THE USE OF GIS FOR THE DEVELOPMENT OF A FULLY EMBEDDED PREDICTIVE FIRE MODEL

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ABSTRACT

Fire is very important for maintaining balance in the ecosystems and is used by fire management across the world to regulate growth of vegetation in natural conservation areas. However, improper management of fire may lead to hazardous behaviour. Fire modelling tools are implemented to provide fire managers with a platform to test and plan fire management activities. Fire modelling occurs in two parts: fire behaviour models and fire spread models, where fire behaviour models account for the behaviour of fires that is used in fire spread models to model the propagation of a fire event.

Since fire is a worldwide phenomenon a number of fire modelling approaches have been developed across the world. Most existing fire models only model either fire behaviour or fire spread, but not both, hence full integration of fire models into GIS is not completely implemented. Full integration of environmental modelling in GIS refers to the case where an environmental model such as a fire model is implemented within a GIS environment, without requiring any transfer of data from other external environments. Most existing GIS based fire spread models account for fire propagation in the direction of prevailing winds (or defined fire channels) as opposed to full fire spread in all directions.

The purpose of this study is to illustrate the role of GIS in fire management through the development of a fully integrated, predictive, wind driven, surface fire model. The fire model developed in this study models both the risk of fire occurring (fire behaviour model), and the propagation of a fire in case of an ignition incident (fire spread model), hence full integration of fire modelling in a GIS environment. The fire behaviour model is based on prevailing meteorological conditions, the type of vegetation in an area, and the topography.

The spread of a fire in this model is determined by the transfer of heat energy and rate of spread of fire, and is developed based on the Cellular Automata (CA) modelling approach. This model considers the spread of fire in all directions instead of the forward wind direction only as is the case in most fire spread models. The fire behaviour model calculates fire intensity and rate of spread which are used in the fire spread model, hence demonstrating the full integration of fire modelling in GIS. No external data exchange with the model occurs except for acquisition of input data such as measured values of environmental conditions.

This cellular automata based fire spread model is developed in the ArcGIS ModelBuilder geoprocessing environment, and requires the development of a custom geoprocessing function tool to facilitate the fast and effective performance of the model.

The test study area used in this research is the Kruger National Park because of frequent fire activity that occurs in the park, as a result of management activities and accidental fires, and also because these fires are recorded by park fire ecologists. Validation of the model is achieved by comparison of simulated fire areas after a certain period of time with known location of the fire at that particular time. This is achieved by the mapping of fire scars and active fire areas acquired from MODIS Terra and Aqua images, fire scars are also acquired from the Kruger National Park Scientific Services.

Upon evaluation, the results of the fire model show successful simulation of fire area with respect to time. The implementation of the model within the ArcGIS environment is also performed successfully. The study thus concludes that GIS can be successfully used for the development of a fully integrated (embedded) fire model.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

AVHRR	Advanced Very High Resolution Radiometer
BROS	Backward Rate of Spread
CA	Cellular Automata
CDSM	Chief Directorate of Surveys and Mapping
CFDRS	Canadian Fire Danger Rating System
DEM	Digital Elevation Model
DWAF	Department of Water Affairs and Forestry
ENPAT	Environmental Potential Atlas
FEWS NET	Famine Early Warning System Network
FIG	International Federation of Surveyors
FROS	Forward Rate of Spread
GFMC	Global Fire Monitoring Centre
GIS	Geographic Information Systems
KNP	Kruger National Park
MODIS	Moderate Resolution Imaging Spectro-radiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalised Difference Vegetation Index
NDWI	Normalised Difference Water Index
NSIF	National Spatial Information Framework
SANBI	South African National Biodiversity Institute
SANFDRS	South African National Fire Danger Rating System
SAWS	South Africa Weather Services
SRTM	Shuttle Radar Topography Mission
USNFDRS	United States National Fire Danger Rating System
VCA	Veld Condition Assessment

1 INTRODUCTION

1.1 Background

Fire is regarded as a driver of the ecosystem and a shaper of the landscape. Ecological studies have found that fire is essential for removing unwanted or overgrown vegetation in order to expose the ground and allow for re-growth of new healthy vegetation. For this and other reasons fire is considered to be very important in the study of the ecosystems and nature conservation. On the other hand fire poses a great risk to life, property and the environment if improper management practices are implemented (Kruger et al, 2006). In order to avoid fire management turning into a hazardous exercise and in order to apply the proper regulation of the ecosystem, the most effective fire management policies are continuously sought (Govender, 2003).

Wildfires are a worldwide problem and are not unique to any specific country or continent. Most wildfires are experienced along the equatorial and tropical regions, with Africa being one of the most wildfire prone regions (Govender, 2003; Trollope and Trollope, 2004; Chuvieco et al, 2008). As a result, this has lead to worldwide academic research into systems that can be used for modelling wildfires in order to aid fire management. With this view in mind, scientific tools including GIS tools have been developed to help conservation managers in their quest for appropriate fire management techniques. These tools do not claim to provide solutions to fire management problems but rather they provide a platform on which fire management methods can be tested and visualised.

Different locations around the world exhibit different vegetations types depending on their climatic conditions; hence they experience different types of fires that have different characteristics. As a result, fire models may be specific to certain vegetation and climatic conditions[1] (Skidmore, 2002). Consequently this leads to the need for development of fire models that are effective for the South African context, which is the main motivation behind this research.

[1] The behaviour of wildland fires and modelling approaches are discussed in more detail in chapter 3.

The Kruger National Park is one of the conservation areas that experiences high fire activity in South Africa. The fire activity experienced in the Kruger National Park is a result of fire management activity as well as wild, unintentional fires.

The Kruger National Park is located in the northern part of South Africa between latitudes 23°S and 26°S and longitudes 30˚E and 32˚E, in the provinces of Mpumalanga and Limpopo. The park was established in 1926 and it covers approximately two million hectares (1 948 528 ha), with elevation ranging between 260m to 839m above sea level (Van Wilgen et al., 2000). The vegetation type found in this region is Savanna grasses and trees, which are also found in almost half of the African continent (Govender, 2003). Most rainfall is experienced in the summer months. On average the rainfall pattern in the Kruger national park can be explained by extended wet and dry periods. The rainfall pattern has an effect on the fire regime of the park and most fires occur during the dry winter season (Van Wilgen et al, 2000; Govender, 2003).

Due to its size and the availability of fire data records, the Kruger National park is selected as the case study on which the methods that are developed will be tested.

1.2 Brief history of Fire Modelling

Most notable work in fire modelling dates back to the work of Byram 1959, and Rothermel 1972. Byram developed mathematical equations for calculation of fire intensity. Rothermel, a researcher at the United States department of Agriculture, developed mathematical equations that can be used to predict the behaviour of wildfires. These mathematical models were designed in order to aid decision making by fire management and predict possible risk relating to fire management activities. This was before the advent of computers and these models were implemented by the use of charts and graphs and as time progressed they were programmed into special calculators that are used by fire managers (Rothermel, 1972; Gould, 2005).

In the last two decades, as the use of computers became standard, these fire models were written into computer programs and the results of these models could be printed out on paper. The spatial component of fire modelling was not implemented until recently as computers in the early days did not have that enhanced graphical display capability.

1.3 Previous Work

Fire models have evolved with the increase in the capability of computers. Geographical Information Systems (GIS) have contributed to the evolution of fire modelling as a result of the ability of GIS to provide spatial representation and visualisation (Skidmore, 2002). Some fire modelling systems still use the traditional methods of performing fire behaviour calculations separately and then transferring the results to a GIS package to view the results with respect to the area in which the calculations were made. More recently, modelling efforts have been sought where GIS plays a more vital role by performing the required calculations and then displaying the results. The historic and current role of GIS in fire modelling is discussed in more detail in chapter 2, along with issues relating to integration of GIS and environmental modelling.

A number of GIS based fire models exist and Chapter 3 provides a detailed review of these models and the different methods and techniques used to model wildfire behaviour and simulate the spread of fire. Although there are many developed fire models, none has been found in literature, that models both the risk of fire occurring (hence risk quantification by the fire danger index), as well as modelling the spread of fire (Perry, 1998; Pastor et al., 2003). Developing a fire model that accounts for the fire behaviour, risk associated with wildfires and also simulates the spread of a fire in case of an ignition incident is considered to be imperative for complete "full integration" of fire modelling in GIS.

Following a review of existing fire spread models, another shortfall of current fire modelling methods has been identified. Most models only account for the forward spread of fire, in the direction of the prevailing wind, without considering the fact that fires are not necessarily restricted to spreading in the forward direction only. This is the reason why the current study accounts for spread of fire in all directions with respect to prevailing wind direction. This is discussed in more detail in chapter 4.

1.4 Initial Hypothesis

The hypothesis tested in this study is that GIS is vital for predictive fire modelling. A fire model can successfully be developed and executed within a GIS environment hence illustrating the notion of fully embedded coupling of GIS and environmental models (through a predictive fire model) which is further discussed in chapter 2.

1.5 Research Methods and Objectives

1.5.1 Research objectives

The main objective of this thesis is to develop a predictive, wind and fuel driven, surface fire model for heterogeneous, Savanna ecosystems. The fire model developed in this study is fully integrated within the ArcGIS environment and accounts for both modelling the behaviour of wildfires experienced by the Savanna ecosystems, as well as modelling the spread of such fires.

The objectives of this study can be outlined as follows:

- Development of fire behaviour model
- Development of fire spread model
- Validation and verification of results of both models
- Visualisation of simulation results

1.5.2 Research steps

Step 1: research the use of GIS in environmental modelling.

Step 2: research the characteristics and behaviour of wildfires.

Step 3: research approaches to fire modelling

Step 4: research fire spread modelling approaches

Step 5: develop an ArcGIS based fire model application using cellular automata

Step 6: validate and verify the results of the model

Step 7: present results

1.5.3 Research Methods

1.5.3.1 Review of wildfire behaviour

The main focus of this research is the use of GIS in fire modelling through the development of a fire model, which requires full understanding of wildfires. Consequently a review of the behaviour of wildfire as outlined by fire ecology studies is the first step in this research. This review follows the work of internationally and locally acclaimed fire ecology researchers and outlines the characteristics of wildfires and the factors that influence this behaviour.

1.5.3.2 Development of wildfire behaviour model

Following a review of wildfires, the most important parameters that explain the behaviour of wildfires, from which quantification of risk as a result of fire can be deduced, as well as those that explain the spreading ability of a fire are identified, these are fire intensity and fire rate of spread[2] respectively. Various equations have been formulated from fire ecology research, hence a decision is made on which of these are most suitable for implementation in a GIS environment, with emphasis on the ability to demonstrate spatial heterogeneity. Hence the implementation of the fire behaviour model follows

1.5.3.3 Development of fire spread model

The development and implementation of this fire spread model follows a review of existing fire propagation models and GIS approaches used. Existing fire spread models are based on either physical heat transfer, logical rules that are based on conditions that influence fire without inferring any mathematical relationships amongst them, or probability of fire spread also based on factors that affect fire (Perry, 1998;Pastor et al., 2003). GIS approaches to fire spread are based on either grid or vector formats. A review of these methods is provided in chapter 3. Following this review the problems with existing models and the theoretical methods on which they are based are identified.

The algorithm defined by the current model improves on the identified shortfall of previous models by integrating existing methods and introducing new methods. The fire behaviour model discussed above forms the basis of the fire spread model developed in this study. This spread model implements grid based calculations and vector format based display, hence exploring the grid and vector aspects of GIS. This model is based on the Cellular automata modelling approach and incorporates calculations of fire rate of spread, physical heat transfer calculations, and logical rules to govern the spread of fire. The selection of Cellular automata for fire modelling is made because it is the most functional method with regards to GIS as spatial analysis in GIS is performed on grid based operations.

1.5.3.4 Model validation and verification

Test fire data acquired from the Kruger National Park and MODIS satellite images are use to verify the results obtained from the model. The Qualitative analysis of the model is performed by similarity analysis; this is described in chapter 7.

[2] Fire intensity and rate of spread are discussed in chapter 3 along with the behaviour of wildfires.

1.6 Scope of Research and limitations

The aim of this research is to develop a fully integrated fire model within a GIS environment, which predicts the risk of fire occurrence in Savanna ecosystems using MODIS satellite imagery and ground data for verification. The model investigates prediction for fires with burning periods ranging from a few hours to a few days (two to three days). MODIS satellite imagery is used due to its high temporal resolution as opposed to other satellite imagery; this is further discussed in chapter 6.

1.6.1 Expected results

The results of this study are required to be as follows:

- High level of accurate prediction of the fire intensity and measurement quantification of the fire danger index
- To correctly predict the spread of a fire and account for the full spread of fire
- To illustrate the progression of a fire event with respect to time at high level of accuracy

1.6.2 Assumptions about data

The fire model developed is tested using data from fire management experiments that were carried out in the Kruger National Park as well as some other fires that took place in the area and were documented.

Validation of the model is done by comparing the recorded burn scars provided by the Kruger National Park from ground observations, as well as visible scars from the MODIS Aqua and Terra satellite images. The assumption is thus made that these two sources of control data are accurate.

1.6.3 Limitations

Availability of weather data, and unlimited and discernible previous fire records is a major limitation of this study, as it limits extensive robust verification of the accuracy of the model.

- **Weather data**

  Weather data is available in point form from only three weather stations within the study area. In order to obtain prevailing weather conditions, at the time of a fire, interpolation of available data between the three weather stations is performed. This leads to inaccurate results, in terms of the actual prevailing conditions at the time of the fire.

- **Fire records**
  Although records of the start locations of fires are available, not many of them can be used because in most cases the support data that explains the behaviour of the fire, such as the prevalent rate of spread and fire intensity at the time the fire started are not known. The records of fire intensity and rate of spread at time of fire are required for validation of the corresponding values calculated within the model. The unavailability of these recorded values limits the amount of test fires that can be used to verify the model results.

- **Satellite imagery**
  The efforts to acquire satellite images of high spectral resolution and high temporal resolution were unsuccessful. A decision had to be made on whether it is important to acquire images with high spectral resolution or high temporal resolution. Due to the dynamic nature of fires, high temporal resolution satellite images are preferable for analysis purposes and high spectral resolution images are used for background display purposes only.

1.7 Contribution to knowledge

Most existing fire models are either fire behaviour models or fire spread models. The fire spread models depend on calculations of fire behaviour variables such as the rate of spread of fire. Since these are not calculated internally by the fire spread models, they are acquired externally. This defeats the purpose of a fully integrated (embedded) model as some calculated data needs to be imported from another model. The model presented in this study calculates fire behaviour variables, including those that are required by the fire spread model such as the rate of spread of fire; hence no transfer of data from an external model is required. The model developed in this study accounts for the spread of fire in all possible directions, hence it accounts for the "backward" spread of fire (that component of fire spread which is opposite to the direction of the prevailing wind direction).

The results of the fire behaviour model is a fire risk index with a fire classification level, which shows the risk level with respect to the areas making it possible to identify areas that are most prone to fire occurrence at a particular time.

This fire behaviour model can also be used as a decision support tool. In the event of a fire occurrence fire managers are able to identify the direction in which the fire is spreading and also identify the infrastructure at risk.

The findings of this research will help fire managers to make better informed decisions, for example, the allocation of resources to areas based on the fire risk levels predicted and placement of fire breaks. In the event of a fire, the managers will be able to better plan the response to the event. For example, they will be able to deduce the best evacuation route, which roads to use and where to get water to extinguish the fire. It can also be used in the planning of prescribed burns to simulate and visualise the resultant spread of fire under different simulation conditions.

1.8 Outline of Thesis

Chapter one: Introduction

The current chapter provides an overview of the research conducted. The reasons why the research is conducted and the objectives of the study are presented and finally an outline of the thesis is provided.

Chapter two: Theory of Environmental Modelling and Integration with GIS

This chapter discusses the principles of environmental modelling (EM). The complexity of the environment is presented and the reasons why environmental models need to be modelled are provided. The process followed in modelling environmental processes and the role of Geographic Information systems in EM is presented.

Chapter three: Principles of Fire Modelling

This chapter begins with a discussion of wildfires as environmental systems. Secondly, fire ecology concepts that describe wildfires, such as the causes of wildfires, the different types of wildfires and the factors that influence their behaviour are described. Thirdly, the two types of wild fires models, namely fire behaviour models and fire spread models are presented.

These are followed by the discussion of the methods used to develop fire behaviour models. Finally, the approaches used to model simulations of fire spread including cellular automata are described.

Chapter four: Conceptual design of the fire models

The theoretical concepts and the method that is used to model fire behaviour are presented first. Secondly, the fire spread model is described.

Chapter five: Design of fully integrated model within ArcGIS

The technical model design aspects of the research are discussed. The steps followed in model development and design, are thoroughly outlined.

Chapter Six: Data Acquisition and preparation

Data that is required for fire modelling is presented. The possible data vendors from which this data can be acquired, the metadata, and the accuracy at which this data is available are also discussed. Data accuracy and the reliability of data sources and data vendors with compliance with the Spatial Data Infrastructure Act (No. 54 of 2003) of South Africa are discussed.

Chapter seven: Analysis of Results

The results obtain from the fire behaviour model and the fire spread simulation model are analysed and presented.

Chapter eight: Conclusions

This chapter discusses the findings and conclusions about the research as well any limitations that hampered achieving greater accuracy of results.

Chapter nine: Recommendations

The recommendations to improve the work presented in this thesis are detailed.

2 PRINCIPLES OF ENVIRONMENTAL MODELLING

The purpose of this chapter is to provide a description of the process of building environmental models. In order to build a successful model, one has to understand the concepts of model development. This chapter discusses the principles of environmental modelling. First, a broad description of what a scientific model entails is provided. The following sections discuss the purposes of building models and the types of models that can be developed. Finally, a description of the techniques used to model environmental processes is provided.

As mentioned in chapter one, the purpose of this study is to investigate the use Geographical Information Systems (GIS) coupled with environmental modelling (EM) techniques to develop fire models. As a result the issue of integrating GIS and Environmental modelling techniques (otherwise commonly referred to as coupling) is also discussed in this chapter.

2.1 The complexity of the environment and the need for modelling

Before explaining the principles of modelling, it is important to understand the system that is being modelled in order to understand why the system requires to be modelled. This also helps to decide which type of modelling is best suited for the system.

A system, in simple terms, is an entity that consists of a variety of elements and is described by the relationship between these elements. The complexity of a system is defined by the relationships between its components. Consequently, a complex system is one that can be broken down into smaller sub systems which in turn can also be broken down until the simplest form is acquired (Clarke et al, 2002). Based on the facts presented above, the entire environment is considered to be a complex system.

The natural environmental processes consist of inter-connections and interaction between various phenomena on and below the surface of the earth. These phenomena are not completely understood thus also leading to the complication of environmental processes. Wainwright and Mulligan (2004) concur with the simplified definition of a system that states that the complexity of a system is defined by the interconnection of the parts that make the whole. They improve on this definition by stating that the complexity of a system is determined by the amount of information that can be used to describe it.

The complexity explained above can further be substantiated by the illustration in Figure 2-1. In this diagram, the enclosed environment is represented by dashed lines to show that only a sample of the earth's environmental processes are included.

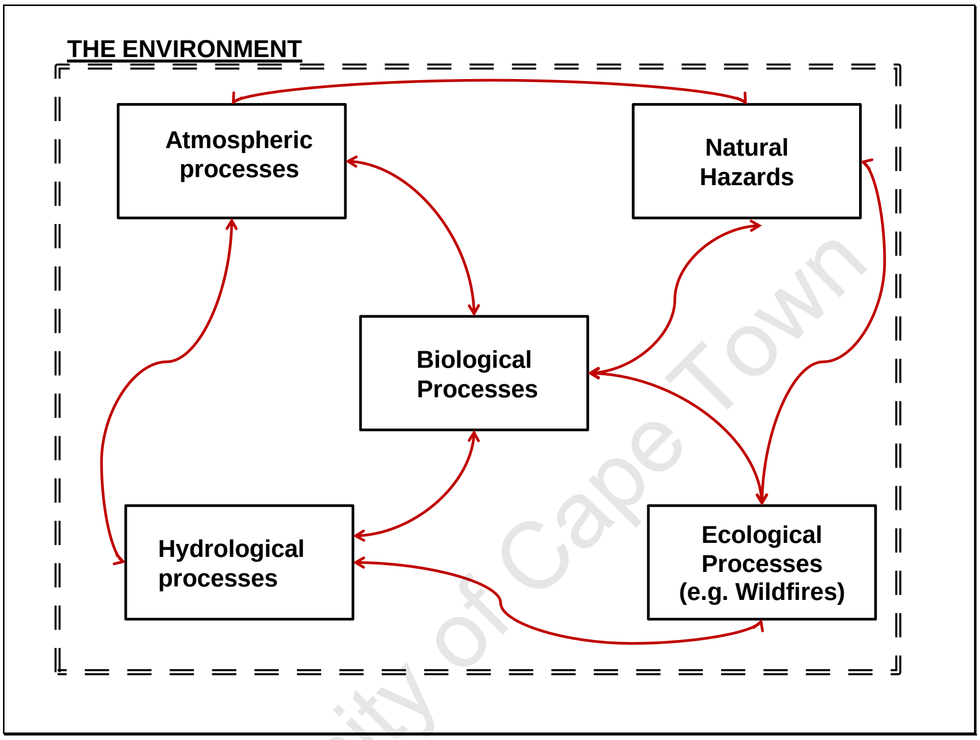


Figure 2-1 An illustration of the earth's environment as a complex system showing part of the complex environmental processes and subsystems (inspired by Wainwright and Mulligan, 2004)

The components of the environment shown above are also complex systems because they can also be broken down into sub systems, which can also be described by other simpler elements. A typical example that is relevant to this study is that of ecological processes. Wildfires contribute to ecological process because they have an effect that drives the behaviour of an ecosystem; these fires can also cause natural hazards if not properly managed as mentioned in chapter 1 and further discussed in detail in chapter 3. Consequently, this relationship between the ecological processes and natural hazards is shown by the linking arrows. Wildfires also have sub systems that control their behaviour as will be discussed in chapter 3.

2.2 Characteristics of environmental systems

According to Rizzoli and Young (1997), apart from the complexity that is discussed above environmental systems have other characteristics in common; a selection of the most important of these characteristics is discussed below.

- **Dynamic**

  Environmental systems are dynamic, which means their processes occur over duration of time, and they evolve over this duration. A typical example is a natural hazard such as an earthquake, which occurs over a finite time frame. Another example from observation, that is more relevant to this study, is wildfires which burn for a limited period of time. The occurrence of wildfires during certain times of the year is also not consistent, meaning that there may be more fires in dry seasons opposed to rainy seasons. The behaviour of a wildfire may also change throughout its duration (Trollope et al, 2002).

- **Spatial coverage**

  Environmental processes occur in space whether on the earth's surface, above or within the surface. Atmospheric processes such as cloud formation usually occur above the surface of the earth. Ecological processes and hydrological processes such as wildfires and runoff of water respectively, occur on the surface of the earth.

- **Heterogeneity**

  The surface or medium within which environmental processes occur is not always consistent and continuous. Two examples are provided to illustrate this. In surface water runoff measurements, the surface does not always have the same slope, and in the case of wildfires the vegetation though which the fire burns is not always continuous.

Following discussions in sections 2.1 and 2.2 above, any of the sub systems of the environment are complex systems hence they require simplification, which is attained through modelling processes. The issues pertaining to modelling environmental systems are thus discussed in the following sections.

2.3 Model definition

A model is defined as an abstraction of reality (Wainwright and Mulligan, 2004), that can be used to analyse past events, define present events and make inferences about the future (Clarke et al, 2002). According to Brimicombe (2003), a model is also defined as a simplification of real life events. A model is considered to be good if it uses only a few parameters, is easy to understand and can be used with ease. In a model, only the factors that are easy to measure and are perceived to be most influential in solving the problem, by the modeller, are included (Wainwright and Mulligan, 2004). As a result, there can be a number of models for one phenomenon that take into account different factors but yet all still produce good results.

Emphasis is placed on the models ability to produce “good” or “reasonable” as opposed to “perfect” results. This is because since a model is merely a simplified representation of the environment, and the fact that it only considers certain factors based on the modeller’s discretion of what factors are important, it is not possible or even expected to present entirely accurate results (Lopes et al, 2002;Brimicombe, 2003).

2.4 Purpose of building models

Scientific models are built with a definite purpose in mind, which will vary depending on the application domain and purpose of the model. A number of researchers have made publications relating to the purposes of building models (Rizzoli and Young, 1997; Wainwright and Mulligan, 2004). However these are all subsets of those purposes of scientific models published by Chorley and Hargett (1967) and reiterated by Brimicombe (2003). These purposes are discussed below:

- A model can be used as a device that allows for the visualisation and interpretation of the interactions of complex processes.
- It can also be used to describe the mechanisms and workings of a phenomenon.
- Models can also be built when comparisons between different situations or processes need to be analysed.

- They can also be built for the purpose of automating data management. These models simplify the collection, manipulation and storage of large datasets.

- The most common reason for building models is model development in support of specific scientific theories. A model can be built to explore new theories; to support, test and validate an existing theory; to extend existing theory; and for prediction as a result of one or more theories. Wainwright and Mulligan (2004) further support this purpose as the most important reason for model development. They emphasise the importance of model development in order to understand the phenomenon being modelled. Models are also used as simulation tools. Through simulation the user is able to make better inferences about the behaviour of the event being modelled.

The extent to which a model is effective can only be established once the purpose of a model has been identified (Brimicombe, 2003).

2.5 Basic structure of models

A model comprises of different types of (input) components. These (inputs) components can be variables, constants or parameters. A variable is a value in the model that changes without restraint from any other components such as space and time. A parameter is a value that is constant only in a specific case in the model; it changes from case to case or from model step to another. A constant is a value that remains unchanged throughout all the model processes (Wainwright and Mulligan, 2004).

2.6 Classification of models

A number of different model classifications have been identified in the literature. Environmental modelling is very broad and the classifications described below are not necessarily applicable to all cases. The most relevant classification identified is that of Brimicombe (2003) following Chorley and Hargett (1967). Brimicombe identifies four different types of models; these are natural analogues, hardware models, mathematical models and computational models. This classification coincides with Wainwright and Mulligan (2004), although they identify only two classes being physical (same as Brimicombe's hardware) models and mathematical models.

- **Natural analogues**

  Analogue models are models that refer to an incident that occurred in the past in order to represent the phenomena being modelled. Analogue models are not usually made for analysis purposes, but they are made in order to give a general idea of the behaviour of a phenomenon. They are often descriptive models and can use diagrams and maps for further descriptions.

  Natural analogue models are classified as historical analogues and spatial analogues. Historical analogues refer to the case where a past event is used to model or give inference about the present. Spatial analogues refer to models where events in a certain place are used to describe situations in another place.

  An example of analogue models is the work of Cannon (2007), where he used values of weather elements in a weather station to make inference of values that can be found in other neighbouring weather stations.

- **Hardware models**

  Hardware models are referred to as physical models in some texts. Physical models refer to tangible models that are built out of materials similar to those of the feature that is being modelled. The purpose of these models is usually to study the general behaviour of the feature being model, its reaction to certain conditions, and the resultant changes that it undergoes.

  An example of a hardware model that is relevant to this study is illustrated below in Figure 2-2. This is a constructed hardware model of a fire that is conducted in an enclosed space, which simulates the actual behaviour of wildfires. This model tests the response of fire on specific vegetation to conditions that imitate the external environment in which this vegetation is found.

Figure 2-2 A hardware model of an enclosed wildfire, which is used to analyse the behaviour of wildfires (Gould, 2005)

- **Mathematical models**

  Mathematical models, as the name suggests, refer to the case where mathematical equations, functions or statistics are used to describe the state or rate of change of environmental phenomenon with respect to a number of variable parameters.

