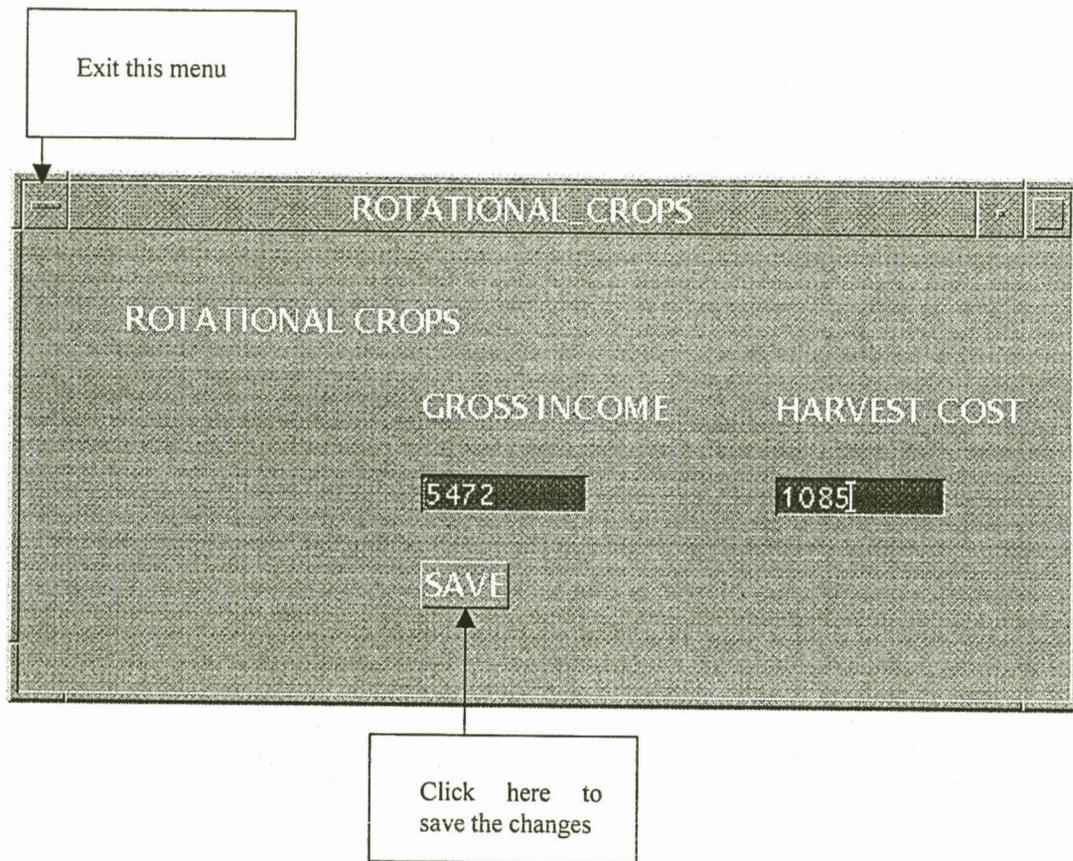
- HARVEST DAMAGE**
 - GROSS INCOME: 11969
 - HARVEST COST: 892
- CROP DAMAGE**
- ESTABLISHING COST**: 23700
- VINEYARD ESTABLISHED**
 - NPV BEFORE FLOOD:
 - NEW: 74277
 - YOUNG: 67903
 - OLD: 47037
 - NPV AFTER FLOOD: ALL AGES: 26305
- VINEYARD RECOVERED**
 - NPV BEFORE FLOOD: ALL AGES: 22190
 - NPV AFTER FLOOD: ALL AGES: 16643
- SAVE** button

Callouts from external boxes:

- "Exit this menu" points to the top-left corner of the menu window.
- "Harvest damage variables" points to the HARVEST COST field.
- "Click here to save the changes" points to the SAVE button.
- "Net present values when the crop is replanted" points to the NPV AFTER FLOOD: ALL AGES: 26305 field.
- "Net present values when the crop is not replanted" points to the NPV AFTER FLOOD: ALL AGES: 16643 field.