  The further classification of these mathematical models is also subjective and there is no generally renowned classification, hence a number of different classifications exist. However the most common classification depicts mathematical models as empirical, conceptual or physical models (Wainwright and Mulligan, 2004). The physical mathematical models should not be mistaken for physical hardware models. Mathematical models are more common than physical hardware models; this is based on the fact that hardware models require a lot more cost to maintain compared to mathematical models.

  A relevant example of a mathematical model, to this study, is a calculation used to determine the rate at which a burning fire would spread. The equation which is given below (see equation 2-1) calculates the rate at which a fire spread based on the parameters that influence the spreading of a fire. This equation will be explained in more detail in chapter 4.

$$I = H \times w \times r \qquad \textbf{2-1}$$

The classification of mathematical models will be discussed in more detail at a later stage with respect to fire modelling instead of environmental modelling because as already mentioned, environmental models are diverse and classifications do not necessarily apply to all kinds of models. In line with this research, the classification of mathematical models is explained with reference to fire models in chapter 3.

- **Computational models**

  These are models that employ the use of a computer to manipulate data using computer code or a pre-existing computer program to determine the function or state of a phenomenon. Computational models may use some aspects of mathematical models especially the deterministic and stochastic subtypes, hence are often confused as such. Apart from mathematical subtypes computational models employ Boolean operators, logical operators and set operators, to mention a few. Although they may be loosely based on their mathematical counterparts, computational models are generally less accurate and less strict about their functions. Mathematical models are more so because they are based on strict mathematical rules and only use equations and functions that have been or can be proven mathematically. The advantage of computational models over their mathematical counterparts is that they offer a sense of practicality and their results can be visualised directly. To further clarify the difference between the two types of models, computers can be used for mathematical models although they can function without a computer. Computer models on the other hand can neither be constructed nor function without a computer.

  Computational models are often built to describe dynamic processes. These models often include visualisation of results over time or changing state of a parameter that is being studied.

Selection of the type of model that one decides to use depends primarily on two issues. Firstly the type of model is chosen depending on what the model that is being built will be used for, and secondly on the depth of knowledge that the developer has about the phenomenon to be modelled. Time constraints, availability of data and the type of existing models for that same task also have an impact on the choice of model (Brimicombe, 2003).

Mathematical models and computational models are the most common types of models that are used for fire modelling hence they will be discussed in more detail in sections and chapters that follow.

2.7 Stages of mathematical modelling

Wainwright and Mulligan (2004) quoted Cross and Mascardini (1985) on the stages followed when constructing mathematical models, Clarke et al (2002) and many more researchers also outline these stages. As a result the stages of mathematical modelling as assembled from the works of various researchers are outlined below:

- **Identification of the problem**

  This involves identifying the problem that the model addresses or the phenomena to be modelled, and specifying the goals that should be achieved from the modelling process. The expected outcome and the accuracy at which the model results are required are also addressed at this stage.

- **Gestation period**

  This period includes breaking down the problem identified above into smaller components that can be solved one at a time. Once the problem has been identified the information on how to solve the problem is collected and important aspects of the literature are identified.

- **Model building**

  The model building stage involves the development of necessary equations to solve the different segments of the identified problem. This may at times involve the use of pre existing equations. The testing and verification of the model sections is also carried out.

It is also important to specify the scale, as well as the area to which the model will be applicable. Since a model is only an abstraction of reality, during the modelling process, it is not likely to account for all processes of the system being modelled; therefore assumptions need to be made. In most cases the assumptions made are not entirely correct or they are factors that have not been verified, however this is tolerable only if their incorrectness does not affect the reliability of the model in question. Consequently, assumptions need to be made with extra caution. An example to illustrate this is, when a parameter is considered to be constant because its variability does not have a significant effect on the results of the model. Hence these assumptions must be clearly stated and documented, and the model must only be used for the purpose for which it was developed (Clarke et al, 2002).

Before building a model a decision on which parameters (inputs) to use in the model must be made. The reliability of a model does not entirely depend on the number of parameters defined. Models with few parameters can lead to results with the same degree of accuracy as models with more parameters. This may be attributed to the fact that model parameters are correlated with each other; therefore the inclusion of such parameters is not necessary if they do not improve the accuracy of the model (Wainwright and Mulligan, 2004).

Although there can be defined stages in the development of a model it is a recurring and interdependent process. Each stage depends on the success of the previous stage (Clarke et al, 2002). The illustration that follows below provides a summary of the model development process:

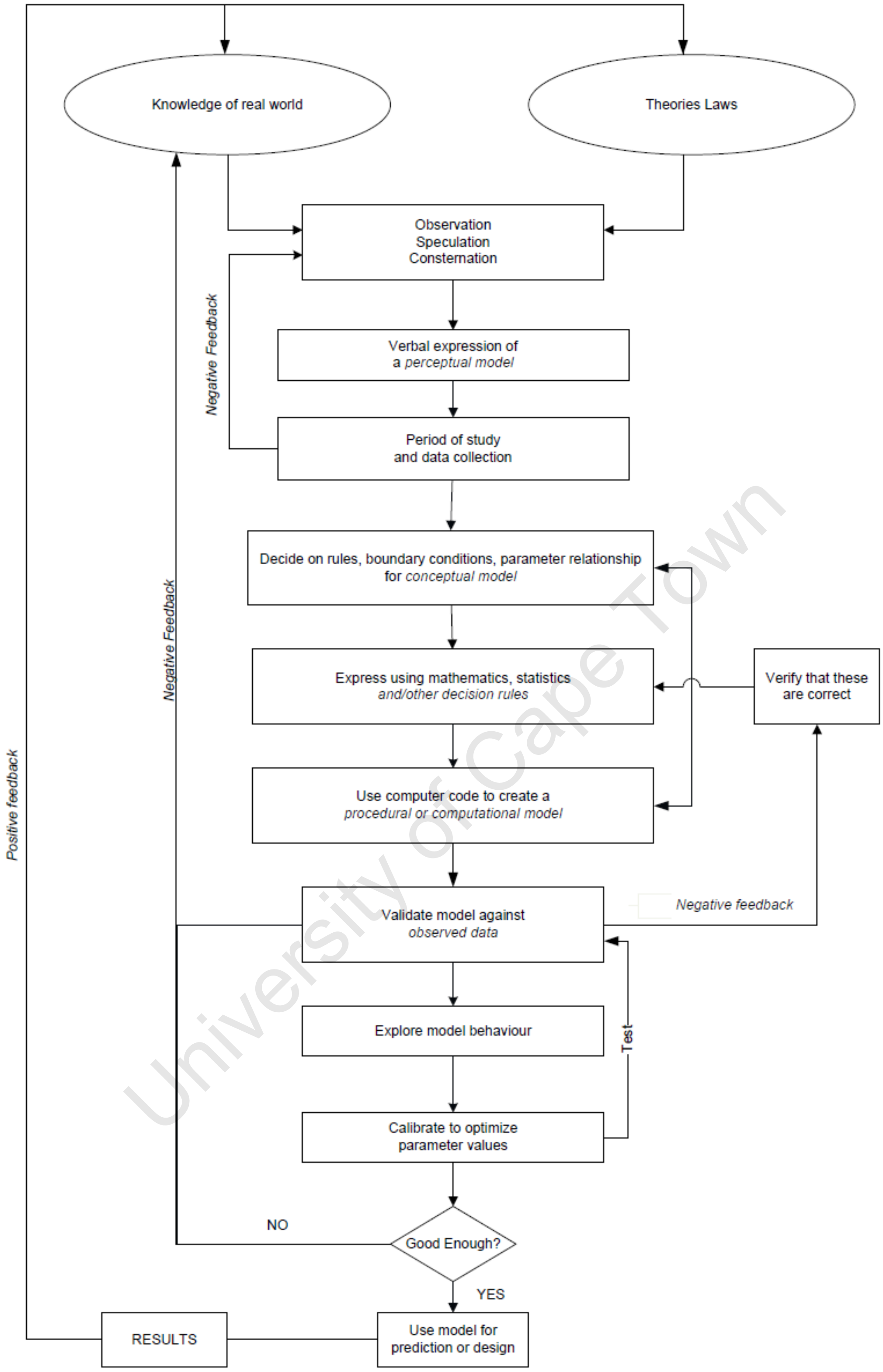


Figure 2-3 Illustration of modelling process (Brimicombe, 2003)

2.8 Integration of Environmental models with GIS

Environmental modelling can be used to define any aspect of the earth's environment. Example application areas of environmental modelling are Atmospheric systems, hydrological processes, biological and ecological systems (Clarke et al, 2002). Environmental models cover various scales, use large amounts of data from different sources and are spatial in nature hence the integration with GIS (Clarke et al, 2002; Fallahi et al, 2008).

Environmental models seek to present representations of the earth's processes. These models deal with the ever changing states of environmental systems and the change in quantity of the parameters with respect to time, therefore they are dynamic in nature (Brimicombe, 2003).

2.8.1 The early role of GIS in Environmental modelling

The primary function of a GIS is the ability to handle large amounts of data. The general definition of GIS states that amongst other functions, these systems can be used for storage, manipulation and visualisation of data.

During the early 1990s the role of GIS in environmental modelling was only considered as aiding tools in pre-processing, post-processing of data and visualisation of results from models (Karimi and Houston, 1996). GIS were considered to be fairly static and unable to represent the ever changing states of environmental phenomena. The most common use GIS was to aid in representing relationships between different phenomena and showing the location and distribution of these phenomena (Brimicombe, 2003).

A generally accepted fact was that environmental models lack a spatial representation component even though they represent system of the earth's environment that are spatial in nature. It was thus agreed that GIS complement environmental models by their ability to demonstrate the spatial distribution of phenomena. As a result, these two technologies complement each other; hence GIS have a role to play in environmental modelling. In order to apply a spatial component to environmental models data must be acquired and this is usually from different data sources. GIS helps in bringing this data to a common spatial reference for analysis, manipulation and visualisation (Skidmore, 2002).

Different approaches to integrating environmental models with GIS were bought forward by various researchers (Fedra, 1993; McDonnel, 1996; Karimi and Houston, 1996; Brandmeyer and Karimi, 2000; Mitasova and Mitas, 2002 as quoted by Yassemi et al, 2008; Sui and Maggio, 1999 as quoted by Brimicombe, 2003). All these approaches can be generalised following Brimicombe (2003) and are discussed below, an illustration of the different ways of integrating these two technologies is also provided in Figure 2-4:

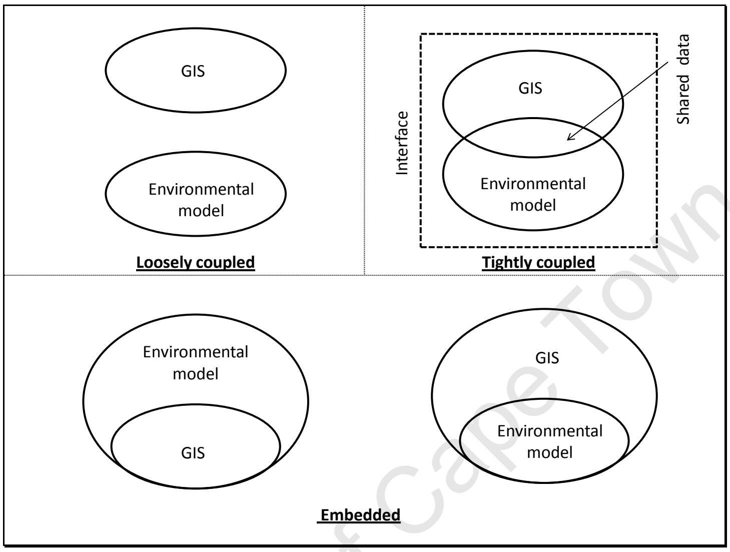


Figure 2-4 Levels of integration between GIS and environmental models (Brimicombe, 2003)

- **Independent**

  This corresponds to Nyerges' (1992) isolated coupling, which refers to cases where GIS and environmental modelling are used to perform different duties towards a common goal, without any interaction.

- **Loose coupling**

  In this case the GIS and the environmental model share data files. One of the main tasks of the GIS in loose coupling is using it as a database manager for storage of data. Another example is taking data from an environmental model into a GIS for visualisation purposes. The result is an export/ import of data relationship between the two systems (Karimi and Houston, 1996; Brimicombe, 2003). Figure 2-5, which is adapted from Karimi and Houston (1996), provides a demonstration of the interaction between GIS and environmental models as it occurs in loosely coupled systems. In this case GIS is used to facilitate the storage of input and output data that is used by, and produced by the environmental model.

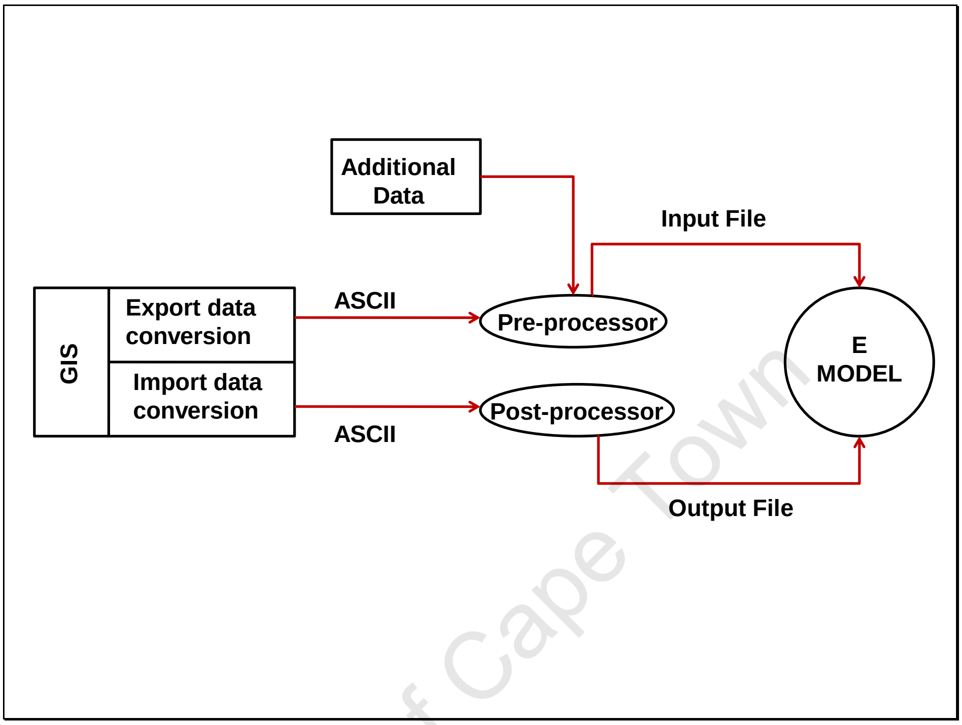


Figure 2-5 An illustration of the structure of loosely coupled systems (following Karimi and Houston, 1996)

Although loose coupling can be performed irrespective of type of software (for example, ArcGIS, Idrisi or any of the open source GIS software packages can be used), it has some disadvantages. The main disadvantage is that this type of integration slows down the modelling process which is often required to be fast. In some cases the results are required in real time, which is thus not possible through loose coupling. Loose coupling is thus deemed to be the lowest level of integration (Karimi and Houston, 1996).

- **Tight coupling**

  This encompasses data coupling and GUI coupling levels of integration as described by Brandmeyer and Karimi (2000). Tight coupling is the case where GIS and environmental modelling functions can be accessed through a common interface. Usually the GIS and environmental model share data files, and if different the two systems require different data formats, there exists a file management system that converts data to the format required to enable file sharing. Tight coupling in summary encompasses the functionality that is found in loosely coupled systems but has the additional function of providing this under a common user interface. Interaction with the GIS and the environmental model is attained through one interface and the data is stored in a central location as illustrated in Figure 2-6 below, which is a modification of the structure of loosely coupled systems.

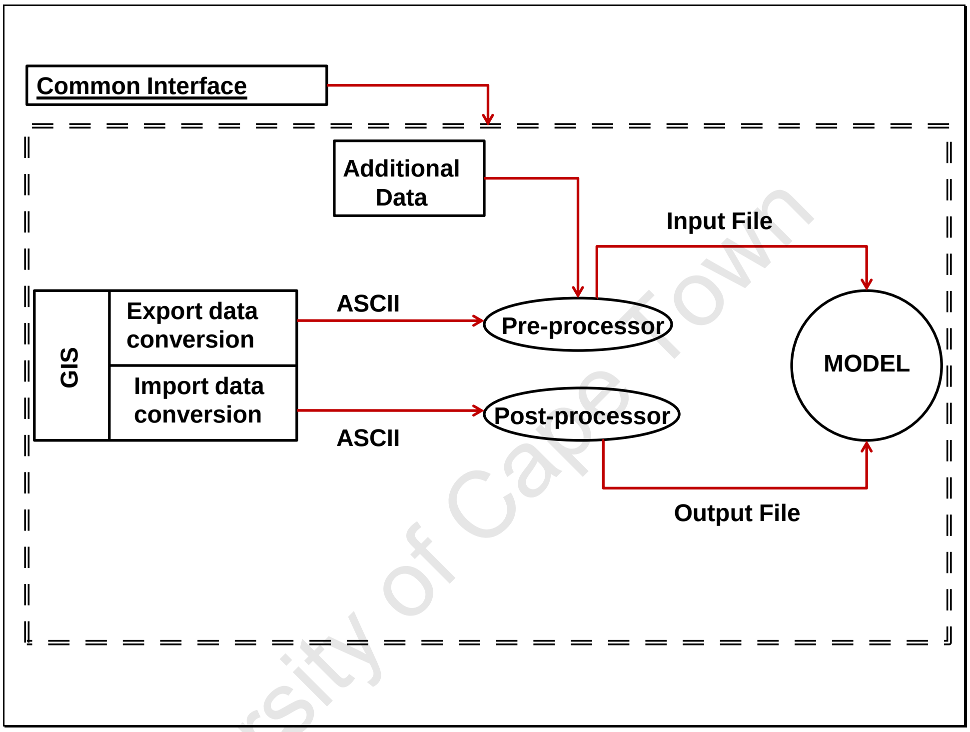


Figure 2-6 The tightly coupled system where the user interacts with both systems through one interface and data is stored in one location (modified from (Karimi and Houston, 1996))

- **Embedded (full integration)**

  Embedded coupling is often considered to be the same as tight coupling; however this is not the case. Embedded coupling refers to cases where environmental models are built-in a GIS or GIS functionality is available in environmental modelling systems. In the 1990s, this was achieved through programming macro languages and scripting languages that exist within software. An example of embedded coupling is a GIS system which has an environmental model that is programmed and executes within the GIS (Brimicombe, 2003).

Embedded coupling was perceived to be a better form of integration compared to loose coupling and tight coupling in terms of fast data transfer and providing a higher level of integration; it was however still found to have some flaws. The macro languages provided with GIS software packages were not sufficient to represent complex model algorithms and iterative processes, as they have limited programming capabilities (Karimi and Houston, 1996).

The role of GIS in environmental modelling has however changed with the advent of improved programming capabilities within GIS software. This is discussed in the following sections.

2.8.2 Integration of GIS and Environmental models in recent years

The current decade has seen the growth of the capabilities of computer systems in terms of speed of processing and their storage capacity. This development has resulted in renewed capability of GIS software.

A recommendation was made during the 1990's by Brandmeyer and Karimi (2000) regarding the improvement of tight coupling of GIS and environmental models. They suggested that the programming capabilities built in GIS software need to be improved to allow developers to be able to program in different languages. Most of the recommendations regarding what functionality modellers would want to see implemented in GIS to enable tight coupling, were in line with improvement of programming languages within GIS, as this exhibited the most shortfall. These recommendations together with the rising power of computer systems lead to the rise of geocomputation in order to enable tight coupling of GIS and environmental models.

2.8.2.1 Geocomputation

In general terms, Geocomputation refers to the use of computer based approaches to address problems in the geosciences, be it physical or human geography. This term that was established in the late 1990's but became most popular in the current decade (Openshaw, 1998). Geocomputation takes advantage of high powered computer systems to perform spatial data analysis, dynamic modelling, visualisation and simulation (Camara and Monteiro, 2001).

Geocomputation involves more than the basic functionality of GIS such as pre- processing, post processing and visualisation of data (Longely et al 1998 as quoted by Openshaw, 1998).This involves extending GIS capability and functionality using, among others, Artificial intelligence, fuzzy logic and dynamic modelling tools such as Cellular Automata. These tools can be embedded and integrated with existing GIS systems. These additional tools require the use of scientific theories to represent environmental processes in a modelling environment, thus providing additional functionality to existing GIS tools and methods in the form of plug-ins. These can also be employed in the creation of completely new modelling and analysis methods (Openshaw, 1998; Camara and Monteiro, 2001).

Opportunities to revisit old geographical problems that seemed not to be feasible initially and those to develop more intensive models that have just become of interest are provided by geocomputation.

In environmental modelling terms, geo-computation refers to the use of spatial computation tools to build environmental models (Brimicombe, 2003). The use of geo-computation in environmental modelling has led to the development of powerful models and is quickly replacing the use of traditional analytical model building because it has allowed for the building of more complex, larger and more integrated models (Clarke et al, 2002). The rise and success of the geo-computation paradigm can be attributed to the ever improving quality of computers in terms of processing power and speed and the affordability of such computer systems (Brimicombe, 2003). In other terms computation or computer simulation is viewed as a final stage in building environmental models, however a strong argument has been provided above to demonstrate that it is in fact a computational approach that can be used on its own supported by scientific knowledge.

2.9 Discussion

The basic principles of modelling have been discussed in this chapter. The steps followed during the modelling process have been explained. Most significant to this study, the importance of GIS with respect to environmental modelling has been demonstrated.

Tight coupling with the aid of geocomputation has been identified to be the more preferred coupling method as they offer the highest level of integration between GIS and environmental modelling (Karimi and Houston, 1996). This option provides fast transfer of data between the GIS and the environmental model as well as providing developers with the ability to improve the functionality of these models by enabling programming with the most common languages such as C++, Visual Basic (.NET), C#. This also enables integrating even those models that have the most complex algorithms in addition to performing iterations to represent the dynamic nature of environmental models. It has been explained that geocomputation models require the functionality that is found in mathematical models to effectively represent and model environmental systems. As a result, mathematical models through geocomputation have been selected as the most relevant methods for fire modelling.

It has also been described that with added functionality of current GIS software, GIS now forms part of a workflow which can be dynamic in nature and may integrate models which are based on real-time input, hence increasing the importance of GIS in environmental modelling.

The following chapter discusses fire modelling as a division of environmental modelling. The principles of environmental modelling are discussed with particular application in fire modelling and geo-computational techniques that enable fire modelling are also reviewed.

3 FIRE MODELLING

The previous chapter presented a description of environmental systems and the reasons why such systems require modelling. This chapter presents fire modelling as a branch of environmental modelling and the issues pertaining to fire modelling are thus discussed. First a definition of wildfires is provided and the types of wildfires are described. This is followed by a discussion of the behaviour of wildfires including the factors that influence the behaviour and spread of wildfires. Finally, the application of GIS based techniques used to predict and model the spread of wildfires is presented. In conclusion to this chapter a summary that highlights the aspects of fire behaviour and the spread of wildfires that are important to this study is presented.

3.1 The basic behaviour of wildfires

The basic behaviour of wildfires is reviewed in this study to answer questions such as, what is a wildfire; what causes wildfires; what factors accelerate the spread of wildfires and what is meant by fire risk. This information is vital to the design of fire spread models and is used accordingly as is discussed in the following chapters.

3.1.1 Definition of a wildfire

A number of definitions can be found for wildfires. Two of these many definitions are presented below:

The Global Fire Monitoring Centre (GFMC) define a wildfire as “any unplanned and uncontrolled wild land fire, which, regardless of ignition source may require suppression[3], response, or other action according to agency policy” (Chuvieco and Mills, 2003).

The Table Mountain National Park (TMNP) fire management provides another definition which states that a wildfire is a fire that is burning out of control in wild vegetation or a plantation, which originates unintentionally either through natural causes or by human negligence (Forsyth and Bridgett, 2004).

[3] Suppression is the ability to subdue or reduce the intensity of a wildfire (Kennard and Fowler, 2008)

3.1.2 Causes of a wildfire

The TMNP fire management's definition of a wildfire describes the causes of wildfires as either natural or by human interference; this view is supported by most wildfire literature. Although the causes of wildfires may vary from one geographical region, which experiences the same fire behaviour conditions, to another, the most common causes are either natural causes or human induced. Human induced fires are those that result from human negligence or arson; these are often referred to as anthropogenic sources of fire. The most common natural cause of wildfires is lightning (Chuvieco and Mills, 2003;Forsyth and Bridgett, 2004).

3.1.3 Factors that influence the spread of wildfires

Fire spread refers to the movement or transmission of a fire front[4] from the source location to neighbouring locations. This movement occurs through the transfer of heat energy between fuel patches as a result of one or more heat transfer mechanisms namely; convection, radiation and conduction (Burgan and Rothermel, 1984;Ntaimo et al, 2008).

3.1.3.1 Vegetation

Vegetation provides fuel for the wildfires, where fuel refers to the material that is burned or consumed by a fire. In order to establish whether vegetation will provide the fire with sufficient fuel, an analysis of the type of vegetation, the vegetation health, and vegetation moisture content is conducted (Skidmore, 2002).

The type of vegetation is assessed because some vegetation types are more susceptible to burning than others. Type of vegetation together with the density at which this vegetation occurs is also considered because in some cases, although the vegetation may be highly combustible, it may not occur in enough quantities to start a wildfire of a size that can cause a considerable threat (Mansor et al., 2004).

The moisture available in vegetation is assessed because vegetation provides best fire fuel when dry, although it may burn when it is not completely dry (Verbesselt et al., 2006; Dasgupta et al., 2007). Moist vegetation has a smothering effect on fire. The water vapour released by the moist vegetation reduces the oxygen in the air that is required to sustain the burning process (Trollope et al, 2002).

[4] A fire front refers to the flaming part leading the fire in the direction in which the fire is moving (Kennard and Fowler, 2008)

Another factor that is indirectly related to fuel is land use. In a case where arable land, set aside for agricultural purposes, is left unattended, weeds which are often ignored can grow on such land resulting in unsolicited fuels. If left unattended for long periods, these weeds can dry out resulting in fire fuel, which can cause a wildfire when ignited (Vazquez and Moreno, 2001).

Wildfire spreads uniformly in homogenous vegetation types and inconsistently in non-homogenous vegetation (Ntaimo et al, 2008).

3.1.3.2 Topography

The most important elements of topography to the spread of wildfires are slope and aspect. Both elements have a direct linear relationship to wildfires. It has been proven that fires spread faster on steep slopes than on flat areas. The slopes increase the chances of pre-heating fuels ahead of the fire front as a result of convection[5], and this eventually leads to those fuels reaching the required temperature for ignition; hence the fire spreads faster (Mansor et al., 2004).

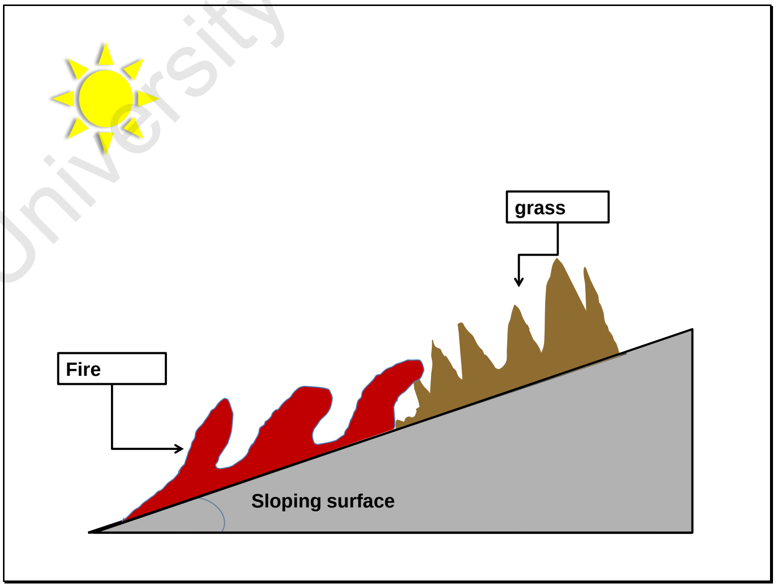


Figure 3-1 A cross section showing the behaviour of fire on sloping ground

[5] Convective heat transfer is the transfer of heat energy from one place to another (from a hotter place to a cooler place) facilitated by the movement of air or fluids (Cutnell and Johnson, 2001).

Figure 3-2 An illustration of an actual fire burning on a slope, courtesy of (Forsyth and Bridgett, 2004)

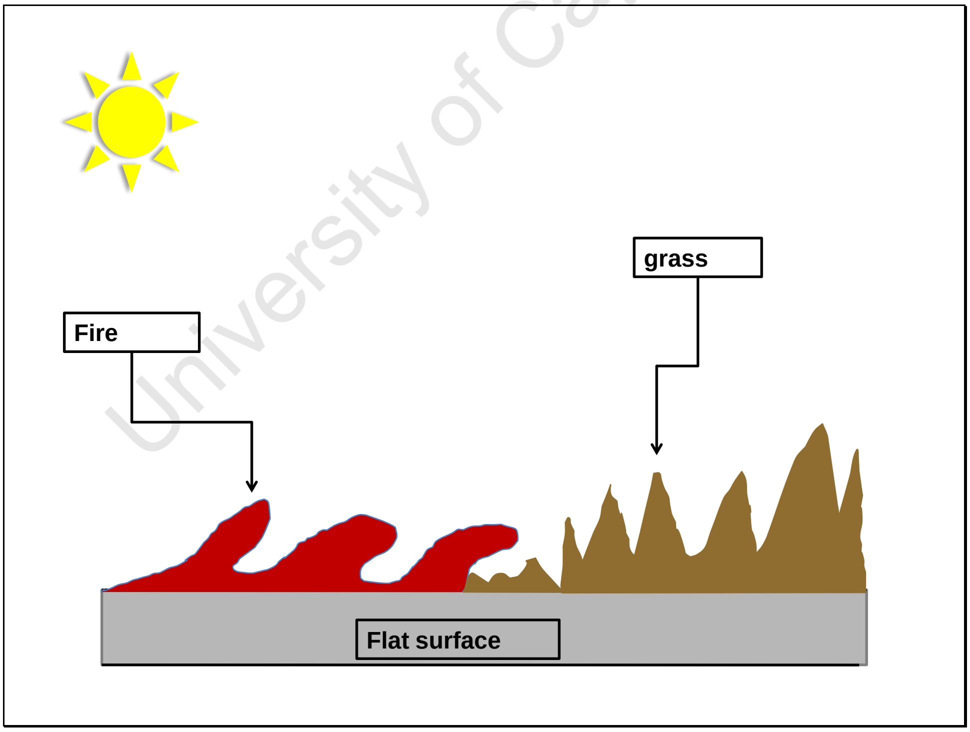


Figure 3-3 A cross section showing the behaviour of fire on a flat surface

Aspect is defined as the direction in which a land surface is facing, and it can also be described as the direction of the slope. Vegetation that grows on slopes facing the direction of the sunlight are heated faster and thus dry out faster, which results in the vegetation igniting much more easily (Skidmore, 2002;Mansor et al., 2004;Chuvieco and Congalton, 1989). In some instances, aspect leads to the faster production and growth of vegetation. This case is often observed in vegetation that grows on slopes that on average receive plenty of sunlight throughout the day; this sunlight stimulates the growth processes of vegetation. After optimum growth, the moisture content of this vegetation eventually decreases to a point that it becomes fuel for wildfire (Ntaimo et al, 2008).

3.1.3.3 Weather

Wind speed, wind direction, relative humidity, precipitation and temperature are weather variables that are considered to be most important in relation to wildfires. The most favourable conditions for the spreading of a wildfire are: no precipitation, low or no relative humidity, high wind speeds, and high temperature (Skidmore, 2002).

Wind speed increases the rate at which wildfires spread. The effect of wind speed is almost similar to that posed by slope. High wind speeds force the fire flame to lean towards fuels in front of the fire causing them to dry out and hence be ignited much quicker than they normally would (Ntaimo et al, 2008).

Relative humidity is directly related to the moisture content of vegetation. When relative humidity is high the vegetation tends to absorb the moisture and thus exhibit high fuel moisture content which is not conducive to burning. Moisture from humidity can also settle on the vegetation hence making it to appear wet and less likely to burn easily. Temperature has an effect on the relative humidity and the moisture content of vegetation. In the South African context, when the temperature is high the vegetation loses moisture as a result of evaporation, hence making it more prone to ignition (Trollope et al, 2002).

The effect of weather variables is most dynamic compared to topography and vegetation as they may change on a daily basis or in an even shorter time frame. The effect of topography does not change at all whereas vegetation may burn out and decrease fuels; however it eventually grows back. The direct effect of the factors discussed above to wildfire spread will be discussed in more detail in section 3.4.

3.1.3.4 Secondary factors

Other secondary factors that affect the spread of wild fires include land use, roads and water features; these factors have an effect on anthropogenic fires. Roads can affect wildfires in two different ways: they can act as fire breaks depending on how wide they are and, the size and intensity of the fire. Roads also symbolise human activity which can be viewed as a threat especially in areas that are prone to manmade fires. Streams and other water bodies may be useful for fire extinguishing purposes but the most overlooked effect of water bodies is that they provide moisture to vegetation around them which reduces the chances of the vegetation to ignite (Mansor et al., 2004;Sherrill, 2002).

3.2 Wildfires as complex systems

Wildfires occur as a result of interactions among various factors such as meteorological (weather) conditions, topography, and vegetation. This chapter thus far has illustrated that wildfires are complex systems, in line with the discussion in chapter 2 about complexity of environmental systems. A complex environmental system is defined as a system that consists of interactions among its constituent parameters. The parameters that make up a complex system are also complex systems themselves in the sense that, they are not easy to understand and can be further broken down. Modelling efforts are applied to complex systems in order to understand them. Having demonstrated that wildfires are complex systems, the following sections discuss the issues pertaining to modelling wildfires. The different types of wildfires are presented as well as modelling approaches that are applied to wildfires.

3.3 Types of fire models

Pastor et al (2003) proposed a generalized classification of fire spread models. This classification of fire models is done according to the physical system being studied. The fire models are classified as surface fire spread models, crown fire models, spotting fire models and ground fire models. The classes are discussed following Pastor et al (2003) briefly in the following sub sections and an illustration is provided in Figure 3-4.

3.3.1 Ground fire models

The matter that makes up the physical system for these models comprises of organic materials that lies on the ground, which is formed by fermented material and humus that lie above the soil, including litter (Pastor et al., 2003).

3.3.2 Surface fire models

The material for surface fire models consist of small trees, fallen trees, bushes and herbaceous vegetation. These are generally fuels less than 2 meters in height (Pastor et al., 2003).

3.3.3 Crown fire models

The fuel for crown fires comprises of surface vegetation as well as taller vegetation including tall trees (Pastor et al., 2003).

3.3.4 Spotting models

The physical system of spotting models consists of fire brands including portions of burning material that are transported by wind during either a surface or crown fire. These materials are carried away from the perimeter of the burning fire and therefore start new fires relatively close to the perimeter of the fire they were transported from (Pastor et al., 2003)**.**

Rothermel (1983) identifies three factors that need to be addressed with regard to the problem of spotting. These are:

- What are the source of the fire brands
- How far will these far brands travel
- On landing, what is the probability that the fire brands will ignite and cause a fire

Again according to Rothermel (1983), there are two different types of spotting, these are short range spotting and long range spotting. Short range spotting refers to the case where particles from the fire are carried over a short distance. These particles are not certain to land a distance away from the current fire where they will start a fire that is independent from the current fire. Long range spotting on the other hand results in fire particles being transported over fairly long distances away from the main fire and they produce new fires which grow independent from the main fire, before it could reach their location.

The transportation of fire particles away from the main fire can occur in two ways (Rothermel, 1983):

- The particles can be carried and transported by strong winds and may fall in different areas from where the fire is burning resulting in a new a fire.

- Fire brands can also be carried in a fire whirl that moves out of the main fire area and may also be dropped away from the main fire depending on how heavy or how large they are.

The different types of fire discussed above are illustrated in Figure 3-4 below:

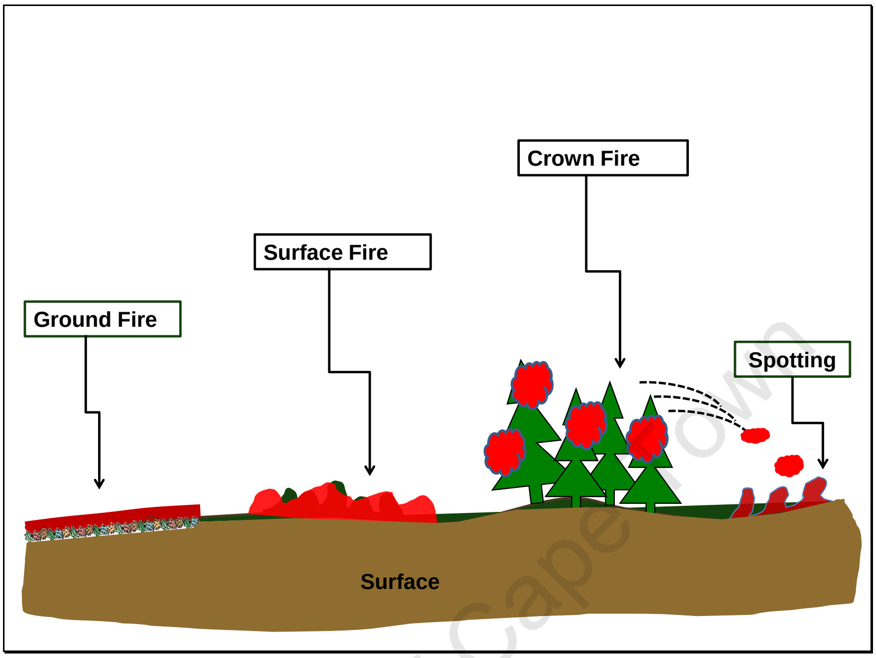


Figure 3-4 A simplified cross section illustration of the four different types of fires (adaptation of (California, 1995))

The most significant types of fire models to this study are the surface fire models and the spotting models; therefore the behavior of wildfires is discussed with relevance to these models in the following sections.

3.4 Fire behavior

Fire behaviour refers to the characteristics that a wildfire displays. The characteristics of a wildfire are influenced by factors such as the fire intensity, flame height, and rate of spread. These are the most important factors that can be used to describe the characteristics of a wildfire (Black et al., 2007). The characteristics of a wildfire are important for the modelling process.

3.4.1 Fire intensity

Fire intensity is the most important factor in modelling fire behaviour specifically because it is easy to measure (Trollope et al, 2002). Fire intensity is the amount of heat released per unit time per unit area and measures the rate at which heat is released by a fire. It can also aid in determining the difficulty of containing and control a fire.

Various ways of assessing the fire intensity exist. The most common way of determining fire intensity is presented by Byram (1959), where fire line intensity is the product of available heat and the rate of spread. For the South African Savanna context Trollope suggested and proved that fire intensity is greatly influenced by fuel load, fuel moisture, relative humidity, and wind speed (Rothermel, 1983; Trollope et al, 2002; Kennard and Fowler, 2008).

The most common measure of fire intensity is the fire line intensity which has been discussed in the previous paragraph. The forest encyclopaedia (Kennard and Fowler, 2008), gives a comprehensive list and discussion of the component fire intensities; these include reaction intensity, radiant intensity, convection intensity, and total fire intensity. The total fire intensity is the rate of heat released by the fire as a whole. It is a function of area burnt, fuel load and the heat yield of the fire.

3.4.2 Rate of spread

Rothermel (1983) described the rate of spread as the rate at which the fire front advances. Rate of spread is also described as the horizontal distance that a flame moves per unit of time. Basic estimation of the rate of fire spread can be done by noting the time it takes a flame to travel between two marked locations which are at a known distance apart.

The rate of spread of a fire is greatest in the direction in which the wind is blowing and least in the opposite direction to the wind. The flanks of the fire have a spread rate that is between the two rates already mentioned (Kennard and Fowler, 2008).

The main factors that affect the rate at which fires spread are; the wind, topographic gradient (slope), aspect, and the vegetation (also referred to as fuel) (Kennard and Fowler, 2008; Rothermel, 1972). These effects have been discussed in more detail in section 3.1.3.

3.4.3 Flame height and flame length

Flame length, denoted (L) in the diagram below, is the distance from the centre of the base of a flame to the tip of the flame. Conversely flame height (h) is the vertical distance from the ground to the tip of the flame. While the flame height is always perpendicular to the ground, the flame length may be either vertical or inclined (Kennard and Fowler, 2008).

Although they may sound the same, flame height and flame length should not be confused as they represent two different characteristics. The illustration below clearly distinguishes between flame length and flame height.

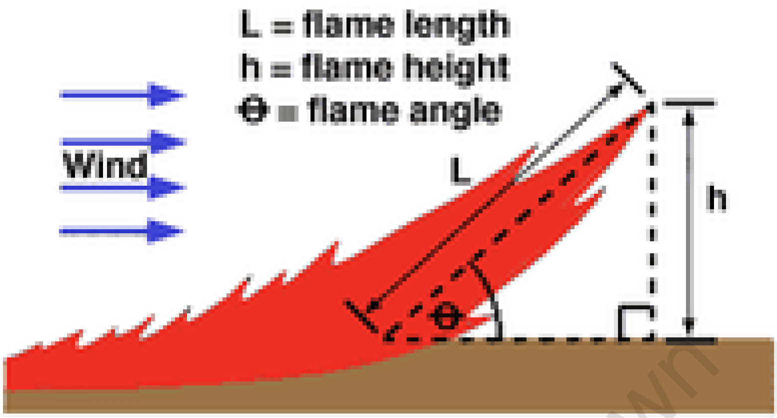


Figure 3-5 The relationship between flame length, flame height and wind (courtesy of (Kennard and Fowler, 2008))

The wind is the driving factor behind the flame length and flame height. High wind speed causes the flame to tilt more towards the fuel in front of the fire hence decreasing the flame angle (which is also illustrated in the diagram). The decrease in the angle of inclination of the flame (flame angle) causes the flame height to be reduced (Trollope et al, 2002). At very low wind speeds, no driving force is exerted on the flame causing it to tilt at an angle, hence the flame length and flame height may be the same. This effect can also be observed with fires burning on flat ground (Rothermel, 1983).

Section 3.4 only discusses the most important and most widely used fire behaviour variables. Burgan and Rothermel (1984) provide a full description and discussion of fire behaviour variables.

3.5 Wildfire danger and risk assessment

It has been mentioned that fire has a beneficial role to the survival and maintaining health and diversity for ecosystems. Fire also has a negative effect when not applied correctly or if conditions are not conducive for prescribed burning. The following section discusses the danger aspect of fire and how GIS can be used in risk assessment.

A wild fire becomes dangerous and poses risk if it burns out of control and requires immediate action. Fire danger is a measure of a combination of factors that influence ignition, rate of spread and difficulty of suppression (Gould, 2005). In summary, fire managers use the factors and fire behaviour variables discussed above to assess the fire danger, hence implement risk assessment strategies.

3.6 Fire models

Fire models are developed to further understand the behaviour of fires and to examine the influence of certain factors on wildfires. Therefore there exist two different kinds of fire models and these are: fire behaviour models, and fire spread models (Yassemi et al, 2008).

Fire behaviour models estimate the quantities of fire behaviour variables which lead to the development of wildfires, such as those mentioned in section 3.4 and others not mentioned here, such as the burning index and its components including; the energy release component, flame length, spread component and many more. A review of fire behaviour models was performed by the CSIR (Willis et al, 2001), for the department of water affairs and forestry, in preparation for the development of a fire danger rating system for South Africa. This review covers the most well defined fire behaviour models developed throughout the world; which includes systems from Canada, Australia, USA, France and others.

Fire spread models on the other hand, seek to predict the propagation of a fire in the event of ignition. These models follow the propagation of a fire front with respect to time.

3.7 Classification of Mathematical fire models

Different types of environmental models were introduced in chapter 2. However, due to the broad nature of the subject of environmental modelling, the sub classification of these models was not discussed. These will be dealt with in this chapter.

In chapter 2, the types of environmental models are introduced as hardware models, natural analogues, mathematical models, and computational models. In fire modelling literature, no clear distinction is made between mathematical models and computational models, hence the assumption will be made that fire modelling follows the notion of mathematical models and apply geo-computation instead of considering computer models as different kinds of models. Due to the hazardous nature of wildfires, physical (hardware) wildfire models are very rare and if applicable they are carried out within enclosed tightly monitored environments as illustrated in Figure 2-2. The most commonly used models in fire modelling are mathematical models; hence these will be discussed in this chapter.

Mathematical models consist of equations that take as input factors that influence the behaviour of fire such as fuel moisture or weather variables such as relative humidity to yield the numerical values of variables that explain the behaviour of wildfires such as fire intensity, rate of spread, flame length and others, that evolve with time (Pastor et al, 2003;Yassemi et al, 2008).

The classification of mathematical models is done according to the nature of their equations (Pastor et al., 2003). In most literature, mathematical fire spread models are classified into three different classes namely, stochastic models, deterministic models and probabilistic models (Glasa and Halada, 2008; Pastor et al., 2003; Yassemi et al, 2008). The different classes of mathematical models are discussed in the following subsections.

3.7.1 Stochastic models

Stochastic models are also known as empirical models. These models are based on the study of a number of fire experiments performed either in the laboratory similar to hardware models, or outdoors under known fuel, weather and topographic conditions. Statistical equations usually in the form of regression analysis are then derived following observations of these fires; and these equations are subsequently used to model the fire behaviour (Favier, 2004;Glasa and Halada, 2008).

The most appropriate example to this study is the equation for fire intensity by Trollope (2002), where the fire intensity is given as a function of environmental conditions such as fuel conditions and meteorological conditions. The equation for predicting fire intensity (FI) that resulted from the research is as follows:

$$FI = 2729 + 0.8684(x_1) - 530(x_2)^{\frac{1}{2}} - 0.907(x_3)^2 - 596(x_4)^{-1} \qquad \textbf{3-1}$$

Where: x_1 is the fuel load (kg/ha),

x_2 is percentage fuel moisture (%),

x_3 is the percentage relative humidity (%),

x_4 is the wind speed (m/s)

Another school of thought argues that for a model to be stochastic at least one of its variables needs to be derived stochastically. In this instance using equation 3-1 as an example, the relationship between the constituent variables is derived stochastically hence the fire intensity is derived empirically. It is worth mentioning that various interpretations of stochastic modelling such as the two that have been discussed above exist, however for the purpose of this study the interpretation that is adopted by majority of the fire modelling fraternity worldwide (following Pastor et al, 2003) is adopted. An internationally recognised example of such a model is the equation for rate of spread which was developed by Rothermel (1972). This equation has been referred to throughout most of fire spread literature. A brief description of this equation is provided in chapter 4, section 4.3.2.3, and a thorough discussion is provided in Rothermel and Burgan (1984).

Although useful, these models are almost always effective only in conditions for which they were created. They may need to be re-parameterised for other locations and thus must be applied with caution (Favier, 2004;Glasa and Halada, 2008). Trollope's fire intensity model has only been verified for Savanna type fuels; however Rothermel's rate of spread of a fire front has reportedly been tested extensively and has been found to be "robust and stable" (Ntaimo et al, 2008). Some texts however refer to Rothermel's equations difficulty to implement in real life terms (Higgins et al., 2008).

3.7.2 Deterministic models

Deterministic models can further be classified as physical models and semi-empirical models (Perry, 1998;Pastor et al., 2003;Glasa and Halada, 2008;Yassemi et al, 2008), and these are discussed below.

3.7.2.1 Physical Model

Physical fire spread models are based on the transfer of heat energy from burning to un-burnt area. The transfer is explained using the laws of physics governing energy transfer and combustion. Such models distinguish between the transfer of energy by radiation, convection and conduction. These models include solving systems of sophisticated differential equations over small areas and very small time intervals. As a result, they require the use of very powerful computers in terms of processing speed and storage capacity; they are also time consuming. Although they require much computation skill, they have been proven to be more accurate and effective than the empirical models (Albright and Meisner, 1999; Favier, 2004; Johnston et al, 2006; Glasa and Halada, 2008).

Since these models use defined laws of physics, they often clash with the coarse scale at which input data such as fuel and meteorological data are available, hence making them less accurate on large scales (Johnston et al, 2006).

3.7.2.2 Semi-Empirical

These models are also known as Physical-Statistical models. As the name suggest, they exhibit both the properties of physical models and statistical analysis. They use the laws of physics to model the transfer of heat energy between burning fuel and un-burnt areas. These derived physical properties are then applied to a number of experimental fires to derive statistical correlation (Albright and Meisner, 1999; Glasa and Halada, 2008).

Such models are much more easily applicable to real life situations. They are also much easier to implement compared to physical models (Glasa and Halada, 2008).

3.7.3 Probabilistic models

As the name suggests, probabilistic models are based on the probability that a fire will spread from one location to another. Unlike the types discussed above these models do not actually calculate fire behaviour characteristics and variables. In these models each of the factors that are perceived to cause fires are assigned a category and stored in contingency tables. The probabilities of when a fire will burn are derived from the high values of the parameters stored in the contingency tables. The similarities between these and stochastic models is that they are almost always effective only in area for which they were developed (Albright and Meisner, 1999).

3.8 Fire Spread Modelling Approaches

A number of different fire spread modelling techniques have been developed and they all depend on one or other of the mathematical classes discussed above. All these models fall within two general categories, namely vector models and grid based models. These approaches to fire spread modelling differ in terms of how they represent the surface of the earth or the surface being modelled and the process which describes the spread of fire (Hernandez et al., 2007;Yassemi et al, 2008).

Grid based models represent the modelled surface as a set of regular grid cells, usually square but irregular grids have also being found, whereas the vector models represent the landscape as a continuous surface (Albright and Meisner, 1999; Pastor et al, 2003; Yassemi et al, 2008). The grid based models split the landscape into grid cells that share the same characteristics. The fire propagation process is based on transition rules that govern how fire will spread from one cell to the next or by the probability that a fire will spread. The most widely used grid based models employ the use of Cellular Automata and Bond Percolation (Pastor et al, 2003; Yassemi et al, 2008); these will be explained in more detail with appropriate examples in upcoming sections.

The vector based models assume the propagation of a fire front as a polygon that grows with respect to time (Yassemi et al, 2008; Finney, 1998). The most familiar or widely used polygon to represent the growth of a fire is an ellipse. Fire spread models that apply to homogenous fuel conditions usually use a single ellipse that aggregates the growth of fire, whilst models that apply to heterogeneous fuel conditions usually use multiple ellipses that are then aggregated to produce the fire front (Finney, 1998; Yassemi et al, 2008). Most vector models use Huygens' Principle of wave propagation to model the growth of fire fronts (Finney, 1998; Hernandez Encinas et al, 2007; Yassemi et al, 2008; Pastor et al, 2003). Huygens' wave propagation will be discussed in more detail in section 3.8.1.

Vector models are more effective than grid based models in heterogeneous environments, where environmental conditions that govern the spread of fire such as meteorological conditions, fuel conditions and topology are irregular. This is a result of the fact that grid models make a generalized assumption that environmental conditions within a cell are constant, whereas in reality this is not necessarily the case (Yassemi et al, 2008). Be that as it may, grid models are more easily implemented in a GIS than vector models. This is because in order to perform calculations in most GIS packages data is required in raster format, which means that even vector based models if based on any form of calculation will need to be converted to raster format initially. These results are further processed to produce final results in vector format (Perry, 1998). This is an involved process that potentially results in loss of accuracy of results.

The following sub sections discuss the most commonly used vector based and grid based modelling methods with the aid of appropriate examples.

3.8.1 Vector based fire spread modelling

3.8.1.1 Wave propagation

The spread of vector fire fronts is usually achieved through elliptical wave propagation as discussed above. The concept of elliptical shape of fire fronts was introduced by Van Wagner in 1969, where the rate of spread of a fire and the prevailing wind speed and wind direction, at the time of the fire, are used to approximate the general shape of the fire. The semi major axis is parallel to the direction of the prevailing wind and increases in length according to the wind speed (Perry, 1998). This is illustrated in Figure 3-6.

The most common method of approximating the fire front using elliptical wave propagation follows Huygens' Principle of wave propagation. Huygens principle of wave propagation considers every point on the wave front as the source of tiny wavelets that move at the same speed as the specific location on the wave that they originate from; therefore a wave at a particular point in time gives rise to more waves at a following time instance (Cutnell and Johnson, 2001).

According to Anderson et al (1982), fire models that follow the notion that fire fronts simulate Huygens principle of wave propagation argue that a fire propagates on a continuous surface as an ellipse (this is in agreement with Van Wagner's model) with finite segments. Anderson et al (1982) further state that each vertex that joins any two segments on the fire front is a new ignition source that will in turn result in a new elliptical fire area. The aggregation of the new ellipses that develop from the new fire ignition points results in a new fire front in the subsequent time instance as illustrated in figures 3-6 and 3-7, (Pastor et al., 2003; Glasa and Halada, 2008).

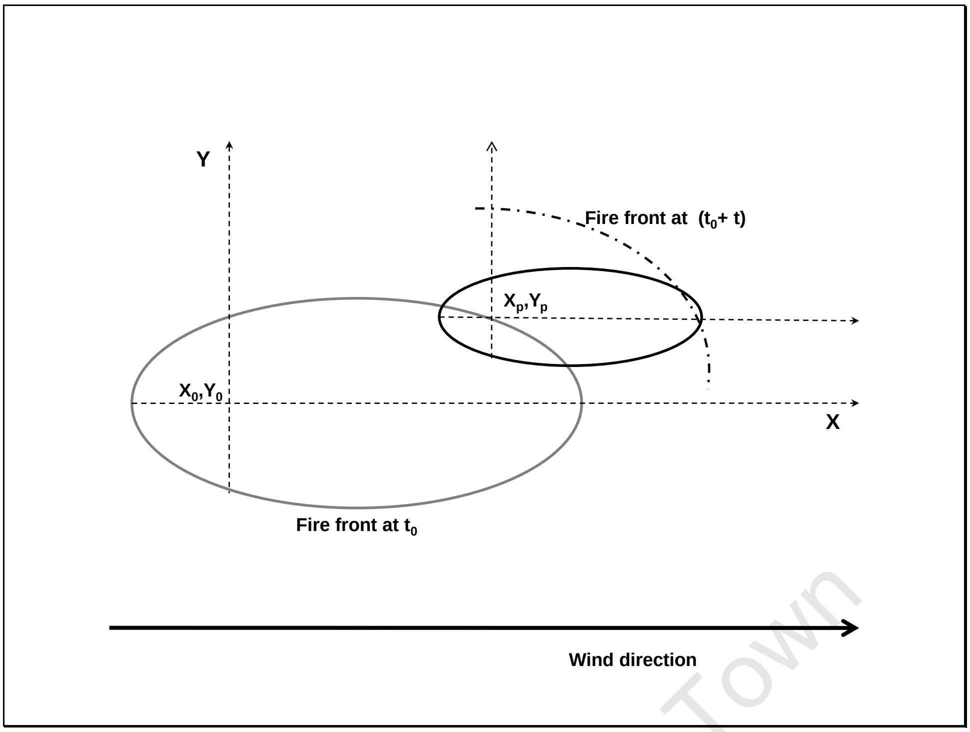


Figure 3-6 Fire front propagation in accordance with Huygens' Principle of wave propagation, showing the ignition location (X_0,Y_0) at time t_0 and one ignition location (X_p,Y_p) at next time instance (t_0+ t), along with the corresponding fire fronts. (An adaptation from (Anderson et al., 1982))

In this method, the rate of spread is calculated from local environmental conditions, following the mathematical models of fire rate of spread, whether deterministic or empirical. Similar to Van Wagner, the rate of spread that is calculated is used to determine possible locations for the fire front through time, using an elliptical shape. Although GIS raster data may be used, the final fire front is produced as an aggregated ellipse shaped vector layer (Johnston et al, 2006; Perry, 1998).