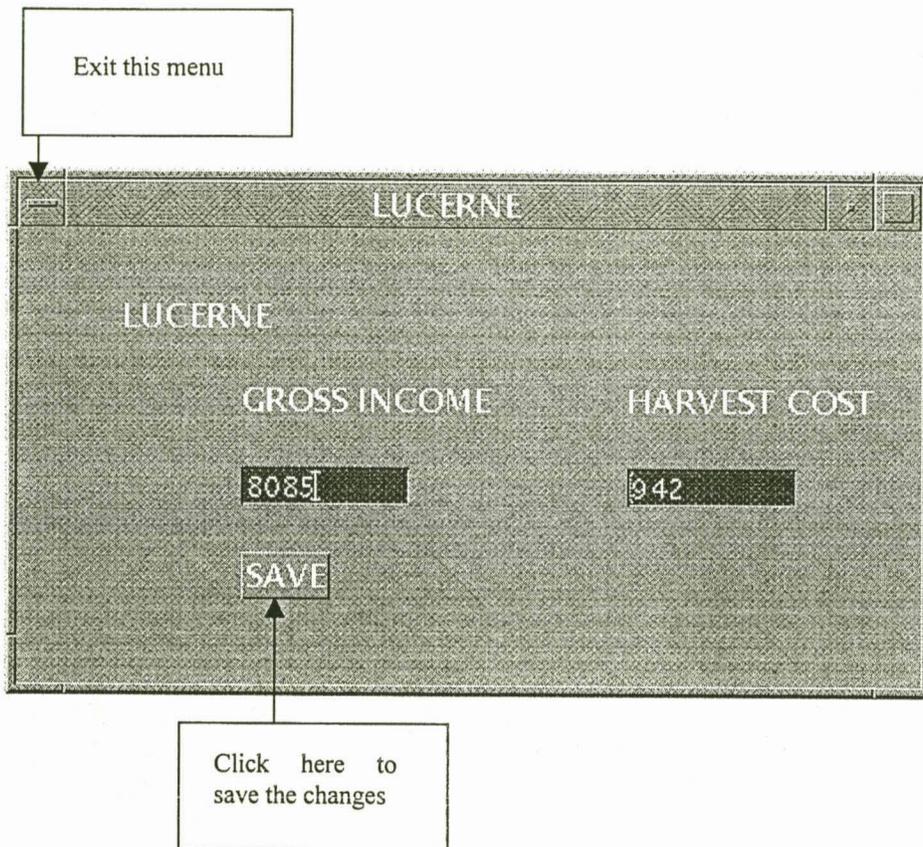
I.4 ROTATIONAL CROPS

The symbol used for rotational crops is 'rc'. The menu looks like this:



I.5 LUCERNE

The symbol used for lucerne is 'l'. The menu looks like this:



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ABSTRACT

Viljoen, Du Plessis and Booysen (1995) started in 1992 with the development of a flood damage simulation model (FLODSIM) for the Lower Orange River area. This model was based on GIS technology and was completed in 1994. The main shortcoming of this model was that it was location specific. A successive project was piloted in 1995 for the modification of the model so that it would be generally applicable in flood prone areas. Weiss (1976) already did extensive work on the estimation of flood damage for the Mfolozi floodplain and it was therefore decided to demonstrate the model on the Mfolozi floodplain.

A Setup program was written to be able to adapt the model according to the different situations of floodplains. The Setup program prompts the user to indicate the features that should be included in the model and then it guides the user through a series of menus to define the variables that are required to include the specified features. Features that can be included into the model include a DTM, levees, contours, spot heights, cultivated fields, infrastructures and buildings. Flood damage can be computed for cultivated fields, infrastructures and buildings.

Programs were also written to speed up the process of acquiring new hydraulic data after levees were added or removed. This includes programs with which topographic data that are required by numerical flood models can be extracted from the DTM and programs with which the hydraulic data that were computed with the numerical flood model can be imported into FLODSIM. An interface with Mike 11 was also developed to illustrate the coupling between FLODSIM and numerical flood models.

Other enhancements of the model include programs for the manipulation of levees, loss functions for sugarcane and infrastructure and a program that computes the flooded areas.

In a literature study that was conducted to investigate different methods for obtaining data it was found that data can either be acquired in digital form from another company or it has to be digitised from maps. When no data are available for the area it may be collected

in situ or by means of remote sensing. Remote sensing can also be of great value in updating data such as land use patterns that change over time. The sources that are used to derive DEM data vary from ground surveys, photogrammetry and existing contour maps to radar or laser altimetry.

OPSOMMING

Viljoen, Du Plessis en Booysen (1995) het reeds in 1992 begin met die ontwikkeling van 'n vloedskadesimulasiemodel (FLODSIM) vir die Benede-oranjeriviergebied. Hierdie model was gebaseer op 'n GIS-benadering en is in 1994 voltooi. Die grootste tekortkoming van die model was dat dit gebiedspesifiek was. 'n Opvolgprojek is in 1995 geloods om die model so te veralgemeen dat dit toepasbaar op verskillende vloedgeteisterde gebiede kan wees. Weiss (1976) het reeds omvattende werk ten opsigte van vloedskadeberaming vir die Mfolozirivier gedoen en daar is besluit om die gebruik van FLODSIM op die Mfolozi vloedvlakte te demonstreer.

'n Opstellingsprogram is geskryf om dit moontlik te maak om die model aan te pas na gelang van die verskillende situasies in vloedvlaktes. Die opstellingsprogram laat die gebruiker toe om die kenmerke van die gebied aan te dui en lei dan die gebruiker deur 'n reeks menu's om die veranderlikes van elke kenmerk te definieer. Kenmerke wat deur die model ondersteun word, sluit 'n DTM, noodwalle, kontoerlyne, hoogtepunte, landerye, infrastruktuur en geboue in.

Programme is ook geskryf om die verkryging van nuwe hidrouliese data te vergemaklik nadat noodwalle bygevoeg of verwyder is. Dit sluit programme in wat die topografiese data wat deur numeriese vloedmodelle benodig word, vanaf die DTM kan genereer en programme waarmee die hidrouliese eienskappe wat deur die numeriese vloedmodelle bereken is, weer ingetrek kan word in FLODSIM. 'n Koppelvlak met Mike 11 is ontwikkel om die koppeling tussen FLODSIM en numeriese vloedmodelle te demonstreer.

Ander verbeteringe tot die model sluit programme in vir die manipulasie van noodwalle, verliesfunksies vir suikerriet en infrastruktuur en 'n program vir die bepaling van gebiede wat oorstroom.

In 'n literatuurstudie wat uitgevoer is ten opsigte van die verskillende metodes vir die verkryging van data, is gevind dat die data enersyds in digitale formaat vanaf ander

instansies gekry kan word indien beskikbaar, of vanaf analoogkaarte versyfer kan word. Indien daar geen data vir die gebied beskikbaar is nie, kan die data *in situ* of met behulp van afstandwaarneming versamel word. Die bronne wat gebruik kan word vir die skep van DEM-data, wissel vanaf grondopmetings, fotogrammetrie en bestaande kontoerkaarte tot radar- of laserhoogtemeting.