A much generalised explanation of this application of Huygens' Principle according to Anderson et al (1982) is that at a time interval t, a fire burns out a perimeter or fire front that has the shape of an ellipse. At the next time interval (which is also known as time steps), described as $(t + \Delta t)$, the new fire ellipse is an aggregation of the previous ellipses; it encompasses all the ellipses that were formed in the time step. This continues for all time steps considered (Glasa and Halada, 2008). Figure 3-7 below provides an illustration of fire propagation following Huygens' Principle of wave propagation as described by Anderson et al (1982).

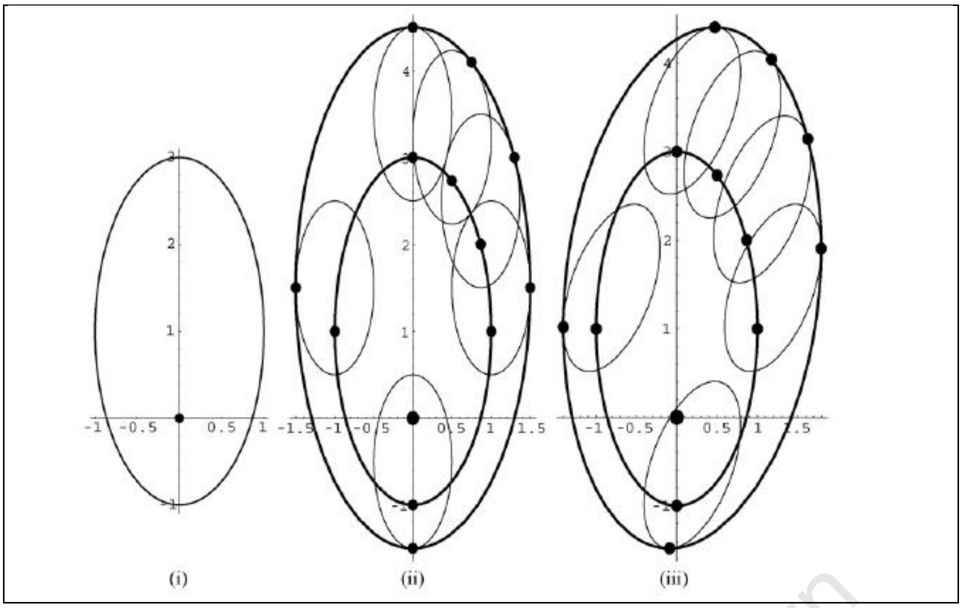


Figure 3-7 An illustration of elliptical fire propagation using Huygen's principle. Figure (i) represents the fire front at a particular time interval (t). (ii) Shows time interval, (t_0+ t); the locations on the fire front in (i) are also fire fronts which lead to the development of smaller elliptical fire areas. (iii) Shows the modification in orientation of the new fire fronts as a result of changing wind direction (Glasa and Halada, 2008)

In 1990, Richards developed a set of differential equations that depict Anderson's theory of elliptical fire front propagation. The equations developed by Richards consider the factors that accelerate the spread of fires which comprise of weather conditions, fuel conditions and topography (Albright and Meisner, 1999). The derivation of Richards' equation is beyond the scope of this study hence a brief description is provided using Figure 3-8 below.

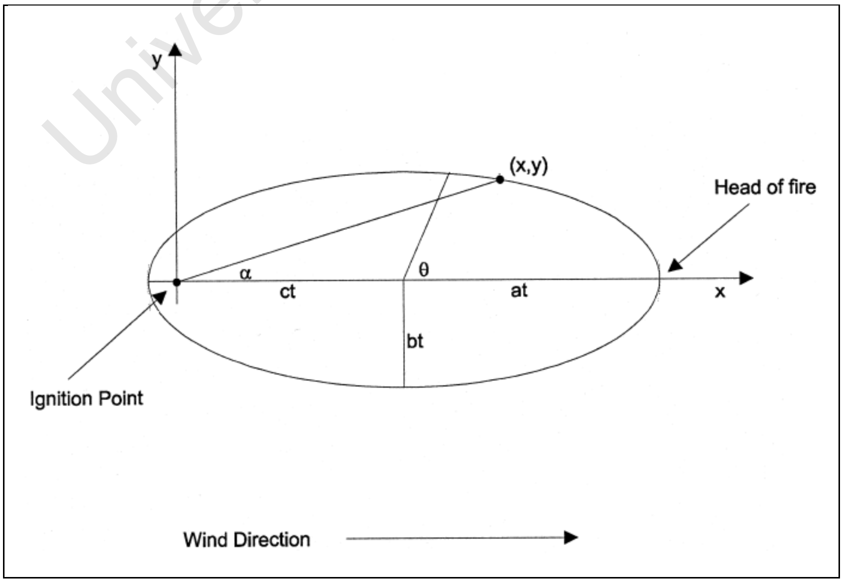


Figure 3-8 An Ellipse representing the perimeter of a fire at time (t), under uniform fire propagation conditions, where *at* and *bt* represent the semi major and semi minor axes respectively, θ is the angle subtended by a circle that encloses the ellipse and *α* is the angle subtended by the ignition point and a point *xy* on the ellipse. *ct* represents the eccentricity of the centre of the ellipse in the direction of the wind (Perry, 1998)

The equations below (equations 3-2), show a simplified method of obtaining the location of a point on the perimeter of a fire (fire front):

$$x = ct + at\cos\theta$$
$$y = ct + bt\sin\theta \quad \text{3-2}$$

An example of the application of vector fire spread modelling is provided in the section that follows.

3.8.1.2 Applications of Vector fire spread models

One well known fire vector based fire modelling environment is the Prometheus model developed in Canada, which uses the Canadian Fire Danger Rating Systems (CFDRS) as the fire behaviour model from which fire behaviour information is acquired. An example of the output of this vector based fire spread model is provided in the following illustration (Figure 3-9) below.

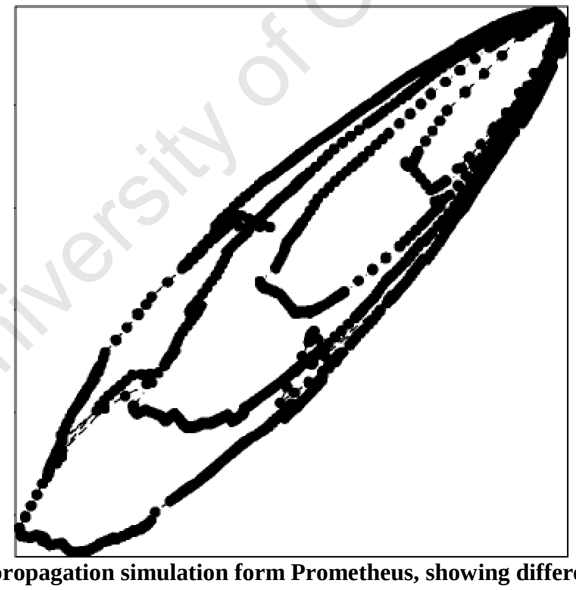


Figure 3-9 Vector based fire propagation simulation form Prometheus, showing different fire fronts at different time instances (Prometheus, 2008)

3.8.2 Grid based fire spread modelling

3.8.2.1 Bond Percolation

Bond percolation models are an example of probabilistic fire spread modelling. The landscape is represented as a grid, with the most common representations being square, hexagonal or triangular lattice of cells. These cells division are populated with information pertaining to environmental factors that affect fire spread such as weather, topography and vegetation fuel. The spread of a fire from one of these cells to another is controlled by the probability of ignition of a cell, and the probability that fire will spread to the recipient cell. These probabilities are based on the factors that are mentioned above (Pastor et al, 2003; Favier, 2004).

These types of models are better illustrated with the use of examples. A bond percolation fire spread model named EMBRY was developed for the Yellowstone National Park, Wyoming USA, by Hargrove et al (2000). This model does not calculate the rate at which a fire will spread but rather the average burn pattern that a fire produces after it has ran its course (Johnston, Milne and Klemitz, 2005). The spread of a fire is simulated on a grid surface and the probability function on which the spread is based, is a function of the individual probabilities (relating to fuel type, fuel moisture, wind speed and wind direction), that indicate that these conditions will cause a fire. The neighbourhood of each cell is defined by the eight, direct neighbour cells of the cell. The probability function is applied to the neighbouring cells and it is then determined if these cells will receive the ignition and burn depending on what state they are in, which is determined by the probability. If the cells are already assigned a state that indicates that they are burnt out, the fire will not spread to these cells and most likely the fire will cease to burn if all the neighbours of the ignition cells are burnt out. Along with the probability the spread of fire is controlled by a predefined critical value. This critical value is a function of the number of neighbours of a burning cell and the propagation rule equation that governs the spread of fire to these cells. The critical value controls whether fire will spread to a certain neighbour cell or not and is recalculated for each defined time interval within which the fire burns. If the calculated burning or ignition probability is less than the critical value then the neighbours will not be ignited and the fire will not spread. The propagation of fire takes place in time steps where a cell can burn for more than one time step only if it still has the capability to ignite other new cells (Hargrove et al., 2000).

The component of the model that defines the fuel type is derived by classifying the vegetation into fuel classes based on the vegetation found in the area and their susceptibility to burning. The relationship between the different fuel types in terms of whether they are able to ignite each other is considered. The arrangement of the vegetation is also considered, if vegetation is sparse, it is less likely to spread fire as compared to dense vegetation. The assignment of probability values is a result of observation and analysis of previous fire in the area. As a result, such a model can only be implemented at the place for which it is designed. If implemented in areas outside the study area, this should be performed with care and it should be considered if these new areas exhibit the same conditions as the area in which this model was developed. If this is not the case the model is most likely to produce results that are not of the same accuracy as it did when it was tested in the study are where it was developed (Johnston et al, 2005; Hargrove et al, 2000).

The probability function component that describes the fuel moisture is based on how long moisture will take to saturate to the diameter of the fuels and how long it will take to dry once it has been saturated (Hargrove et al, 2000).

The wind speed is viewed in terms of the strength of the wind and its effect is divided into three classes which are then converted to probability classes. A “bias” value is determined base on each of the wind speed classes and this is used to modify the probability that the fire will spread. The illustration Figure 3-10 provided below shows how the different wind classes will modify the probability that a fire will spread to the direct neighbour cells. The arrow represents the direction in which the wind is blowing and the numbers around the circles represent the bias values that are applied to modify the fire spread.

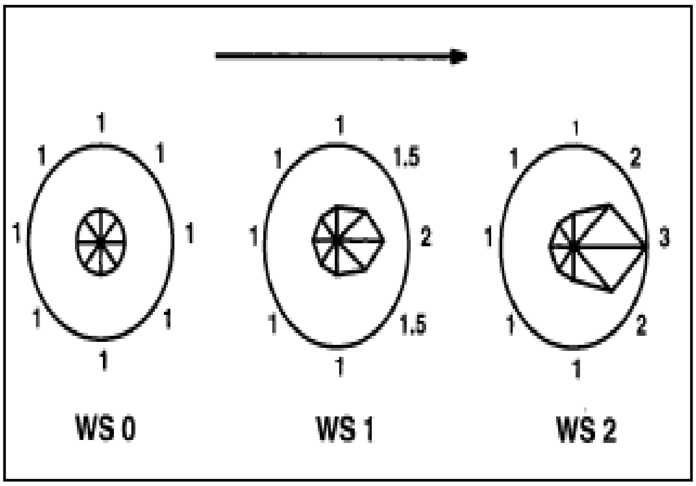


Figure 3-10 A Picture showing the effect of wind speed on the spread of fire. The first picture, (WS0), illustrates the spread pattern at low wind speed. The second, (WS1) and third (WS2), pictures illustrate the fire spread behaviour under differing strengths of the wind speed, with the latter indicating the greatest wind speeds class, in the direction of spread (Hargrove et al., 2000).

The images that follow show the results of the EMBYR fire model:

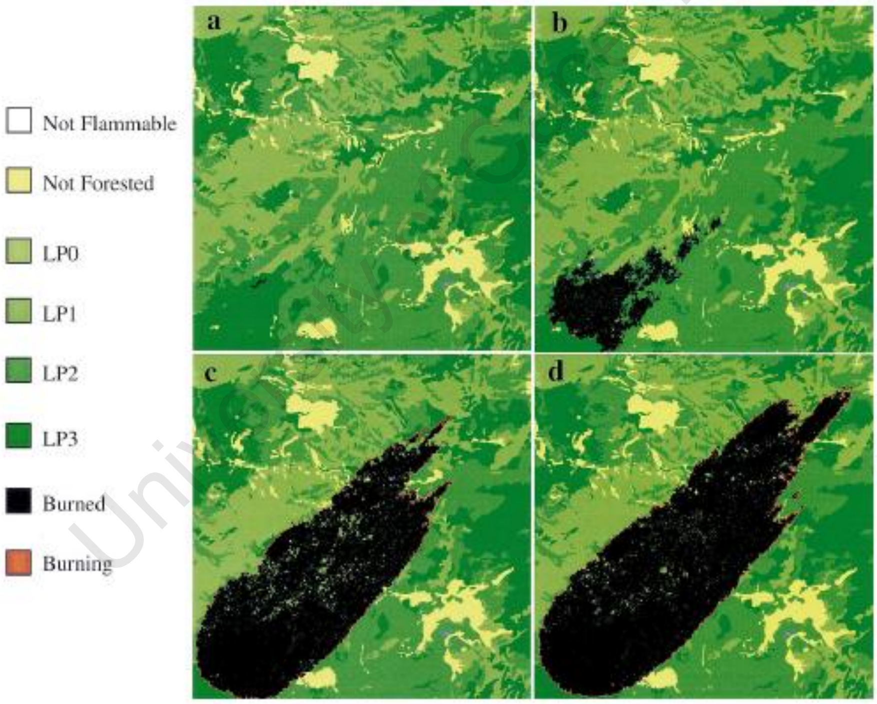


Figure 3-11 The Results of fire spread simulation under variable conditions where LP0, LP1, LP2, LP3 represent different fuel classes, successively, based on the flammability of fuels in the Yellowstone Nature Park. The images shows fire spreads under a) moist fuel conditions, b) dry weather and moderate wind speed, c) very dry weather and moderate wind speed, d) very dry weather and very strong winds (Hargrove et al, 2000).

Figure 3-11 shows the fire burn patterns under varying weather conditions. The corresponding images and conditions are as follows a) moist weather conditions, b) dry weather with moderate wind spread from the south west, c) very dry weather with moderate wind speed, d) very dry weather with strong wind speeds.

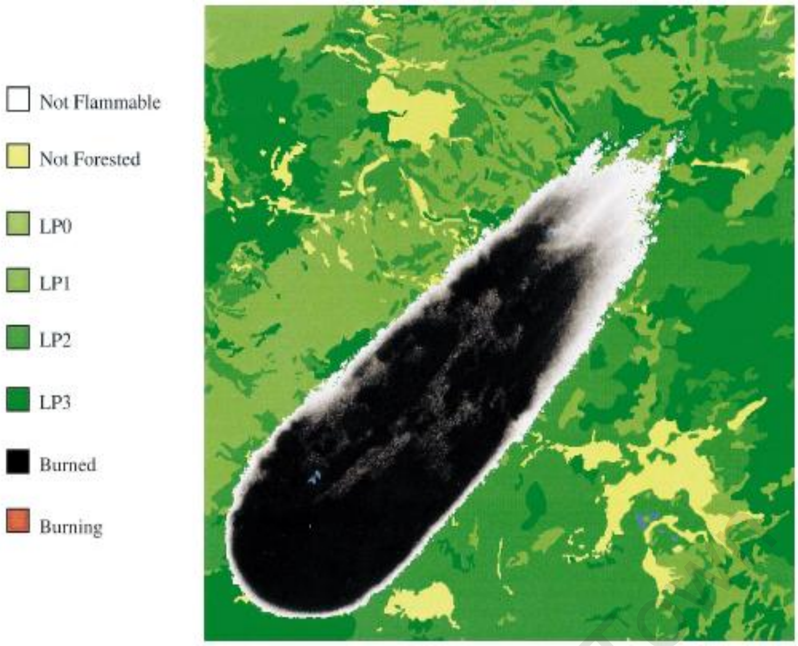


Figure 3-12 The simulated fire spread map showing the average fire burn pattern after the fire has ceased burning. The black colour represents the burn scars and the white colour represents the non flammable locations around the burn scar that lead to the cessation of the fire (Hargrove et al., 2000).

Figure 3-12 shows the average burn pattern that the fire produced while it was actively burning. The colour scale ranges from black to white, with black showing the cells that have burnt out and white showing the cells that are not flammable as a result of the conditions of fuel, weather and topography that are experienced within these cell locations. For this specific illustration, the wind is blowing from the south west. The spread of fire is shown here overlaid with the different fuel types found in the area (Hargrove et al., 2000)

Another example of the bond percolation technique can be found in Favier (2004). This method considers the spread of fire according to transfer of heat energy from burning cells to neighbouring cells that are not burned, where both ignition and combustibility are considered. Similarly to the EMBYR model discussed above topographic, meteorological and fuel conditions are considered. The difference between EMBYR and Favier's model is that the latter can be used to determine the spread of an active fire on an hourly basis or time step basis, whereas EMBYR is only used to assess the spread pattern once a fire has completely burned out (Favier, 2004). The percolation model by Favier is based on the physical behaviour of fire and was not developed for any specific region; it is thus believed to be effective on any region as long as the input parameters are available. The EMBYR model on the other hand is a stochastic model as described above.

From these discussions above, the conclusion can be drawn that the bond percolation technique of modelling fire spread can be based on physical or stochastic fire behaviour models. Bond percolation methods appear to be the least popular techniques used in fire spread modelling and simulation because they make no mathematical inference about the relationship between factors that influence the behaviour of wild fires and they have shown the least success rate (Pastor et al, 2003; Perry, 1998).

3.8.2.2 Cellular Automata

Cellular Automata (CA) is another grid based technique that is used to model the spread of fire. A typical CA consists of a lattice of cells arranged in a regular fashion, although most recently irregular cell arrangements have been developed, with the propagation of the phenomena under investigation based on a set of rules (Hogeweg, 1988;Yassemi et al, 2008). Although CA is used for modelling the spread of fire it was not developed strictly for this purpose. Cellular Automata are methods used for evolving dynamic processes that depend on discrete states. CA were developed and first introduced by Von Neumann in 1966 in order to mathematically represent complex systems, of which spatial modelling environments are part of. The spatial modelling environments that have been modelled using CA include simulations of urban growth, the spread of epidemics (Yassemi et al, 2008), the behaviour of earthquakes and landslides (Malamud and Turcotte, 2000).

The grid cells in a CA model contain information pertaining to fire behaviour variables as described in sections 3.1.3 and 3.4. Special care must be taken when choosing cells; this is in order to ensure that they represent an area that exhibits similar fire behaviour characteristics. In a CA based fire model, the spread of a fire is controlled by a set of rules that apply to all cells. The growth of a fire is represented by the change in state of a cell with respect to time. At any particular time step, the state of a cell depends on the previous state of that cell as well as the states of the neighbouring cells. The neighbourhood of a cell typically consist of the eight neighbours that are in direct contact with it as illustrated in Figure 3-13. In simple terms the propagation of a fire can be explained by a number of calculations and rules that are applied to the cell, the cell values change and this often translates to a change in state of that particular cell (Perry, 1998).

Three basic states are used to explain the response of a cell to a fire. These states are either that a cell is: not burning at all (which means the cell is not affected by fire), is burning or is burned out. These discrete states often correspond to certain values that are calculated based on the predefined propagation rules. In addition to these states some studies introduce intermediate states as they find suitable.

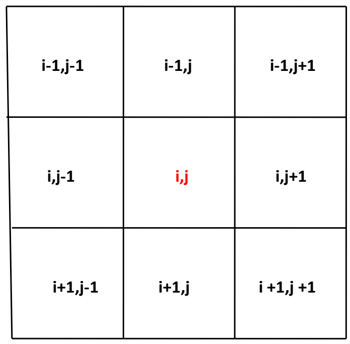


Figure 3-13 The immediate neighbourhood of centre cell (i, j)

The rules of propagation in a CA model can be based on either stochastic or deterministic models. The ability of these models to implement deterministic models most especially the physical deterministic models makes them most attractive to fire modellers as opposed to other grid based models as seen in bond percolation, section 3.8.2.1 and other methods that follow in section 3.8.3 (Perry, 1998).

To further demonstrate the use of CA for fire spread modelling, an example by Yassemi et al (2008) follows. The fire spread simulation model is based on the semi-empirical Canadian fire danger rating system (CFDRS) for fire behaviour characteristics. The neighbourhood of a fire source cell consist of the eight immediate neighbours that are connected to the cell as illustrated in Figure 3-13. The fire spreads from the neighbour cell to the central cell once the neighbour has completely burnt out. The propagation is based on the rate of spread (ROS) of fire and the direction in which the fire spreads (namely the direction of travel, denoted as RAZ) of fire (measured in degrees). These are acquired from the CFDRS's Fire behaviour prediction (FBP) system; a description of this model can be found in Willis et al (1992).

The direction in which fire can spread is restricted by means of spread channel based on the eight basic directions. The rate of spread vector is calculated using trigonometry as follows:

$$ROS_{east} = ROS \times \sin(RAZ) \qquad (3\text{-}3)$$

where 0° < RAZ < 90°

or

$$ROS_{east} = ROS \times \sin(180 - RAZ) \qquad (3\text{-}4)$$

where 90° < RAZ < 180°

The distance that a fire travels within the cell in a time step is given by:

$$\Delta x_t = ROS_{east} \times \Delta t \qquad (3\text{-}5)$$

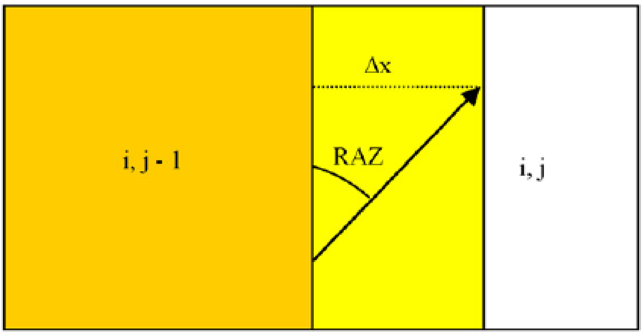
where: Δt = time in step (s)

Δx_t = distance (m)

At the end of each time step the distances that the flame is expected to cover are added up and the area burned is also calculated. The area burned is calculated using the area of a rectangle; by multiplying the distance travelled by the cell size.

Different equations are applied for different wind direction cases. The diagrams provided below in Figure 3-14 show the case where a fire is spreading from the east neighbour, and they explain the equations 3-3, 3-4 and 3-5 provided above:

a)



b)

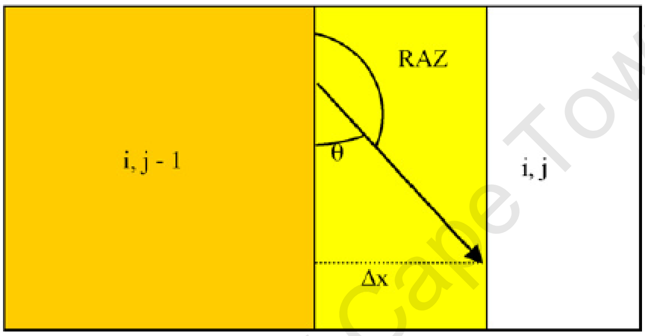


Figure 3-14 Fire spreading east for different directions a) 0 < RAZ < 90 and b) 90 < RAZ < 180 (Yassemi et al, 2008)

An example is also provided in Yassemi et al (2008) of a fire towards the northeast; all other directions follow the same logic as either one of the two cases.

Yassemi's model is selected as an example because it is one of the CA models that have been found to account for the backward rate of spread (BROS). The calculation of the backward spread is one of the outputs of the CFDR's fire behaviour model from which Yassemi's model derives. The backward spreading of fire is however calculated the same way as when the fire spreads forward. The only difference is that the direction of spread component is calculate by reversing (taking a mirror image of) the limiting angle.

This model also accounts for overlaps that occur when more than one neighbour to the burning cell, (from which the fire is spreading), are also burning. In such a model, where the distance of spread within a burning cell is considered, overlaps often leads to over prediction of the fire spread if they are not accounted for. Modifications are also made to the model to account for different wind speeds. The performance of this model was tested against the results of the Prometheus model, which is a vector based wave propagation model that is widely used in the region in which this model was evaluated (Yassemi et al, 2008). The result of the comparison is illustrated in Figure 3-15 below. The results of this model were found to be in good agreement with the simulation results obtained from the Prometheus model.

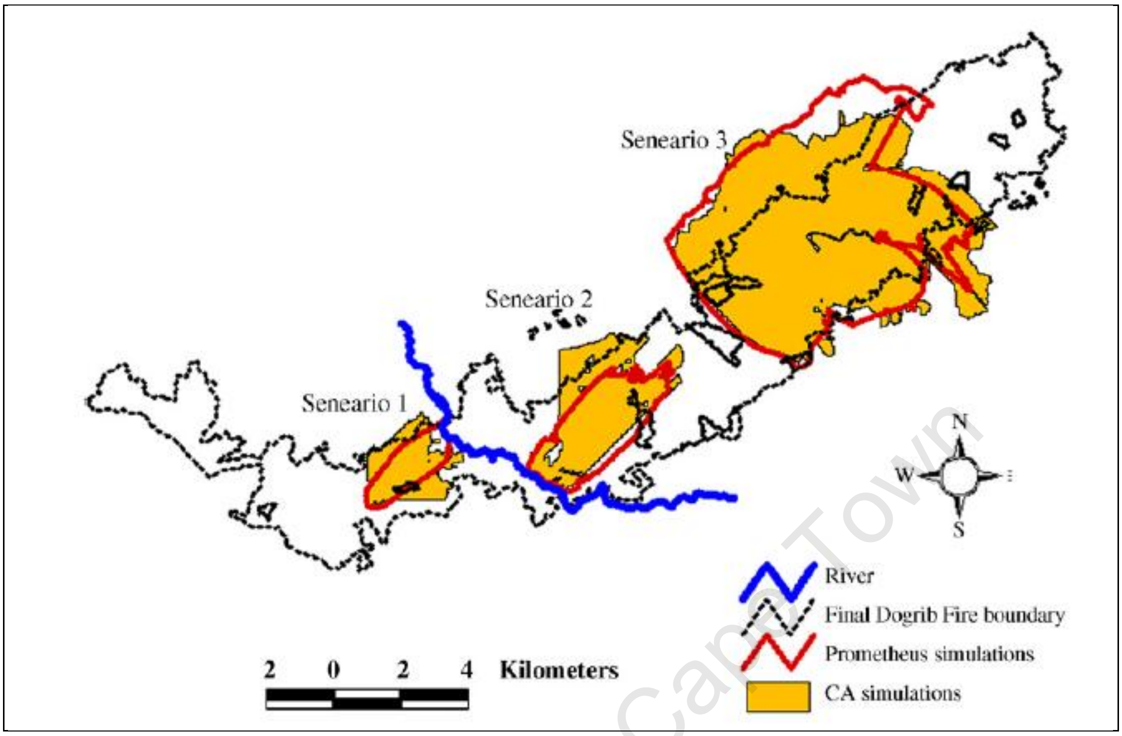


Figure 3-15 Comparison of CA simulations with Prometheus software and the actual fire perimeter (Yassemi et al, 2008). Scenario 1 shows the beginning of the fire from the ignition source until the river, overestimation of fire is evident. Scenario 2 is a new fire resulting from spotting experienced from scenario 1, again this model shows over-prediction. Scenario 3 shows spotting from scenario 2. The 2nd and 3rd scenarios show spotting that is represented as line ignitions because the model does not account for spotting.

Although the vector spread models, similar to those using the elliptical wave propagation method are more accurate than grid based models, the bond percolation and CA models are often preferred due to ease of implementation in a GIS environment. These models do produce reasonably accurate results with bond percolation showing the least accuracy.

3.8.3 Other methods

A number of fire spread technologies have been introduced more recently with the rise of geo-computation. Among these we can mention small world networks, the use of fuzzy logic and neural networks. These methods will only be discussed briefly and for more details references are made to appropriate literature.

3.8.3.1 Small world networks

Small world networks were developed as a result of the inadequacy of grid models, to consider the effects of fire behaviour characteristics beyond those of the immediate neighbour cells. Small world networks also work on a regular lattice of locations, but apart from the immediate location neighbourhood they also consider long range connections that are randomly located throughout the site.

The illustration provided in Figure 3-16 below, gives a summary of how small world networks are designed (Porterie et al., 1998). In diagram a) the connections are free and result from firebrands, whereas in b) the long range connections have been reduced by the general shape of the fire and its influence area.

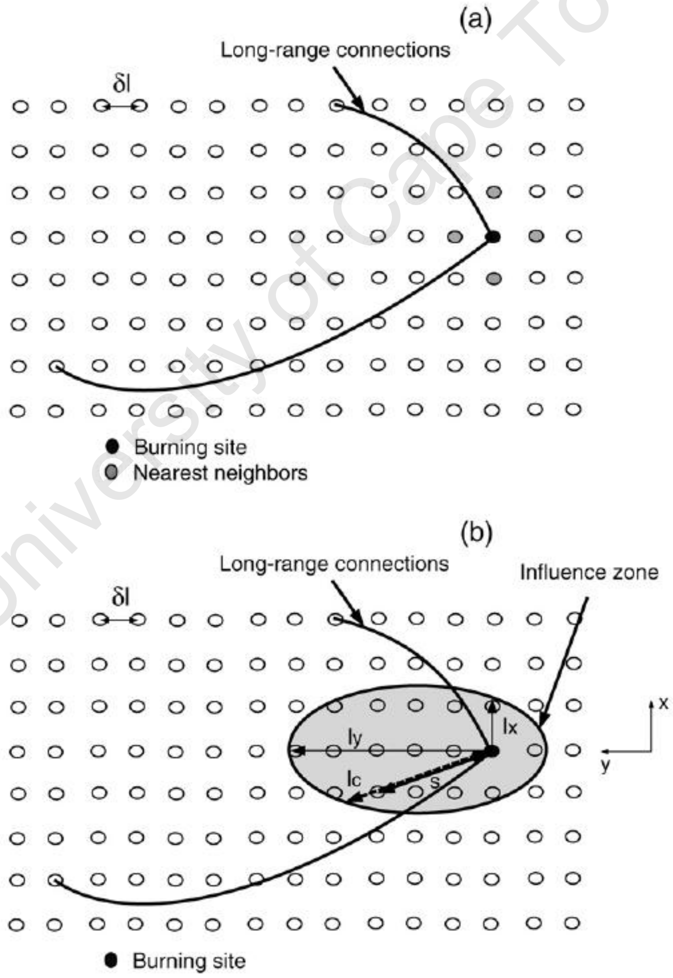


Figure 3-16 an illustration of Small World Networks showing the grid lattice, neighbourhoods and long range connections (Porterie, 2007)

3.8.3.2 Fuzzy logic

Vakalis et al (2004) developed a fire rate of spread model using fuzzy logic. Fuzzy logic is used as a tool to model processes that are too complex for conventional quantitative techniques; hence due to the complex nature of wildfires they were introduced to the fire spread modelling science. It is very helpful when the exact quantities are not exactly known or high levels of uncertainty exist (Vakalis et al, 2004).

A major advantage of fuzzy logic is that it resembles the perceptive behaviour of humans when it comes to decision making by accommodating human language and logic. It uses set theory but fuzzy sets are deviate from conventional set theory. In conventional set theory an item is either a member of a set or not a member at all, but in fuzzy sets the notion of partial set membership exists. In fuzzy sets the partial membership by an item ranges between 0 and 1, where 0 represents none membership and 1 represents full membership.

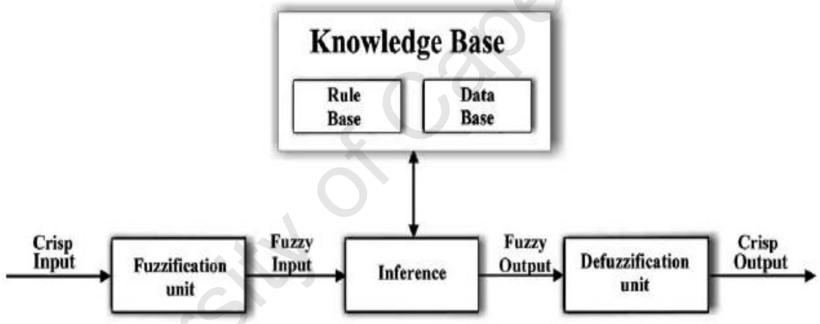


Figure 3-17 The structure of a fuzzy model (Vakalis et al., 2004)

Figure 3-17, from Vakalis et al (2004), above shows the structure and processes that are followed in a fuzzy model. These are further discussed:

- **Fuzzification**
  This is the stage where the inputs to a fuzzy model are allocated into appropriate cells. At the end of this process we have a list of fuzzy perceptions about each input. Fuzzy perception describes each input in terms of its membership to all the fuzzy cells.
- **Fuzzy inference**
  The modelling takes place at this stage. All the inputs go through a series of logical rules in the form of *if-the-else* statements to produce an output in fuzzy logic.
- **Defuzzification**
  The fuzzy outputs are then weighted and the resulting output is a value that is not in fuzzy terms that can be interpreted to have a certain meaning.

3.8.3.3 Artificial Neural Networks (ANN)

Artificial neural networks often refered to as ANN are computational models that simulate the behaviour of biological networks and the functioning of the brain. These networks consist of interconnections between a number of computational units that perform functions that aid in solving a particular problem. ANN systems are trained through exercises to recognise patterns in order to automatically solve problems (Yegnanarayana, 1999).

The advantage of application of artificial neural networks in modelling fire behaviour is that such systems are able to model complex problems that result from multiple relationships amongst different factors in order to produce non linear results (Mc Cormick, 2002). The complex nature of wildfires and the multiple factors that influence their behaviour has been presented in chapter 3. McCormick (2002) developed a grid based ANN model that simulates the spread of wildfires using data from the Huron National forest in Michigan, USA.
The results of this study proved the ability of artificial neural networks to simulate the rate at which a fire will spread, hence affirming ANN as an alternative grid based computational modelling approach to fire modelling.

Artificial neural networks do provide an alternative method to grid based fire modelling approaches such as those cellular automata and bond percolation. This new approach however also has some disadvantages. The in order for the system to work, it needs to be trained on previous occurrences of the phenomenon being modelled. In other applications these systems have been recorded to require long processing times and are thus slow. They have also been found to require substantial computer processing power (Yegnanarayana, 1999).

4 DEVELOPMENT OF FIRE MODELS

4.1 Introduction

The two different kinds of fire models were introduced in chapter three, namely the fire behaviour models and fire spread models. Fire behaviour models describe the characteristics of fires such as the intensity at which a fire burns and the length of a flame in a fire incident. Some fire behaviour models describe fire behaviour in terms of secondary derived fire indices that are based on those already discussed. Examples of secondary fire behaviour variables are the fire danger index and burning index, these are predictive variables that are often based of basic characteristics such as fire intensity.

The purpose of this study is to develop a comprehensive (including both the prediction of fire behaviour and prediction of the spread of fire), predictive fire model that is fully embedded[6] within a GIS. As the aim of the thesis states: one of the focuses of this study is on the development of predictive fire models. Firstly a fire behaviour model is developed, then a fire spread model that is based on the fire behaviour model is developed and finally the visualisation of the simulated spread is presented.

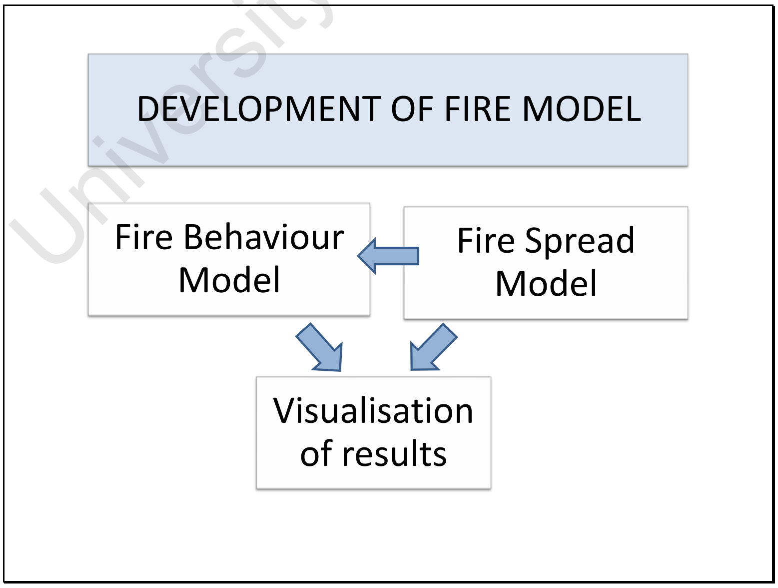


Figure 4-1 A brief overview of the fire modelling processes, more detailed diagrams are presented in relevant sections

[6] An embedded model exhibits both the functionality of an environmental model with GIS functionality, built in, within the same software program. More detailed discussion can be found in chapter 2.

This chapter discusses the theoretical and conceptual design of the fire model. The guidelines of development of fire models on which this design is based are presented, then the methods used to model the behaviour and spread of wildfires are presented.

4.2 Guidelines for development of environmental and fire models

The methods developed in this study are based on the guidelines for the development of environmental models by Brimicombe (2003) which are illustrated in chapter 2, figure 2.1. Clarke et al (2002), and Rothermel (1983) also provide guidelines and steps to be followed in the modelling process; a summary of these guidelines follows. According to Clarke et al (2002), before a model is developed, the modeller must give a clear explanation of why the model is being development, what is to be achieved through the modelling process and at what scale and possibly the accuracy at which the results are to be achieved.

Rothermel states the three main sections of the fire modelling process as follows:

- **The evaluation of input data**

  At this stage decisions are made regarding the required data. These decisions are based on the data that is important for fire modelling process and yet is also easy to assemble.

- **Calculation of desired fire variables**

  This stage involves making decisions as to which variables that describe the behaviour of fires can best be modelled; for example the rate of spread.

- **Interpretation of results from calculations of the fire variables**

  The results of the calculations of the fire behaviour variables are interpreted to give inferences about either more complex variables that cannot be easily modelled, or other variables that are dependent on these primary variables.

- **Visualisation of results**

  The final stage is the display of these results in a manner that can be easily understood such as on a map.

4.3 Development of the fire behaviour model

This section discusses the methods used in the development of the fire behaviour model. First the advantages and disadvantages of the mathematical fire models are presented. The basis of the choice of a specific type of mathematical model is then discussed.

4.3.1 Choosing the type of model

The different classes of mathematical fire models were introduced in chapter three, these are empirical (stochastic), semi-empirical (physical-statistical) and physical models. The choice of which class of model to use is made with the full awareness of the advantages and disadvantages involved. A summary of these advantages and disadvantages of the different classes, following Pastor et al (2003), is provided as a reminder of the full review presented in chapter 3.

Empirical (Stochastic) models have the ability to provide very accurate results, however they are found to be most effective in regions for which they were developed and need to be re-parameterised if used in different regions.

Physical models can most certainly be used anywhere because they are based on physical notions of heat transfer, but they are very computationally intensive and require the use of very powerful computers. Another disadvantage of physical models is that since they are based on laws of physics, they need very explicitly defined data inputs which are not always readily available. For this reason, they become almost impossible to implement with the expectation of acquiring accurate results.

Semi empirical (physical-statistical) models are much easier to implement than physical models and require data inputs that are possible to acquire.

Three reasons guided the choice of model class to pursue in this study, and these are:

- Very accurate results are expected on a medium scale
- A model must use data inputs that are easy to collect and analyse in a GIS environment
- A model must not be excessively computer intensive

The reasons provided above do not encourage the use of physical models as they are computationally intensive, require very explicitly defined inputs that cannot be acquired easily, and can be hazardous to implement (in the case of fire), as a result empirical and semi-empirical models will be pursued alternatively. However empirical models need to be implemented with caution if they have not been previously tested in the study area. Therefore a semi-empirical model is the most appropriate choice.

4.3.2 Fire characteristics to be modelled

A number of characteristics can be used to explain the behaviour of wild fires and a number of indices have been developed throughout the world to model such behaviour. Examples of primary fire behaviour variables include the fire intensity, flame length, flame height. The indices that have been developed to model fire behaviour include the burning index (USA) and McArthur's fire danger rating indices (Australia). A detailed discussion on the fire behaviour characteristics is provided in chapter three.

In this study, three fire variables are selected in order to model the behaviour of wildfires and these are fire intensity, rate of fire spread and a burning index. The main reason for the choice of the fire intensity and rate of spread of fire is that they are primary fire behaviour indicators from which most of the other characteristics of wildfires can be modelled. The modelling of these variables is discussed in the following sub sections.

4.3.2.1 Fire Intensity

The fire intensity is a measure of how hot a fire is burning and more formally it is described as a measure of the rate at which heat energy is released by a fire (Trollope et al, 2002). Fire intensity is correlated with many other fire behaviour characteristics such as flame length, flame angle, and rate of spread of fire as will be demonstrated later in this chapter. There are different kinds of fire intensity as shown in chapter three but for the purpose of this study the term fire intensity will be used to refer to the fire line intensity.

The fire intensity alone can be used in predictive fire studies to give an indication of the potential danger that a fire that would ignite in that specific area would pose.

An internationally used equation for fire intensity is that developed by Byram in 1959, in which fire intensity is defined as the numerical product of heat energy produced, the fuel load, and the rate at which a fire spreads.

$$I = H \times w \times R \tag{4-1}$$

Where: I = Fire intensity (J $s^{-1}m^{-1}$)
H = heat yield (J g^{-1})
R = rate of spread of fire (m s^{-1})
w = mass of available fuel (g m^{-2})

Equation 4-1 shown above is a general mathematical equation that describes the behaviour of wild fires. Stochastic modelling however indicates that fire intensity and fire rate of spread can be acquired through separate calculations, where neither of the two depends on the other. The stochastically derived equation for fire intensity is discussed hereafter, whereas the calculation of fire rate of spread is discussed in section 4.3.2.3. Following research conducted in the Savanna grasslands of South Africa, in the Eastern Cape Province and Kruger National Park, Professor Winston Trollope, a well known and respected fire ecologist, developed a semi-empirical fire intensity based model. Trollope's model is shown below:

$$FI = 2729 + 0.8684(x_1) - 530(x_2)^{\frac{1}{2}} - 0.907(x_3)^2 - 596(x_4)^{-1} \tag{4-2}$$

Where: x_1 is the fuel load (kg/ha),
x_2 is percentage fuel moisture (%),
x_3 is the percentage relative humidity (%),
x_4 is the wind speed (m/s)

Although it is possible for both equations to provide results of the same accuracies, they are fundamentally different. Apart from the fact that Trollope's equation was developed for the Savanna grassland context, it has an advantage over Byram because it is based entirely on weather and fuel variables that can be directly measured from the ground (and ground stations for weather data), displayed spatially and analysed in a GIS. Although this is a predictive study it is important to have data that can be verified by ground truth.

As a result Trollope's model is used in this study, also because it has been tested and validated in the Kruger National Park which is the area investigated in this study. A discussion about the fire intensity model, the inputs and expected results follows.

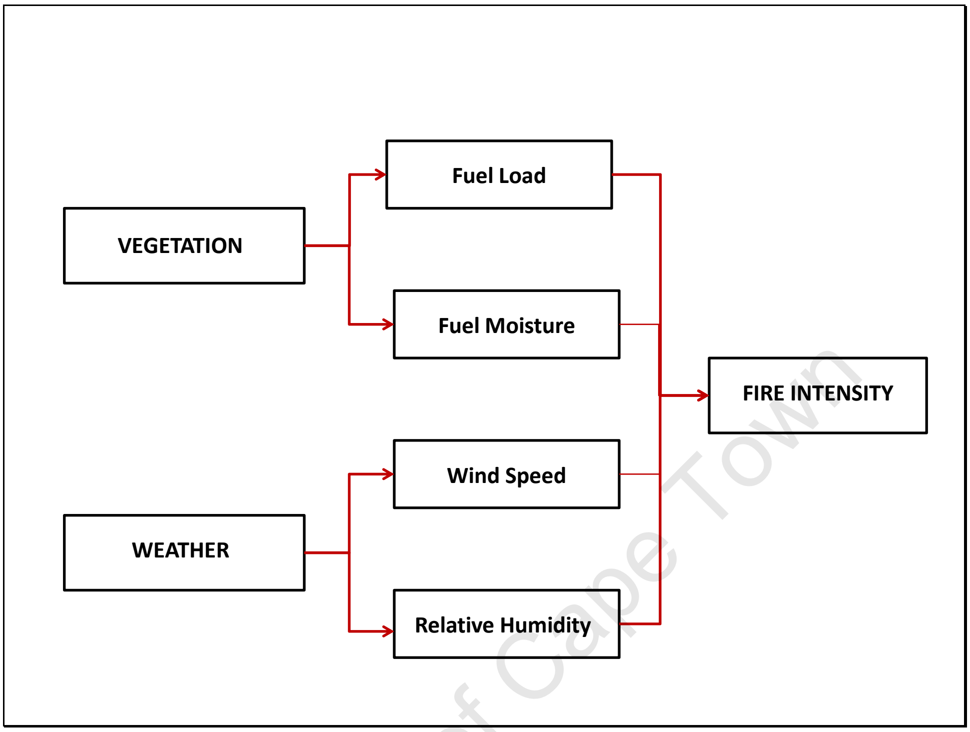


Figure 4-2 The fire intensity model inputs

Figure 4-2 illustrates the components of the Trollope's fire intensity equation. The following section discusses the inputs of the fire intensity model without specifying the acquisition and pre-processing of the data, as this is a major milestone of this study that will be discussed in a separate chapter.

The model inputs are as follows:

- **Fuel Load**

  The fuel load measurements used in this study are acquired from ground measurements that are done in the Kruger National Park at the beginning of a fire season by the national parks fire ecologists (Govender, *pers comm.*). These measurements are obtained by the use of a disc pasture meter that is thrown onto a region of grass and the settling height is recorded in kilograms per hectare (kg/ha), (Trollope et al, 2002).

  The use of Remote Sensing for fuel load measurements was not explored in this study because of the complexity of the subject which is beyond the scope of this thesis. The use of remote sensing to estimate fuel loads has been investigated by other researchers, although most studies referred to forest areas and not grasslands. One can attribute the lack of popularity of Remote Sensing fuel models in grasslands to the height restriction of such fuels which make it difficult to differentiate between the surface and short grass for specialised technologies such as LIDAR (Chuvieco, 2003).

- **Fuel Moisture**

Fuel moisture is a measure of how much water is available in vegetation and this can be done by the use of different vegetation indices such as the NDVI (Normalised Difference Vegetation Index), NDWI (Normalised Difference Water Index) and many others, with the aid of remote sensing techniques. The vegetation indices measure the amount of water available in the vegetation or the general vegetation health depending on which spectral bands are used. Two vegetation indices were considered for this study; these are NDVI and NDWI.

The NDVI measures the health of vegetation by measuring the level of photosynthesis activity within the plants, and is calculated as follows:

$$NDVI = (\rho_{NIR} - \rho_{RED})/(\rho_{NIR} + \rho_{RED}) \qquad \textbf{4-3}$$

Where: ρ_{NIR} is the reflectance of the NIR (near infra-red) band

ρ_{NIR} is the reflectance of the red band of the visible spectrum

The Red band is strongly absorbed by chlorophyll and is strongly reflected by water, whereas the Near Infra-Red band is strongly absorbed by water and is strongly reflected by chlorophyll. The NDVI values range between -1 and 1 with the lower numbers representing poor vegetation health and the numbers approaching 1 meaning good vegetation health.

Although NDVI does not directly measure the amount of moisture in the vegetation, a relationship between NDVI and fuel moisture has been proven by a number of studies (Verbesselt et al, 2006). It has been found that when vegetation dries out the level of chlorophyll decreases and vice versa; this is the basis on which the relationship was drawn.

The NDWI (Normalised Difference Water Index) conversely, focuses directly on the amount of water that is available in water. The calculation of this index is similar to that of the NDVI but the red band is replaced with the short wave infra-red band.

$$NDWI = (\rho_{NIR} - \rho_{SWIR})/(\rho_{NIR} + \rho_{SWIR}) \tag{4-4}$$

Where: ρ_{NIR} is the reflectance of the NIR (near infra-red) band
ρ_{SWIR} is the reflectance of the Short Wave Infra-red (SWIR) band

The SWIR band is strongly absorbed by water and chlorophyll; it is strongly reflected by bare soil.

Although both indices can be used effectively to quantify fuel moisture, the NDWI was chosen as the final index due to its direct relationship with fuel moisture and its better performance over NDVI in the study area, according to a study conducted by Verbesselt et al (2006). However NDVI can also be successfully used in cases where satellite sensors that have SWIR are of too low a resolution.

The NDWI values range from -1 to 1, indicating low water content to very high water content respectively. A study conducted by Gao (1996), shows that healthy vegetation has positive NDWI values and dry vegetation has negative values. Fire studies are interested in vegetation that has low NDWI values; this is the dry vegetation which is more likely to burn hence producing high fire intensity levels.

Although NDWI (fuel moisture content) ranges from -1 to 1, the fire intensity calculation requires fuel moisture content as a percentage from 0% to 100%. As a result the range of NDWI values has to be changed to suit the required scale and yet still representing low water content and high water content correctly; this is achieved through the equation below:

$$NDWI_{range\ adjusted} = \frac{(NDWI + 1)}{2} \quad \textbf{4-5}$$

Equation 4-5 above rearranges the NDWI scale to 0 to 1. Where -1 becomes 0 and 1 becomes 1. The fire intensity requires fuel moisture as a percentage, therefore the following conversion in equation 4-6 is applied to the readjusted NDWI that is obtained in equation 4-5:

$$Fuel\ moisture\ content = NDWI_{range\ \ adjusted} \ \times 100 \quad \textbf{4-6}$$

In some fire models, fuel moisture inferences are made based on general moisture content exhibited by the type of vegetation without actually measuring the content that is available at that particular instant. The calculation of fuel moisture from remote sensing efforts as demonstrated above is preferred over this method because it enables the estimation of the available moisture at the specific time required without generalising, and it also shows moisture differences within similar vegetation types. This therefore accounts for the fact that vegetation of the same type does not necessarily have the same moisture content at any instance.

- **Relative Humidity**

  Humidity has a direct relationship to the moisture content in plants and can also translate to the likelihood of precipitation. Although air temperature has been found to have a significant positive influence to wildfires (Trollope and Taiton, 1986; Trollope and Potgieter 1985), it is excluded from this equation because it is highly correlated to humidity and its inclusion would not add any more value to the calculation (Trollope et al, 2002).

- **Wind Speed**

  The importance of wind speed to the fire behaviour was discussed in depth in chapter 3 and will not be dealt with again here, suffice to say that it is a critical fire behaviour model input

4.3.2.2 Burning Index

The burning index calculated in this model is based on the equation derived in the USA Fire Danger Rating System. The burning index is used to quantify the fire danger arising from the calculation of fire intensity. Although this equation was developed in the USA it is used because similarities have been found between the behaviour of surface fires in the South African Savannas and the tall grass American prairies, where this equation was initially developed (Trollope et al, 2002). The burning index is calculated as follows:

$$Burning\ Index\ (BI) = k[j(FI/60)]^{0.46} \tag{4-7}$$

Where: FI = Fire Intensity

k = 10/ft

j = 100 (a scalar parameter appropriate for SA savannas (Trollope et al, 2002))

4.3.2.3 Rate of Spread

The rate of spread of a fire is the second most crucial fire behaviour characteristic. Similar to the way that fire intensity can be used independently to quantify the risk of fire occurrence, the rate of spread can be used in the predictive analysis of how a fire will spread and where it will spread to.

A number of equations and models have been developed world-wide to predict the rate of spread of wildfires, but one that has been internationally acclaimed is that developed by Rothermel (1972), shown below, as interpreted by Pyne et al (1996):

$$R = \frac{I_R \xi (1 + \phi_W + \phi_S)}{(\rho_b \varepsilon Q_{ig})} \tag{4-8}$$

Where: R = rate of spread of fire front

I_R = reaction intensity

ξ = portion of reaction intensity that raises the neighbouring fuel to ignition temperatures

ϕ_W, ϕ_S = dimensionless multipliers that account for effect of wind speed and slope respectively

ρ_b = dry fuel per cubic foot of fuel bed

ε = dimensionless number that accounts for the proportion of the fuel particle that is raised to ignition temperature by the time combustion starts

Q_{ig}= amount of heat required to ignite one measurement unit of fuel, also known as the heat of pre-ignition

Rothermel's fire rate of spread was tested in the Savanna context by Van Wilgen and Willis in 1988 and was found to be effective; however it lacked adequate fuel models for the Savanna context hence making it difficult to implement (Trollope et al, 2002). Another concern about Rothermel's model being applied in the Savanna grasslands is that since it requires about 17 input variables that can not immediately be understood by the user, thus it is not easy to implement (Higgins et al., 2008). Based on these two observations and the fact that the inputs were in fact found not to be clearly defined, the Rothermel method is not used in this study. This must not be mistaken to mean that the Rothermel method of fire spread is not effective, but rather that it was not found to be the most suitable method to implement, mainly because of the inputs required.

The difficulty to define and acquire the required input data for Rothermel's fire spread model lead to the search for an alternative and yet effective fire spread model, for which data inputs could be sourced and interpreted with more ease.

An alternative model that is considered is a semi-empirical model developed by Higgins et al (2008). The model is based on the same physical principles as that developed by Rothermel but they differ in the way the parameters are estimated. Instead of trying to directly estimate these parameters, empirical data about the rate of spread from previous fires, are used to perform the estimation. The equation is presented below following which, this model is described.

$$R = \frac{\varphi z f(w;a)}{Q_m m + Q_v(1-m)} \qquad \textbf{4-9}$$

Where: $f(w;a) = \frac{w}{w+a}$

φ = effect of wind and slope on flux rate of energy

z ,a = estimated dimensionless parameters (with values of 301 and 119.7 respectively)

w = fuel load (g m^{-2})

Q_v = heat of pre-ignition for vegetation (J kg^{-1})

Q_m = heat of pre-ignition for the moisture in vegetation (J kg^{-1})

m = fuel moisture content

The inputs of this equation are wind speed, fuel moisture and heat properties that have already been estimated in Higgins and others (2008). The parameters z and a, are dimensionless and are estimated using least squares and multiple regression analysis, through analysing data acquired from 200 experimental fires that were conducted in the South African savanna grasslands as described by Trollope, 1998 (Higgins et al, 2008).

The recommended model for the effect of wind speed and slope is that used by Berjark and Hearne (2002) that is shown below:

$$\varphi = \tan^{-1} u \qquad \textbf{4-10}$$

Where: u = wind speed (m/s)

This model is summarised as illustrated in figure 4-3 that follows:

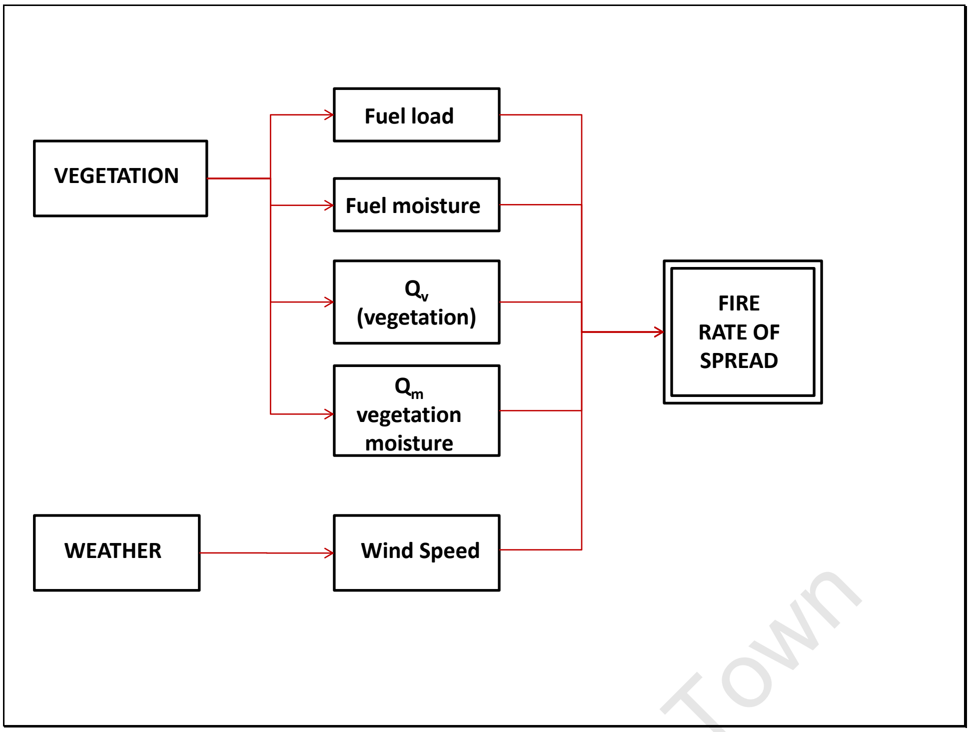


Figure 4-3 The calculation of the rate of spread of a fire showing all the inputs involved

4.3.2.4 Other Derived Calculations

Having performed the calculations for fire intensity which is used to predict the amount of heat released by a fire in the case of ignition, as well as having calculated the predicted rate at which such a fire will spread, further calculations are performed that will assist in the prediction of how a fire will spread after the initial ignition.

In the event of a fire, the heat that will be produced and the direction in which a fire will spread have been explored; however the properties of the flames produced in such a fire have not been investigated. The flames are also important because they interact with external factors to facilitate the transfer of heat energy and hence the spreading of a fire. The most important properties of a flame are the length of a flame and the inclination angle of the flame. These properties were introduced in chapter 3, therefore the focus of the following sections is on their calculations and inclusion in the model. In order to remind the reader about these factors the following illustration is presented again in a much simplified form:

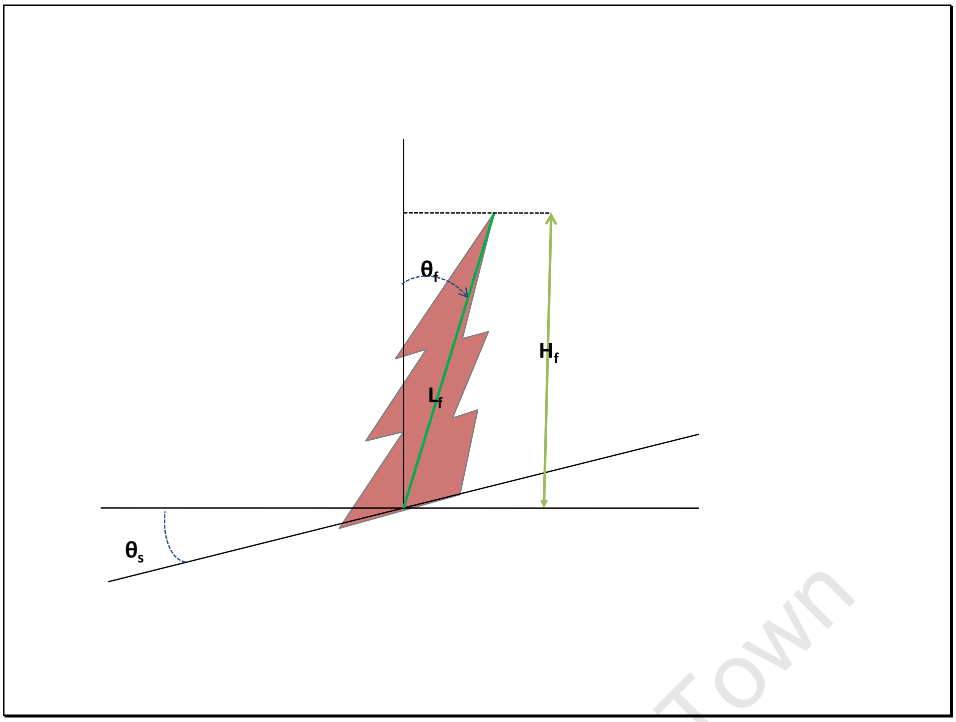


Figure 4-4 Illustration showing the properties of a flame where; θf is the flame angle, θs is slope angle, Hf is flame height, and Lf is flame length

- **Flame Length**

A number of empirical relationships have been established for the flame length and all of them follow the general form developed by Byram (1959), where flame length is a function of fire line intensity as shown below:

$$L_f = \beta_0 I_B^{\beta_1} \quad \textbf{4-11}$$

Where: β_0, β_1 = estimated dimensionless coefficients

I_B = Fire intensity (kJ s^{-1} m^{-1})

The estimated parameters mentioned above are based on different fuel types. Nelson and Atkins (1986) and Wiese and Biging (1996) provided variations to the Byram model and the values are listed below:

Model	**β_0**	**β_1**
Byram (1959)	0.0775	0.46
Nelson and Adkins (1986)	0.0475	0.493
Wiese and Biging (1996)	0.0161	0.70

The efficiency of these models within the savanna grasslands is not known hence the results of these three models are calculated and tested against known field measurements of the flame length acquired during fires that have occurred previously in the study area. The model that displays results closest to the observed values is used in the final fire behaviour model presented.

- **Flame Angle**

As it has been explained in chapter 3 and by the illustration above, the flame angle refers to the inclination of the flame, mainly as a result of the wind blowing across the flame. Putnam (1965) and Nelson and Adkins (1986) developed relationships for the flame angle both relating to the Froude number (Weise and Biging, 1996). The Froude number is a dimensionless ratio that shows the relationship between a burning flame, the wind speed and the gravitational force as follows:

$$Froude\ Number = \left(U^2 / gH_f \right) \quad \textbf{4-12}$$

Where: U = wind speed (m/s)

g = gravitational acceleration (m/s^2)

H_f = flame height (m)

According to Putnam (1965) the calculation for flame angle is as follows:

$$\theta_f = \tan^{-1} 1.4 \left(U^2 / gL_f \right)^{0.5} \quad \textbf{4-13}$$

Where: L_f = flame length (m)

Nelson and Adkins provide a variation of the same formula below:

$$\theta_f = \tan^{-1} 1.22 \left(U^2 / gH_f \right)^{0.5} \quad \textbf{4-14}$$

The variables are as explained in figure 4.3 above. The equations have been reported to perform best for conditions where the slope is very small. Wiese and Biging (1996) provided re-parameterised versions of the above equations for conditions where the slope is significant. The study area being investigated has no significant slopes, hence the former equations are presumed valid, however, should this model be used on significantly sloping regions the variations by Wiese and Biging (1996) are recommended.

A summary of the entire model thus far is presented in Figure 4-5 below.

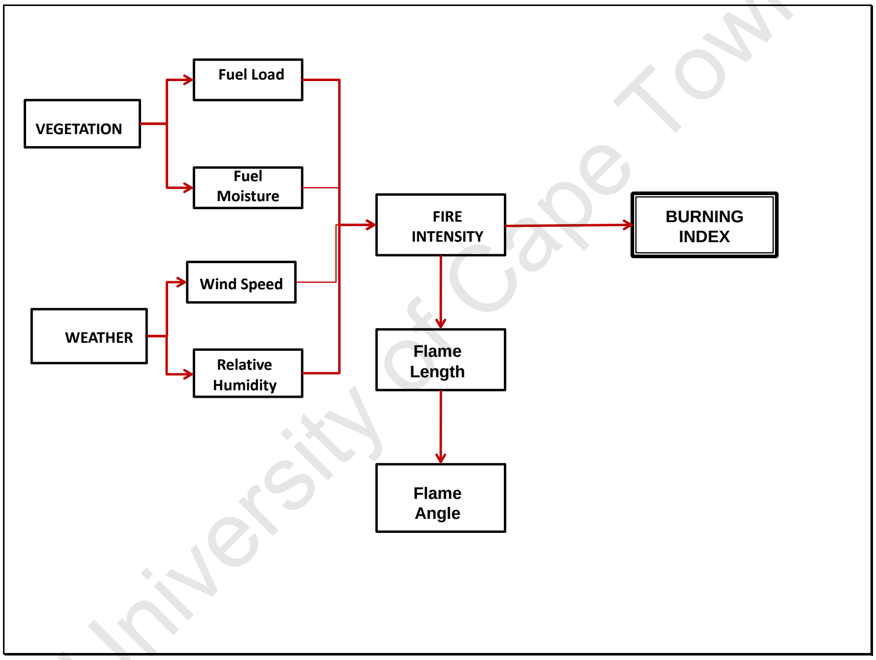


Figure 4-5 Fire behaviour model showing components

4.4 Development of fire spread model

The preceding sections of this chapter discussed the predictive parameters that describe the general behaviour of wild fires. Apart from predicting the behaviour of wildfires, these parameters can also be used as background and support data for fire spread models. The following sections discuss the prediction, simulation and propagation of wildfires.

The types of fires simulated in this section are those that start from point ignitions; therefore line ignitions will not be investigated. The focus is only on point ignition because it has been found that ninety percent of fires in South Africa occur as a result of arson, an only ten percent occur as a result of natural causes, such as lightning (Van Wilgen, 2004). This statement thus indicates that most fires that occur in South Africa are arson fires.

4.4.1 Cellular Automata as a fire modelling technique

A review of fire modelling techniques, including the advantages and disadvantages of each technique, has been discussed in chapter 3. For the purpose of this study, the cellular automata (CA) technique on a regular grid is chosen to be implemented in a GIS environment.

A detailed discussion on CA is given in chapter 3. A short summary of the discussion is given below. The unit of a CA is called a cell or a pixel; however these terms are often used interchangeably. An area is represented by a grid, where each cell exhibits information describing conditions ranging from meteorological conditions, vegetation conditions and topographic conditions for that particular area. The conditions within a cell are assumed to be homogenous.

The advantages of using CA within a GIS environment are as follows (Yassemi et al, 2008):

- The regular grid structure of CA is similar to that of GIS software environments hence no major adjustments need to be done.
- CA are able to model complex situations based on simple transition rules
- CA make it possible to perform dynamic modelling in raster based GIS

4.4.2 Description of method

The CA model developed in this study is based on a square lattice of cells hence all data is represented in grid raster format. The assumption made is that each cell exhibits homogenous conditions of the phenomenon it is representing.

The spread model presented in this chapter takes advantage of the Moore neighbourhood of a cell, on which calculations that govern the spread of fire are performed (Yassemi et al, 2008).

A Moore neighbourhood in cellular automaton theory refers to the 8 cells that are directly connected to the centre cell as illustrated below:

i - 1, j - 1	*i - 1, j*	*i - 1, j + 1*
i , j -1	*i, j*	*i, j + 1*
i + 1 , j - 1	*i +1, j*	*i + 1, j + 1*

Figure 4-6 The Moore Neighbourhood showing 8 neighbours of a cell as used in CA

In some cases a Moore neighbourhood is referred to as any neighbourhood that surrounds a specified cell. This Moore neighbourhood has ranges (r), which are shown below, where C represents the surrounded cell, alternatively named the centre cell (Weissten, n.d.):

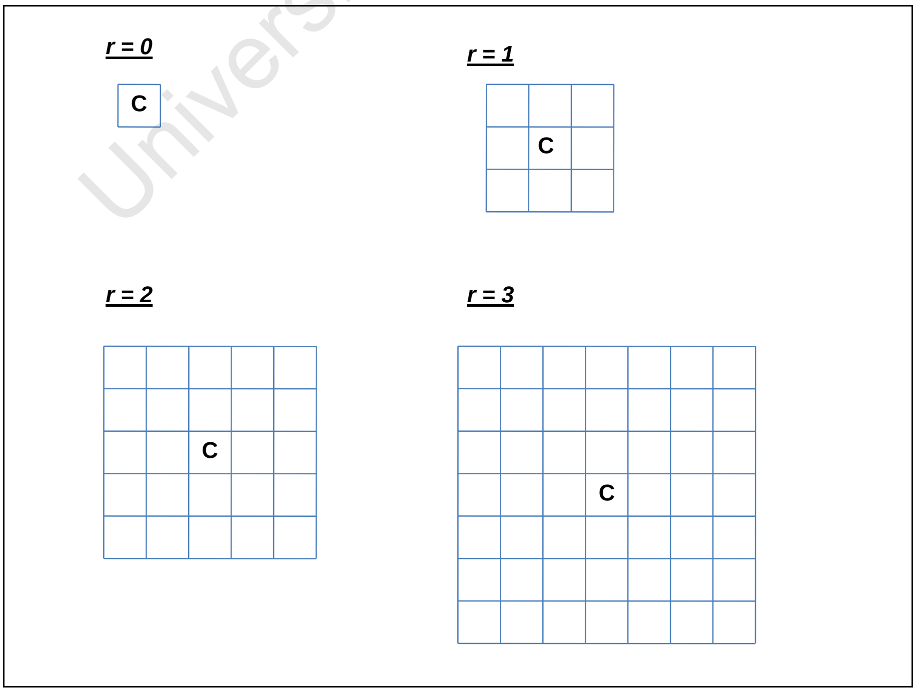


Figure 4-7 Variations of the Moore Neighbourhood, showing different ranges (r) (adaptation from Weinsten, n.d)

In this research, the Moore Neighbourhood refers to the neighbourhood consisting of 8 neighbouring cells that are directly connected to the centre cell as illustrated in Figure 4-7, above.

4.4.3 Heat transfer within fire cells

In order for a fire to propagate from a source cell to any of the neighbouring cells, heat energy must be released by the burning source cell and must then be received by the neighbour cell. This constitutes the basic principle of heat transfer within a burning fire. Heat is transferred from cell to cell by means of convection, conduction and radiation as discussed in chapter 3. A well known fact from physics is that heat is transferred from an area with high temperature to an area with a lower temperature. It can thus be deduced that if a cell does not receive enough heat energy, or if it receives no heat energy at all, the fuel contained within the cell will not burn. As a result it is necessary to do preliminary heat transfer calculations before the actual propagation of a fire is predicted. These calculations will indicate if the heat transfer taking place between two neighbouring cells is sufficient to ignite the receiving cell. The calculations to be performed according to Berjak and Hearne (2002) are for:

- Amount of heat produced by fuel burning in a cell, which reaches the next cell. This is the heat that is generated by burning fuel.
- Amount of heat required to ignite fuel in the neighbouring receiving cell. This is also known as the heat of pre-ignition

These calculations are discussed in the following subsections.

4.4.3.1 Heat generated by burning fuel

The heat generated by burning fuel (H_c) in a cell is calculated as the ratio of the quantity of heat energy released at each burn event within the cell, divided by the burning rate, following Johnston et al (2006).

A simplified version of this equation as used in the model presented in this chapter is as follows:

$$H_c = \frac{\left(\sqrt{A} \times w \times h\right)}{I} \quad \textbf{4-15}$$

Where: A = area of burning cell (m^2)

w = Fuel load within the cell ($g\ m^{-2}$)

h = heat content of the fuel ($kJ\ kg^{-1}$)

I = fire intensity ($kJ\ s^{-1}\ m^{-1}$)

Estimates of heat yield have been made in the grasslands of Australia, USA and South Africa. The estimates are all in agreement with the estimates by Anderson (1982), where heat content was estimated to be 18610 kJ/kg, (Trollope et al, 2002). Hence this value can be safely used.

4.4.3.2 Heat of pre-ignition

The heat of pre-ignition is the heat required to raise fuel from the current temperature to ignition temperature. This takes into account the actual amount of moisture in the fuel and the heat that is required for the water in the fuel to evaporate. Peng et al (2007) developed a semi- empirical model that calculates the heat of pre-ignition based on satellite-derived data and parameters based on the principles of physics. Records of this model being tested in the Savanna context have not been found, thus the model cannot be validated although it is mentioned. The problem experienced with implementing Peng's model was the lack of appropriate information on the specific heat and ignition temperature of dry vegetation relevant to the study area.

$$Q_{ig} = M_f\left[C_{pw}\left(373 - T_f\right)\right] + M_f V + C_{pd}\left(T_{ig} - T_f\right) \quad \textbf{4-16}$$

Where: Q_{ig} = heat of pre-ignition

M_f = Fuel moisture content

C_{pw} = specific heat of water

C_{pd} = specific heat of dry fuel

T_f = temperature of fuel

T_{ig} = ignition temperature of fuel

The rate of spread equation, (equation 4-9), developed by Higgins et al (2008), mentioned previously in section 4.3.2.3, provides estimates of the heat of pre-ignition for the fuels in the Savanna grasslands. These values provided by Higgins et al (2008) are used as an alternative to the model presented above.

4.4.3.3 Combustibility of fuel

Following the calculations of heat of pre-ignition of fuels and the heat produced by burning fuel, a simple ratio named the combustibility index (CI) is calculated. This index is used to assess whether the fuel in the neighbour cell will be ignited or whether the heat energy produced is insufficient to cause ignition (Berjak and Hearne, 2002).

$$CI = \frac{Hc}{Ho} \quad \textbf{4-17}$$

Where: H_c = heat generated by burning fuel

H_o = heat of pre-ignition = Q_{ig}

A CI index less than 1 implies that not enough heat is transferred to the neighbour cell from the burning cell. A value greater than 1 means the burning cell has generated enough heat to be transferred to the neighbour cell. These conditions are made discrete as presented below:

If CI < 1, then nf = 0

If CI >= 1, then nf = 1

The discrete values, nf, controls the spread of fire to neighbouring cells.

4.4.4 Effect of wind speed and available heat energy on rate of spread

The combustibility index (CI) along with the flame angle (θ_f) are used as in the model by Berjak and Hearne (2002) to modify the rate at which fire spreads as shown below, however the component models of heat transfer and rate of spread calculations are different.

$$R_{ws} = R_0 \times \exp(\beta\theta_f) n_f \quad \textbf{4-18}$$

Where: R_{ws} = rate of spread with effect of wind speed

R_0 = rate of spread without effect of wind

θ_f = flame angle

β = scalar coefficient estimated by linear regression

According to this model, high wind speed implies that the flames angle of inclination is large, hence the rate of spread will increase and the opposite is also true. A fire stopping event has also been introduced, namely, the available heat energy in the form of the dimensionless value *nf*. This will be revisited and explained in more detail in the sections to follow.

4.4.5 Effect of wind direction on rate of spread

The effect of wind speed on the rate of spread has been explored in the previous section using the flame angle, which is in turn influenced by the flame length. However, this is found as not sufficient to start simulating the spread of a fire because it does not account for the direction in which maximum fire growth will occur. This resulted in the development of a model that depicts the effect of wind direction on the spread of a fire (λ), by introducing a weighting system to control the direction of maximum spread, which will be applied to the rate at which a fire will spread. The most important result expected from this model is to allow the fire to spread in any possible direction including backwards, as opposed to other models which only allow the fire to move in the direction of the wind. The wind direction weighting system is discussed below.

The model presented in this chapter makes use of the fact that fire spreads faster in the direction towards which the wind is blowing as discussed in chapter 3 and decreases symmetrically towards the opposite wind direction. This is also based loosely on the fact that fire grows into an elliptical shape as in vector fire spread models (Perry, 1998). This is done by setting an axis along the wind direction vector, giving the head direction a weight of 1 and the end direction a value close to 0 but not equal to 0. If a value of zero is assigned to opposite direction to the wind direction, then, fire will not spread towards this direction (backwards). As a result, the value close to 0 is chosen in such a way that some amount of back spreading is allowed in the model. This is illustrated in Figure 4-8. The arrow symbolises the head of fire whereas the square end indicates the back of the fire, the blue box indicates the starting cell of a fire.

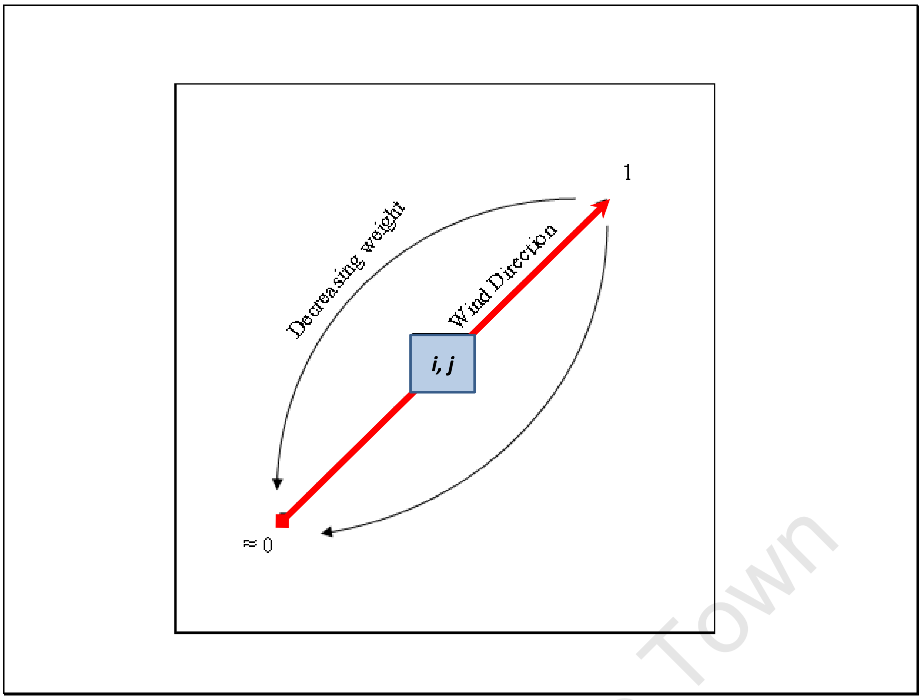


Figure 4-8 The weighting system applied to wind directions based on the prevailing wind direction during a fire event, where the blue box indicates the start cell of a fire and the arrow shows the direction of the head fire and the square indicates the backfire end.

This is implemented by modifying the normal compass directions from north, in such a way that the direction in which a fire is burning is given a direction of 180^o (degrees) and the opposite direction 0^o. Following the example above, the wind direction is towards the North east, according to the new convention the North East (45°) direction becomes (180°) and the South west direction (225°) becomes (0°). This is illustrated in Figure 4-9 below.

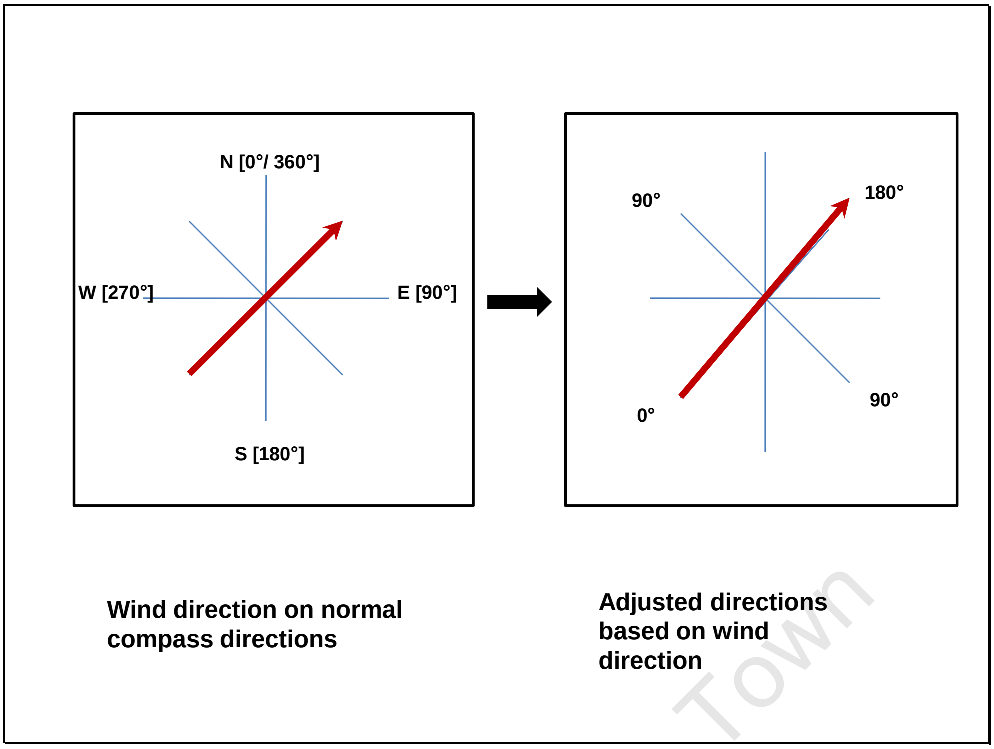


Figure 4-9The modification of wind direction to symmetric directions in preparation for the wind direction weights

The following equation is then applied to the adjusted directions that are based on the wind direction in order to obtain the appropriate weights.

$$\lambda = \frac{\left(1 + \left(\theta/_{180}\right)\right)}{2} \qquad \textbf{4-19}$$

Where: θ = wind direction (°)

In simple form it becomes:

$$\lambda = \left(\frac{1}{2} + \frac{\theta}{360}\right) \qquad \textbf{4-20}$$

This equation introduces wind direction vector weights based on how the fire will spread in each direction. An illustration is provided in Figure 4-10.

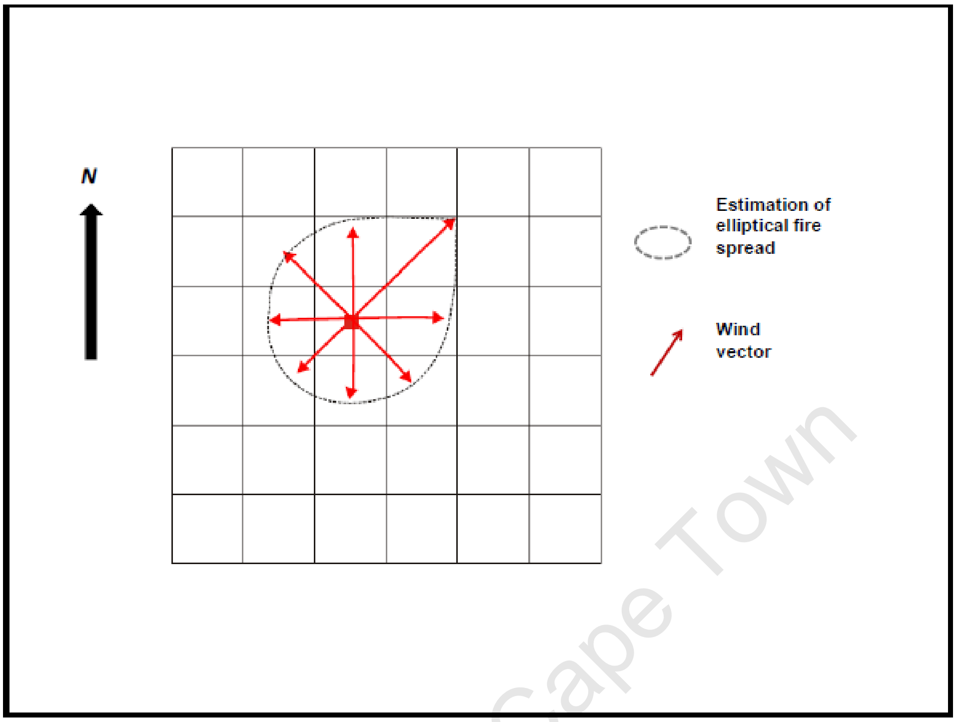


Figure 4-10 Approximated effect of wind direction of fire spread outward from a source cell to the 8 neighbour cells

These weights are multiplied into the equation for fire rate of spread in order to account for the effect of wind direction. These weights are included in order to enable interpretation of how long it will take a fire to cross a cell as will be explained in following sections. Finally the simulation of fire propagation can be performed.

4.4.6 Fire cell states

In the previous sections, the spread of heat energy resulting in the spread of fire has been discussed from the point of view of the cell from which the heat energy is emanating. From this point on, the propagation of a fire is viewed from the cell receiving the heat energy for ignition. The calculation for the state of a cell describes whether the fuel within the cell has been affected in any way by a fire ignition event. A centre cell is able to receive heat from any of the eight neighbouring cells, however the purpose of the model presented here is not to calculate how much heat is received by a cell, but whether enough heat is received by the cell to cause fire ignition. This depends on the rate at which fire is spreading in the neighbouring cell. The contributing heat energy from the adjacent cells is calculated separately from the diagonal cells because of the differing distances that the fire effects have to travel between the cell centres to the focus cells centre. Two illustration are provided below to give an explanation, Figure 4-11 shows the different diagonal and adjacent cells to the centre cell, whereas Figure 4-12, demonstrates the difference in travel distance from these neighbour cells to the centre cell.

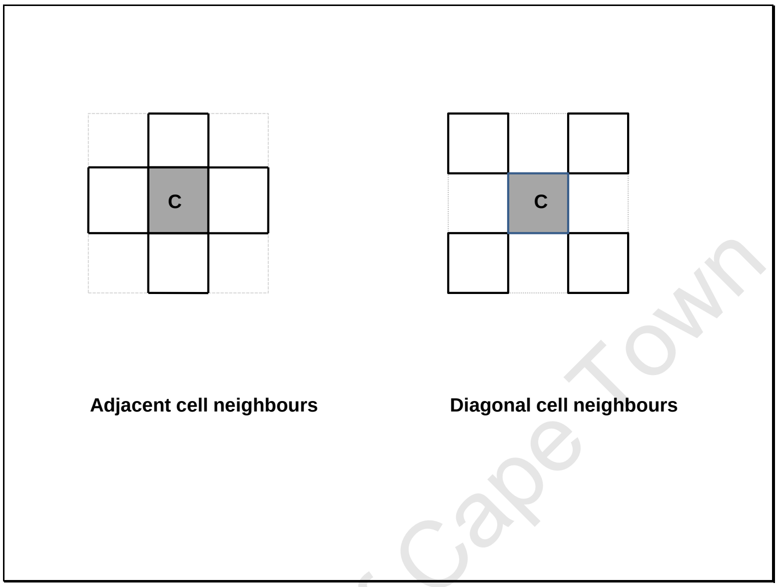


Figure 4-11 The Moore neighbourhood showing adjacent and diagonal cells (based on discussions by Berjak and Hearne (2002) and Yassemi et al (2008))

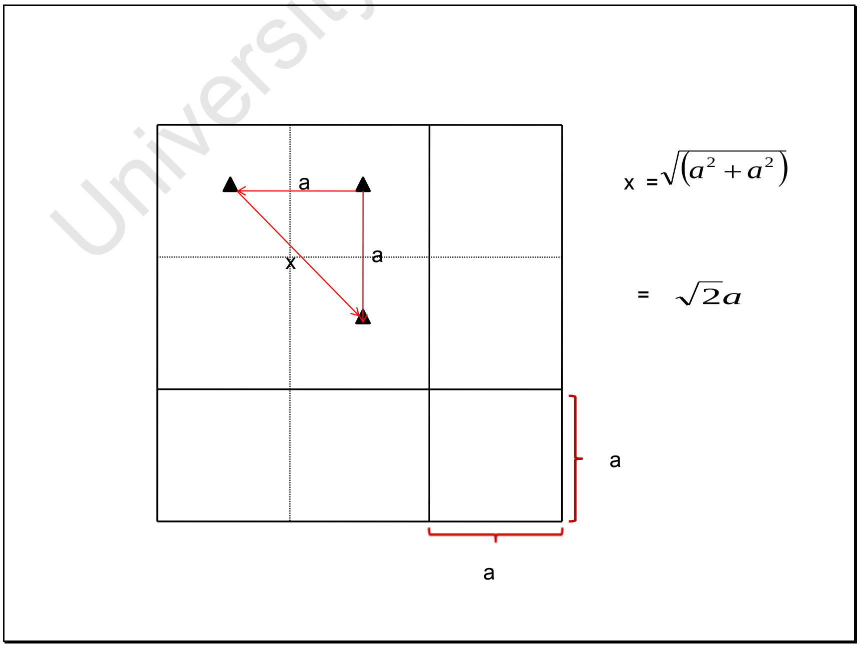


Figure 4-12 the distances to the centre cell from the diagonal cell, and from the adjacent cell. The distance from the adjacent cells is equal to the width of a cell. Strictly speaking, the dimensions of a grid block are (a) width and (b) height, but since the grid cells in this case are square the height and width are equal (a =b)

A cell in the proposed model can be in either one of the following three finite states:

- Not burning
- Burning
- Burnt out

These states are explained in following sections.

4.4.7 Fire propagation rules

The main property of Cellular Automata models is the definition of the rules that govern the cellular propagation. The rules explained in this model include what allows fire to spread to neighbours and what events prevent the fire from spreading.

- The combustibility index discussed in section 4.4.3.3 controls whether a fire will spread based on the amount of heat energy received by a cell, therefore a fire will not burn if it does not receive enough heat energy
- Fire spreads to neighbouring cells when at least one neighbour is burnt out, or has burned to the boundary between them.
- A burnt out cell cannot be reignited and cannot burn after it has completely burnt out
- A cell will not burn if it does not contain any fuel

4.4.8 Spread of fire from initial cell

At the beginning of a fire event one cell is ignited. The state of this cell is calculated as a ratio of the area burnt to the total area of a cell. The area of a cell is calculated as the area of a square because the CA (GIS) grid is based on square cells of equal area.

$$Area\ of\ a\ cell = (a \times b) \qquad \textbf{4-21}$$

Where: a = cell width

b = cell height

However in this case ***a*** is equal to ***b*** because the cells are square:

$$Area\ of\ cell = a^2 \qquad \textbf{4-22}$$

Since a fire burns in a circular fashion under no wind conditions, the area burnt in a cell is calculated as the area of a circle.

$$Area\ of\ circle = \pi r^2 \qquad \textbf{4-23}$$

Where: r = radius of circular area =d

d = (distance across cell)/2

Therefore this equation becomes:

$$Area\ burned\ within\ cell = {(\pi d^2)}/{4} \qquad \textbf{4-24}$$

Hence initial state of cell (S_0) becomes:

$$S_0 = \frac{Area\ burnt\ within\ a\ cell\ at\ (\Delta t)}{Area\ of\ cell} \qquad \textbf{4-25}$$

Where: Δt = time required to cross the focus cell, based on rate of spread

Since a circle is being fitted into a square the cell is considered to have burnt out at when the value of s is 0.785. At this instant fire from a cell will spread to an adjacent cell first and later to a diagonal cell as result of the different travel distances. The same conversion for adjacent cells is used by Hernandez et al (2007), although they do not differentiate the case of diagonal and adjacent cells.

$$s_0 = \left({\left(\frac{\pi a^2}{4}\right)}\Big/{a^2} \right) = \left(\frac{\pi}{4}\right) \approx 0.785 \qquad \textbf{4-26}$$

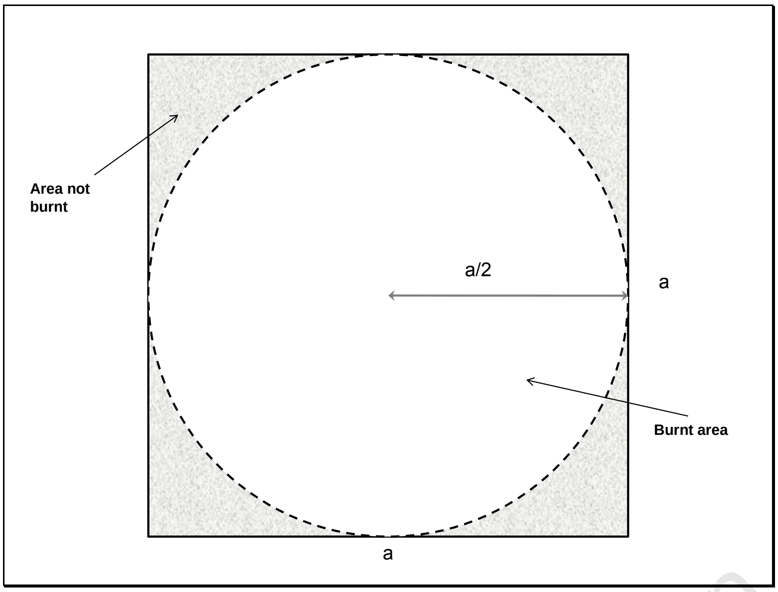


Figure 4-13 The circular area that a fire burns before it starts igniting the neighbours, whilst demonstrating that fire spreads to the adjacent neighbours first (adaptation from Hernandez et al, 2008).

4.4.9 Subsequent spread of fire to neighbouring cells

After the initial ignition and the source cell having burnt out the circular area describe in Figure 4-13, the fire can spread to the neighbouring cells. The subsequent states of any focus cell are calculated as an update to the original cell, by summing up the ratios of the rate of spread of the neighbouring cells to the maximum rate of spread occurring within the neighbourhood, loosely based on Berjak and Hearne (2002).

$$S_{new} = S_o + \left[\left(R_{wd\ adjacent} \right) \big/ R_{max} \right] + \frac{1}{\sqrt{2}} \left[\left(R_{wd\ diagonal} \right) \big/ R_{max} \right] \qquad \textbf{4-27}$$

Where: R_{wd} = Rate of spread corrected for wind speed and direction

R_{max} = maximum R_{wd} occurring within the neighbourhood

The division by √2 accounts for the distance from the diagonal cell (Berjak and Hearne, 2002).

From the discussion presented above, the value of the state of a cell can either be:

- **S_{new} < 0.785**

  This shows that a cell is still burning

- **$S_{new} \geq 0.785$**

  This means that a cell has burnt to the boundaries and is capable of igniting other cells.

- **S = 0**

  This applies to cells that have not been ignited at all and are considered inactive.

Having defined whether a cell is burning, burnt out or not burnt, there is still not enough information to know the level of burning activity in a cell. Hence a second condition is added based on the time a cell has been actively burning and the amount of time required to completely burn out the cell.

$$t_f = \left({}^{\Delta t_m}/_{t_c} \right) \tag{4-28}$$

Where: Δt_m = time corresponding to R_{max} in S_{new}

t_c = time required to completely burn out a particular cell

According to this equation, if:

- **$t_f < 1$:**

  This implies that the time **required** to completely burn a cell (t_c), is **greater** than the time that a cell is **permitted** to burn (Δt_m), in that time interval. This means that a cell will continue **burning** in the next time interval.

- **$t_f \geq 1$:**

  The time **required** for a cell to burn out is **less** than the time limit that a cell is **permitted** to burn in a time interval. This means that a cell will **burn out** at the end of a time interval.

- **$t_f = 0$:**

  This means that a cell has not been ignited by the fire, hence it is still **inactive**.

Combining these two set of conditions the cell states are as follows:

- **If $S_{new} < 0.785$, and $t_f < 1$: cell is still burning**
- **If $S_{new} \geq 0.785$, and $t_f \geq 1$: cell is completely burnt out**
- **If $S_{new} = 0$, and $t_f = 0$: cell is not active**

If a cell is still burning, it is also helpful to know how "hot" the fire in the cell is burning. This is estimated by the calculation of the fire intensity which is then further classified based on the fire danger index values for the region (Mpumalanga and Limpopo) as per the SAFDRS- South Africa Fire Danger Rating System (DWAF, 2001). These are illustrated in the table below:

Table 4-1: The (unit-less) fire danger ratings of Mpumalanga and Limpopo provinces of South Africa (by SAFDRS)

	INSIGNIFICANT (BLUE)	LOW (GREEN)	MODERATE (YELLOW)	HIGH (ORANGE)	HIGH-EXTREME (RED)
MPUMALANGA LOWVELD	0 - 4	5 -19	20 - 24	25 - 27	≥28
LIMPOPO LOWVELD	0 - 4	5 – 19	20 - 24	25 - 27	≥ 28

4.5 Summary of fire behaviour and spread models

A summary of the fire models developed in this study is provided, in the form of illustrations below:

The first step in the modelling process is the fire behaviour model where the fire behaviour characteristics, fire intensity and burning index are calculated:

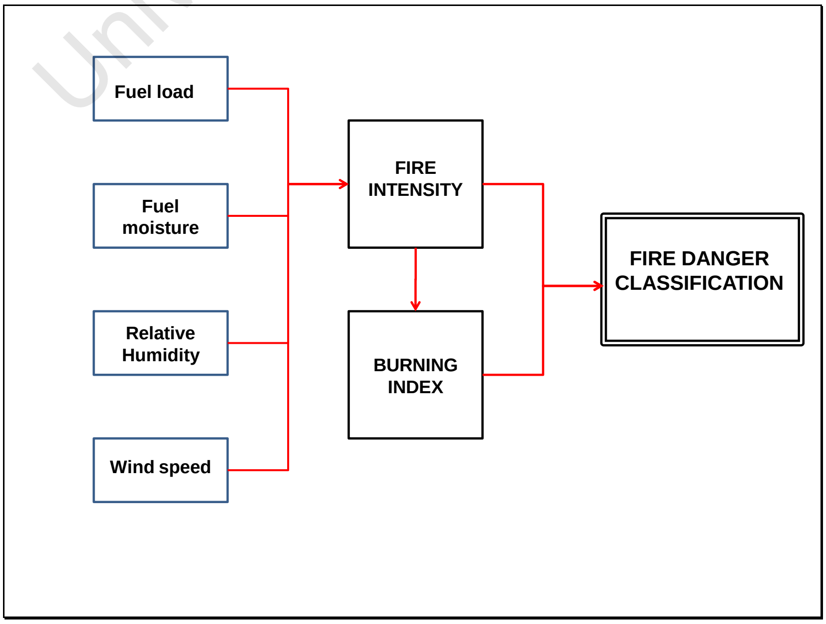


Figure 4-14 Calculation of fire intensity and classification based on burning index

Figure 4-15 shows the calculations performed in preparation for the CA based fire propagation. The fire intensity calculated in the fire behaviour model, Figure 4-14, is then used to calculate the length of the fire flame and the inclination of this flame. The properties of the flame as well as the heat transfer mechanism are used to decide how fire will spread to a neighbouring cell.

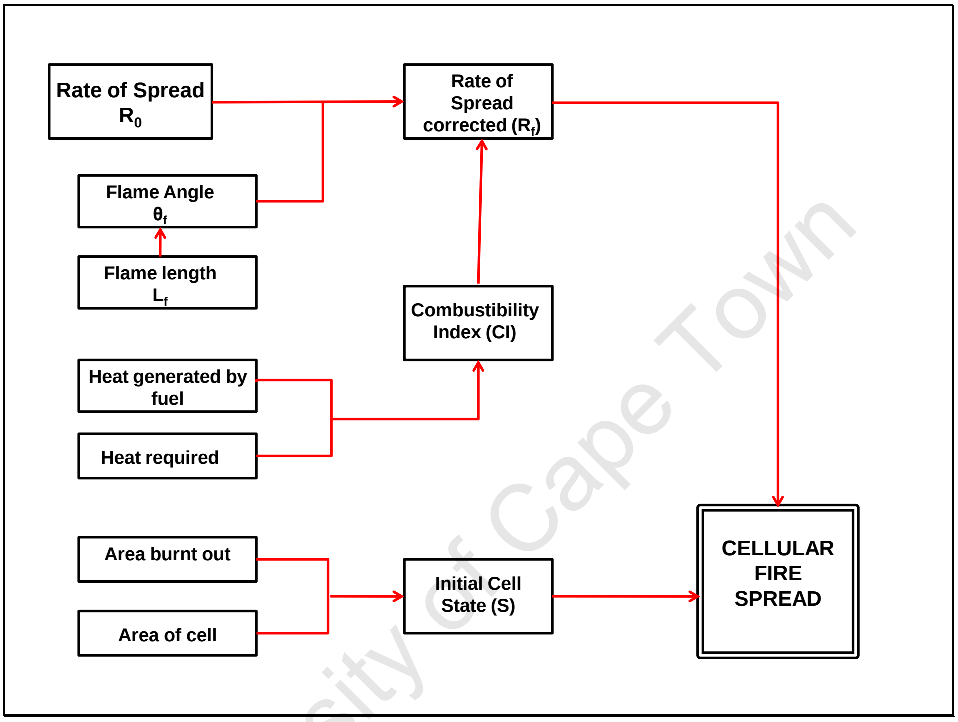


Figure 4-15 Preparation for fire propagation

Figure 4-16 below shows the decision making processes followed by the model to decide whether a cell is capable of spreading fire, and if it is capable, how its neighbour cells will respond to this fire. The main questions are:

- On ignition will a cell burn?
- If it burns how hot will it burn through different time instances?
- Will it ignite its neighbouring cells?

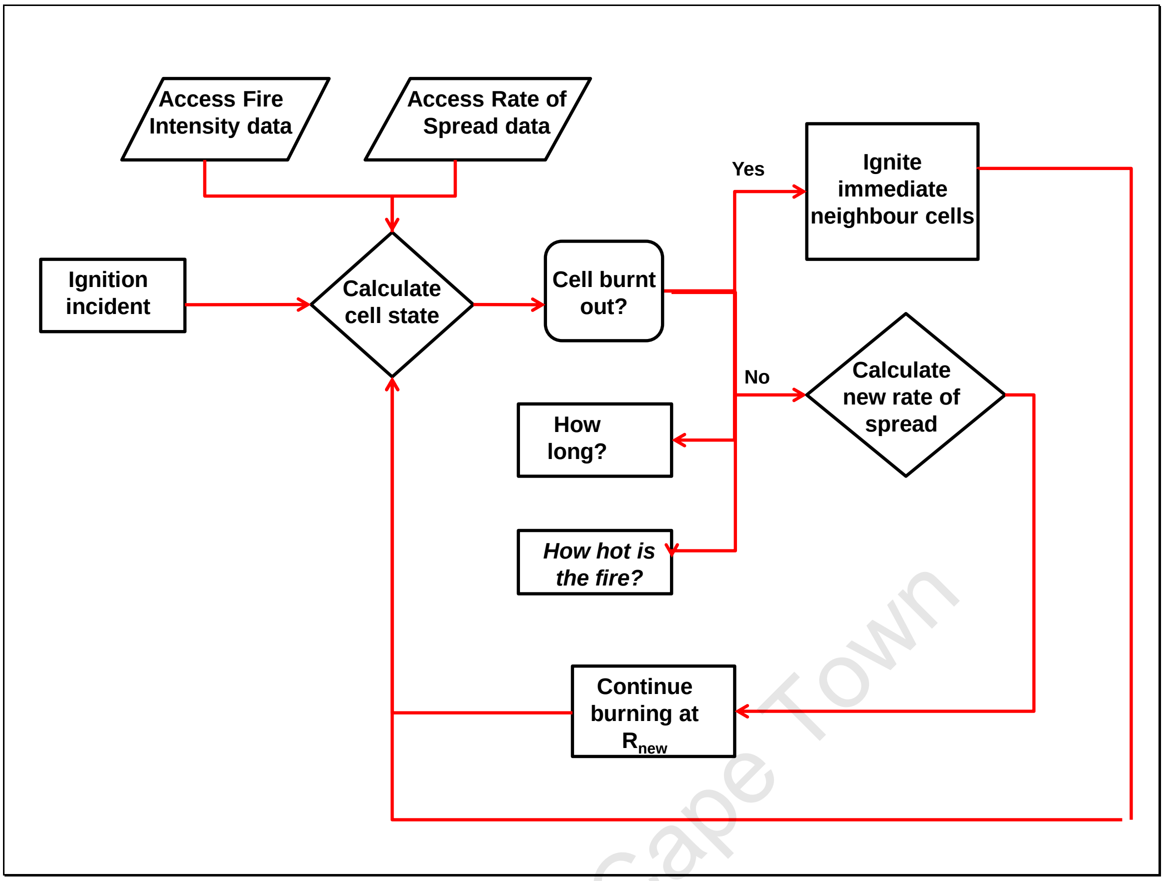


Figure 4-16 Process flow in cellular fire spread model

4.6 Discussion

This chapter begins by describing the characteristics that are used in the development of the proposed fire model. The behaviour of fires is modelled using, mostly locally developed and tested semi-empirical equations. The proposed model derives some fire propagation functionality from other previously developed models such as Berjak and Hearne (2002), Hernandez et al (2007), Johnston et al (2006). This results in a model that implements some physical components of heat transfer and fire behaviour characteristics into cellular automata. The functions included in this embedded model are:

- Performing internal calculations of fire behaviour characteristics such as fire intensity, flame length, flame angle, rate of spread and the fire danger index.
- Determining the danger level of the fire at the fire line.
- Performing animated simulations per time interval
- Depiction of the final shape of a fire

The animation and determination of final shape of fire are based on the implementation of the model in a GIS environment therefore these are discussed in chapter 6.

The following chapter discusses the technical design of the model within the ArcGIS environment.

5 DESIGN OF EMBEDDED FIRE MODEL IN ARCGIS

5.1 Introduction

The theoretical aspects of the model developed in this study were discussed in the previous chapter. This chapter describes the technical design of the developed fire model. The chapter begins with a brief overview of the advantages of fully integrating GIS and Environmental Modelling (EM) as well as geocomputation, hence the choice of the modelling approach. A description of the software that is used is then provided followed by the design process. Finally, a summary of the design of the fully integrated GIS based fire model is presented.

5.2 Integration of GIS and environmental modelling

The integration of GIS and environmental modelling as well as geocomputation, are extensively discussed in chapter 2. The different types of integration between GIS and environmental modelling are namely, loose coupling, tight coupling and embedded coupling. Loose coupling refers to a case where GIS and environmental modelling (EM) are linked by the transfer of data between one another. Tight coupling refers to the case where the GIS and EM tasks are performed in conjunction with each other and share a common interface but their tasks are not performed in the same environment. Embedded coupling, which is also known as full integration between GIS and EM, refers to the case where GIS and EM functions are performed in the same modelling environment where, either GIS functionality is embedded in an EM model or vice versa. In simple terms, embedded coupling refers to the situation where EM and GIS functions are available at the click of a button. The advantages and disadvantages of these methods are discussed in chapter 2. The most important reason why the full integration approach is preferred over the other methods mentioned above is because only one software package is required which offers full functionality.

In this study, full integration between GIS and EM refers to the case where EM functionality is embedded within a GIS environment. Full integration is acquired through geocomputation which is also discussed in chapter 2. Geocomputation leads to the enhancement of GIS functionality by providing built in macro languages in GIS software, and more recently integration of GIS software with full programming languages to provide more analytical functions.

The full integration of GIS and EM, embedded coupling, with the aid of geocomputation, is adopted in the implementation of the model discussed in the previous chapter. Consequently the design of this proposed model within the GIS environment is discussed in the following sections.

5.3 System architecture

The model proposed and described in the previous chapter is implemented within the ArcGIS software environment running on Windows XP technology. ArcGIS is proprietary software developed by the Environmental Systems Research Institute (ESRI) that provides, amongst its many functions, tools and functionality for the analysis, management and visualisation of spatial data (ESRI, 2008). ArcGIS provides a range of products, but for this project ArcGIS Desktop 9.3 on ArcView level, with full extensions, together with ArcObjects developer tools are used. A description of this software is provided in subsequent sections of this chapter.

The different components of the ArcGIS software in use and the purposes for which they are used are summarised in the following illustration (see Figure 5-1).

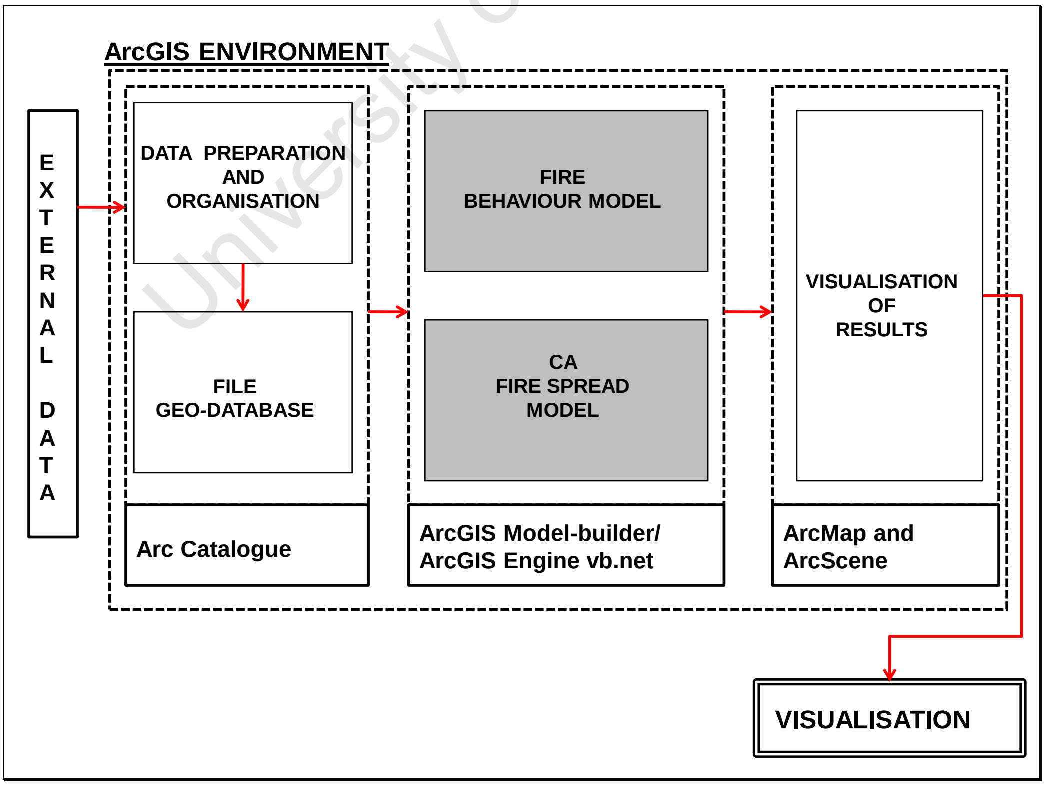


Figure 5-1 Overall System Architecture of fire model

5.4 Data preparation and organisation

This section discusses the use of ArcGIS in assembling and organising of data products from different sources. A considerable amount of work is done in data preparation hence the actual procedures and functions performed in the data preparation phase are discussed in chapter 6.

ArcGIS has a data organisation system named a geodatabase which organises and stores the data for fast and easy access. ArcCatalog is the ArcGIS component application that deals with the storage and organisation of data. ArcCatalog provides tools to manage and browse stored data as well as to view metadata and to preview the data.

The actual system that stores data which is managed by ArcCatalog is a geo-database. ArcGIS offers three different kinds of databases; these are personal geodatabase, file geodatabase and ArcSDE geodatabases. A summary of the differences between these geodatabases is provided in the table below in Table 5-1.

Table 5-1 The types of geodatabases available with ArcGIS (adapted from ESRI, 2008)

Characteristics	**Personal geodatabase**	**File geodatabase**	**ArcSDE geodatabase**
Storage of geo-datasets	Datasets are stored within a Microsoft Access data file (.mdb)	Datasets stored in a file system folder, where each dataset is held as a separate file	Datasets stored as tables in a relational database
Storage size capability	250MB to 500MB	1 TB	Depends on which type of DBMS is used
Platforms	Microsoft Windows	Platform independent	Platform independent
Number of users	One writer and many users	One writer and many users	Multiple user (both data readers and data writers)

The file geodatabase is found to be the most versatile and easy to use option for this project. The use of ArcSDE geodatabases could be ideal if this model is used in larger project settings with many users and more datasets. At this point in time the use of an ArcSDE geodatabase is not a priority because the implementation of this model in a large project setting is not explored. The file geodatabase is preferred over personal geodatabase for the following reasons:

- Since data is stored separately in a file folder, it is easy to access through either ArcCatalog or even Windows explorer whereas a personal geodatabase requires the use of Microsoft access.
- A file geodatabase has more data storage capacity
- According to ESRI (2008), a file geodatabase performs faster than a personal geodatabase

5.4.1 Creating the geodatabase

There are two common ways of creating a file geodatabase; these are through ArcCatalog or by the use of geoprocessing tools. Creating a file geodatabase through the geoprocessing tools is much easier and more direct because it is a guided process as illustrated in Figure 5-2. One does not need to go to the location on disk where the file will be saved, but is rather able to browse through the geoprocessing tool dialog box provided.

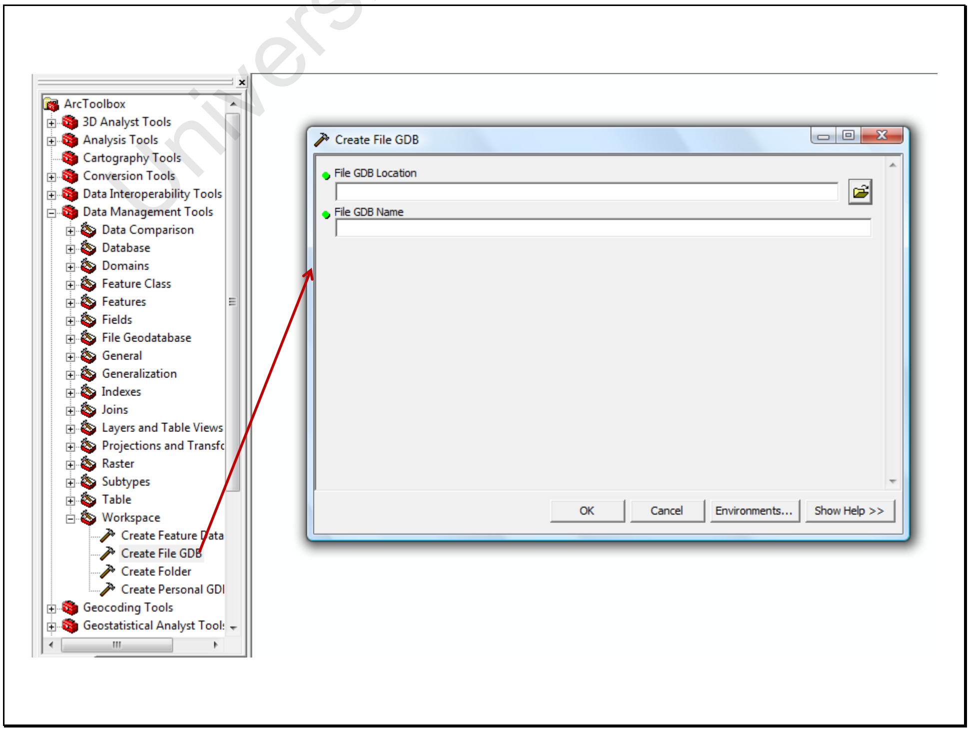


Figure 5-2 Creating a file geodatabase using the geoprocessing tool (ESRI ArcGIS)

5.5 Model development

Apart from the storage of input data, as seen in the previous section and further discussed in chapter 6, data organisation and management is also critical to the model development process for the purpose of storing output data results from the model. The implementation of the fire model, (discussed in the previous chapter), in a GIS environment is performed through the use the ModelBuilder interface, using geoprocessing tools, in ArcGIS by ESRI.

5.5.1 Description of modelling environment

Before the chapter proceeds into the concept of modelling with GIS a distinction has to be made as to the use of the word "model". In the previous chapter the word "model" referred to a fire model as an environmental model. A description of environmental models can be found in chapter 2. Conversely the use of the word "model" in this chapter refers to a GIS model.

In ArcGIS, a model is one of the two ways of automating large spatial analysis processes which is achieved by linking a number of smaller processes together. The modelling of spatial analysis processes is required in cases where a number of complex operations need to be performed on a frequent basis, and it is time consuming to re-build them often. The modelling framework is often used for large, frequently used spatial analysis projects, with examples such as modelling surface runoff, modelling the instability of slopes, etcetera. The environment in which such models are built is called the ModelBuilder application and the spatial analysis processes used in this environment are the geoprocessing tools found in the ArcToolbox. The ArcToolbox is a collection of toolsets which contain geoprocessing tools in ArcGIS. A model consists of three primary components, namely input data, process (geoprocessing tool) and the output data that is produced (ESRI, 2008b). A basic model showing the components is illustrated in Figure 5-3.

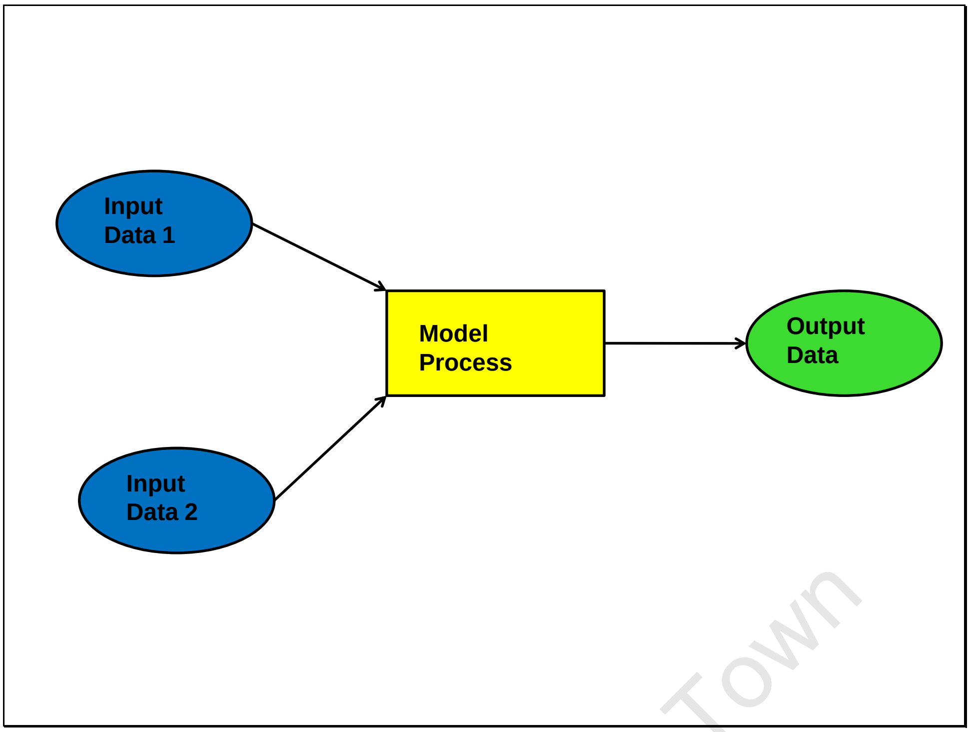


Figure 5-3 A basic model in ArcGIS ModelBuilder application

ModelBuilder simplifies the process of building spatial models, in the following ways (ESRI, 2000c):

- The processes and relationships between these processes are illustrated in a flowchart that can be updated dynamically every time a change is made. This makes the models easy to understand.
- Properties of the components of a model as illustrated in Figure 5-3 can be set and recorded within the model; this makes the output of the model easily reproducible.
- Information about input data and assumptions made by the model can be documented; this makes the model easy for the user to understand.
- ModelBuilder provides functionality for storing and managing output data files on disk.
- The structure of a model can be edited by adding, deleting, or changing relationships between processes.
- The properties of processes can be changed in order to experiment with alternative outcomes

- ModelBuilder provides functionality for performing iterations in order to handle dynamic processes. This can be done by defining an iteration list or chaining the final output of a process as input in order to get a different outcome.

5.5.2 Enhancing ArcGIS functionality

The geoprocessing tools which are used in ModelBuilder form the core of spatial analysis using ArcGIS; however ArcGIS users can extend this functionality by developing geoprocessing tools to suit their own requirements.

There are a number of ways in which ArcGIS functionality can be extended, examples include developing custom extensions, custom commands, custom script tools, and the one which is of interest in this study is building personalised geoprocessing function tools. The enhancement of ArcGIS through developing custom tools is done through the use of ArcObjects.

ArcObjects is a collection of platform-independent software components that are written in C++; they make use of Component Object Model (COM) which makes it possible to develop new software applications using C++, C#, VB.Net or any other COM compliant programming language. The applications that are built using ArcObjects are compiled as dynamic link libraries (.dll); this makes it possible for them to be distributed or reused in order to build other applications (Dietel and Dietel, 2006; ESRI, 2008b). To develop custom tools in ArcGIS, the ArcGIS developer toolkit and access to the ESRI developer Engine are required.

5.5.3 Creating the fire model in ArcGIS

The calculations involved in determining fire behaviour and spread characteristics are outlined in chapter 4 and these involve numerous mathematical calculations. ArcGIS works with two different types of data models; these are the raster data model and the vector data model. Vector models represent data as points, lines or polygons, whereas the raster model provides a representation of the surface as a regular lattice of cells (pixels). Mathematical calculations within ArcGIS are performed only on raster (grid) datasets. This is because a raster surface is continuous. The attributes that describe the surface that the raster dataset represents, are often in numerical form. These numerical attributes are stored within the raster cells and are the values that are used to perform the mathematical calculations.

5.5.3.1 Choice of cell size

Before performing mathematical calculations it is important to decide on what cell size is most appropriate to represent the data. This is important because it ensures that all important features that are required can be represented. Although cell size primarily depends on the lowest resolution of data that has been acquired in order to achieve reliable results, it is possible to resample to represent the features that are important.

In this research, a combination of vector data and raster data is used as input into the fire models, thus it is necessary to be able to account for both raster data and vector data in the mathematical calculations. This however would result in choosing a cell size that would identify even the smallest roads in the area. On the other hand, a very small cell size affects the speed of processing of a computer. As a result the choice of raster cell size in this case is made to allow acceptable processing speed by the computer as well as representing important features. A cell size of 50m is therefore chosen. The effect of roads, rivers and water bodies is accounted for when interpolating fuel load measurements hence when such a feature is encountered no fuel is assigned. This issue is discussed further in the data preparation section. Resampling changes the cell size of a raster without changing the extent of the raster. There are a number of resampling techniques available within ArcGIS; these are, nearest neighbour, majority resampling, bilinear interpolation and cubic convolution.

Briefly described, nearest neighbour is used mainly for discrete data, for example in land classification, and it does not change the cell values. Therefore this does not affect the output results that are based on a resampled layer because the cell values have not been changed. Majority resampling is also used in the same cases as nearest neighbour but it produces a much smoother result and it changes the cell values. The cell values are changed based on the most popular values within the filter window; this could affect the accuracy of output data because the original cell values have been changed. Bilinear interpolation and cubic convolution also change cell values while changing the cell size. The nearest neighbour method of resampling is used in this model because the aim is to change the cell size within raster without changing the cell values, hence not risking the possibility of altering the data and acquiring less accurate results. The nearest neighbour method is illustrated below in Figure 5-4.

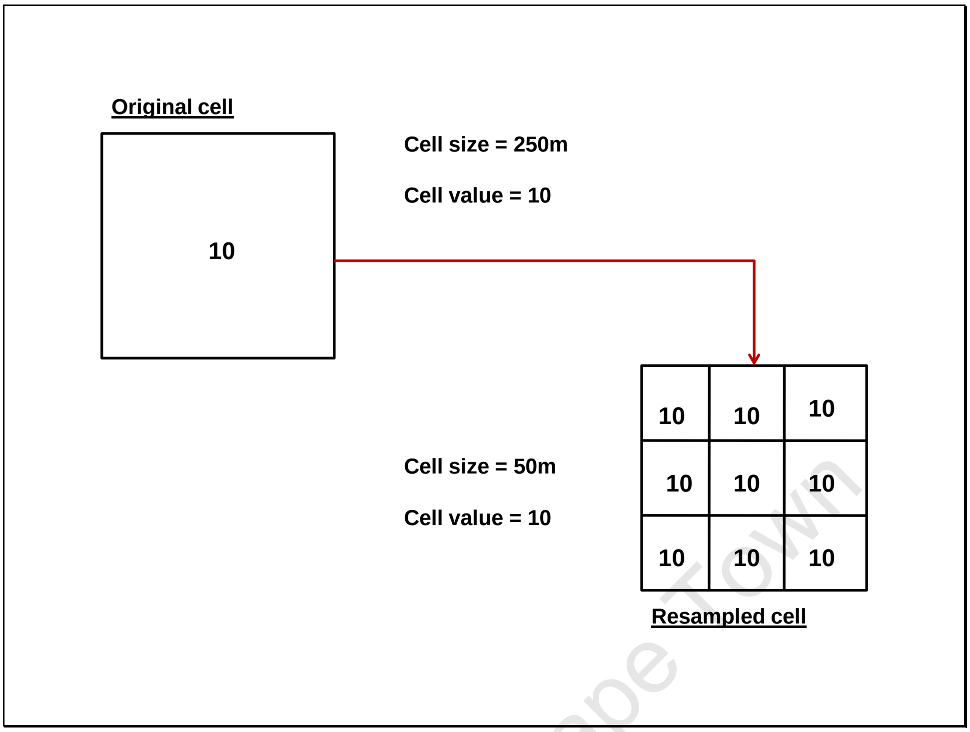


Figure 5-4 An illustration of the nearest neighbour resampling technique

5.5.3.2 Mathematical functions

ArcGIS offers built in tools to perform mathematical functions on raster datasets. These functions are performed using the spatial analyst geoprocessing tools. The range of mathematical functions available includes simple arithmetic functions, trigonometric functions and logical operations. These functions are performed on a cell by cell basis on two overlaying raster datasets.

The calculations of fire behaviour parameters are all based on mathematical functions. If the calculation encounters problems such as division by zero and the output value of the cell is undefined, the pixel is assigned a no data value. This causes a problem in the calculations that depend on the derived output of this operation because it implies that this cell is now excluded from all calculations that follow. To overcome this problem, a conditional statement is used to avoid division by zero. An example of solving such an issue is by not allowing cell values to be zero, but rather a number that is very close to zero. This is however done with care such that it does introduce errors in results. Hence mathematical functions as well as logical (conditional statements) functions can be carried out with geoprocessing tools, apart from the standard editing of datasets which traditional GIS are known for.

In general, the calculations for fire behaviour characteristics; which are fire intensity, rate of spread, flame length, flame angle, combustibility index and its components as well as the burning index are implemented within the model using core geoprocessing tools within the following toolboxes:

- Data management tools
- 3D Analyst toolset
- Spatial analyst toolset
- Analysis tools
- Conversion tools

It is also possible to embed a completed autonomous model within another model, which then becomes a sub model tool in the higher level model, within ModelBuilder. This is very helpful in cases where the portions of a model need to be re-used; as an alternative to re-building the model components again, it is possible to re-add the sub model that was used previously. If the output data sets produced will not need to be used again then they are overwritten in this new instance of the sub model. The advantage of dividing the model into sub models is that it makes the entire model more compact and neat; therefore it is much easier to read and follow. Since the inputs of the sub models can be over-written, it saves disk space.

5.5.4 Developing a custom geoprocessing tool

In chapter 4, a description of the CA model used in this study showed that the state of a cell depends on the states of the cells in its neighbourhood. This fact shows that in order to perform such CA modelling it must be possible to access and edit portions of a raster dataset. Amongst the licensed geoprocessing tools available within ArcGIS none was found to be capable to perform CA calculations as well as being suitable to use in the ModelBuilder environment. As a result a custom geoprocessing function tool had to be developed that would provide the required functionality.

The VB.NET (2005) programming language with ArcObjects (9.3) is used to perform this operation. A discussion about ArcObjects has been provided earlier in section 5.5.2. The following sections discuss the steps followed in developing the tool and more detailed descriptions of programming with ArcObjects and VB.NET are provided.

5.5.4.1 Developing a geoprocessing function tool with ArcObjects

A geoprocessing function tool has two main objects namely the function object that implements IGPFunction and the function factory object that implements IGPFunction factory. These are geoprocessing interfaces within ArcObjects. The IGPFunction provides access to methods and properties that are required to build a function tool. The IGP function factory provides a wrapper to the function that is created to make it accessible through the ArcToolbox; hence the purpose of the function factory is to manage the geoprocessing function tool. A discussion of the component methods and properties of the function and function factory follows.

The IGPFunction object has a number of properties and methods, some of them compulsory and some are not. The compulsory components will be discussed and the optional components are only mentioned. The compulsory properties are the name, display name, full name and the ParameterInfo properties, whereas the optional properties are the helpfile, metadata, Dialog CLSID. Briefly, the optional properties describe the extra files that describe the tool such as the metadata and help files. The DialogCLSID property is used to override the default dialog box that a tool displays at run time, if not over written, the toolbox will have a dialog box which is similar in appearance to all the other built in tools. A short description of each of the compulsory properties is given below:

- **Name property**

  This is the name of the tool that it is identified by within the code and if required in the code of another tool. It is the name that is used to identify it in scripting or command line therefore it must be unique to the particular tool and must not contain spaces. For example the tool developed here has the name: "CalculatePixelValue"
- **Display name**

  This is the name that it is identified by and is displayed in the toolbox. Following our example, this will make our display name: "Calculate Pixel Value"
- **Full name**

This is the function name object for the geoprocessing tool and is created by the function factory; therefore a function factory must first be created before implementing the full name property.

- **ParameterInfo property**

  This is where the parameters of the function tool are defined, including the characteristics of the input and output parameters. In the code, an array of parameters objects is returned. Only the compulsory parameter information is provided below:

  - Name

    The name of the parameter, which does not contain spaces
  - Display name

    The name used by the user interface to identify the parameter in the dialog box
  - Parameter type

    This indicates if the parameter is required, derived or optional. A derived parameter is used in the case where the tool does not create an output dataset but rather updates the input dataset. It is used in ModelBuilder to provide proper linking of tools which will then displays the input again as output as illustrated in Figure 5-5 below.

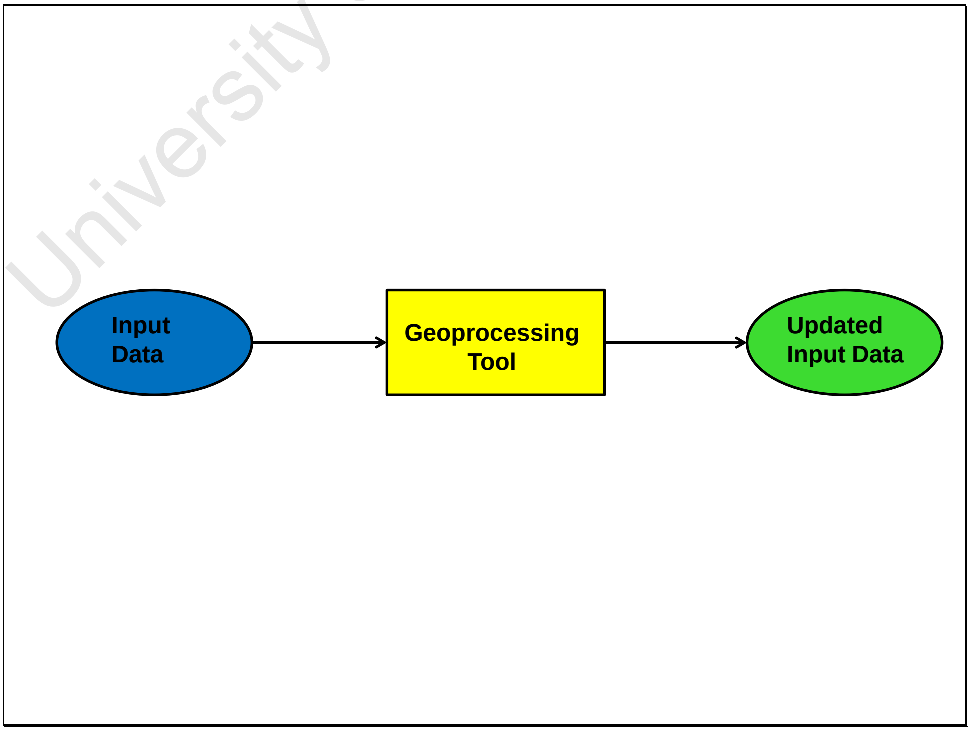


Figure 5-5 The chaining of tools in model builder where the input data has parameter type derived

Derived parameter types are not displayed on the tool's dialog box as is the case with the required and optional parameter types. The tool will not run without a required parameter as this is mandatory, but it will do so without a parameter with type optional. The optional data types are sued in cases where one needs to apply more control over the output or requires additional results.

- Direction

  This indicates whether the parameter is an input or output
- DataType

  This indicates if the parameter is a raster, feature, table, string or number. It controls that only data of the specified type will be input, for example a string cannot be input if a raster is required, or otherwise the tool will not run.
- Value

  This defines the default value for a parameter.

The compulsory methods of IGPFunction are the Validate and Execute methods.

- **Validate**

  The purpose of the validate method is to check that the parameter information supplied is of compatible formats with all the information in the ParameterInfo properties. If the parameters supplied do not match the parameter information then validate method returns a warning message stating which parameter does not comply with the requirements that are stated in ParameterInfo property. If all information about the parameters is correct no message is returned.
- **Execute**

  This is the method that includes the code that will be executed when the tool is run.

The order in which the code executes when the tool runs is explained by the illustration below Figure 5-6.

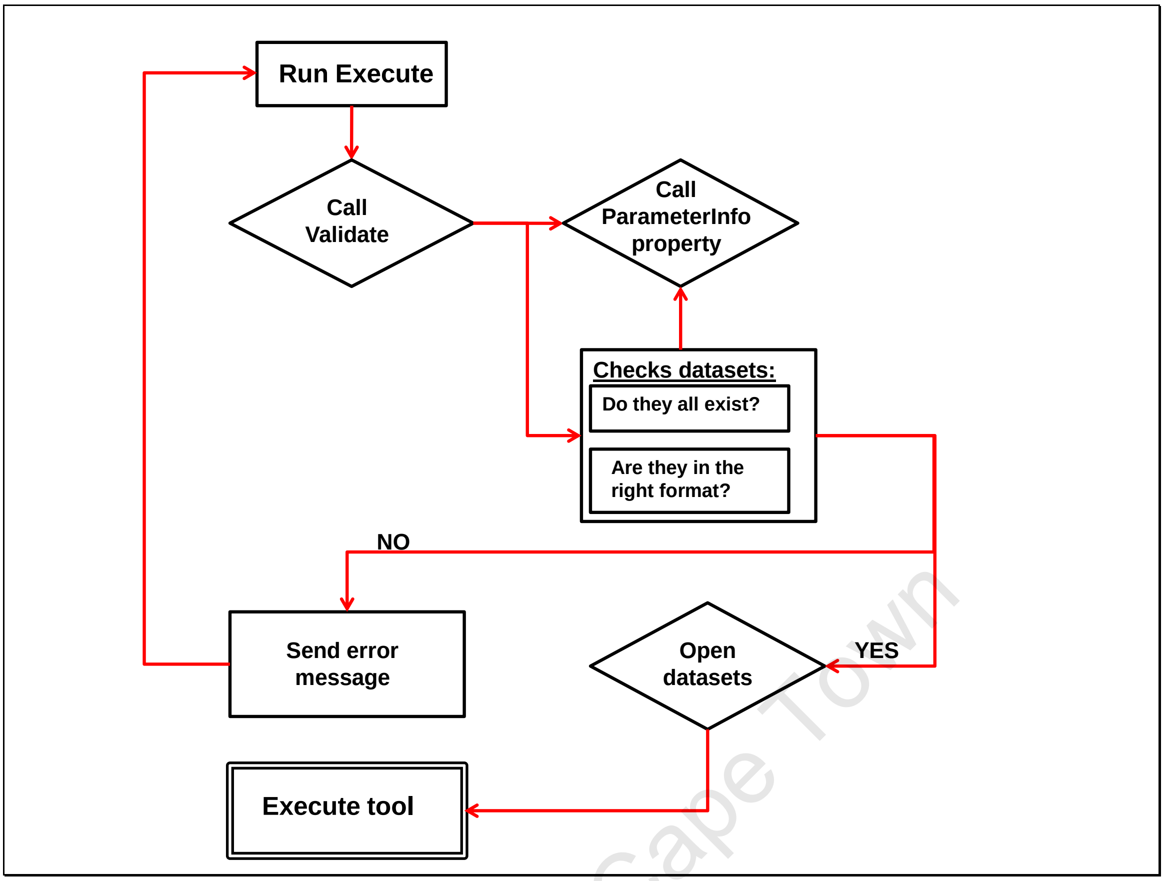


Figure 5-6 Process flow in execution of geoprocessing tool

IGP Function Factory methods are used to provide access to the tool and to register the tool in ArcGIS and these are GetFunction, GetFunctionName, GetFunctionNames. The compulsory properties are:

- **CLSID property**

  This is the class identifier of the function factory

- **Name Property**

  The name of the function factory which is used in Arctoolbox as the name of the toolbox that contains the function tool described above.

- **Alias Property**

  The alias name of the function factory is used in command line or scripting when specifying to the function tools contained within the factory.

5.5.4.2 Programming with VB.NET and ArcObjects

The previous section described the structure of how a geoprocessing tool is created using ArcObjects. The objects, methods and properties used to do this were explained; this section describes how this is incorporated into the VB.net 2005 programming language that was used to develop the tool.

After creating a new VB.net project, the next step is to create a class library and then add references to the ESRI object libraries that are required. The object libraries used are listed below and a brief summary of each is provided:

- **ESRI.ArcGIS.Geodatabase**
  Provides access to types that control any activity relating to access of datasets, whether raster, vector, table or any other supported dataset in ArcGIS
- **ESRI.ArcGIS.Geometry**
  This contains types of any geometry objects in ArcGIS, such as points, polygons and polylines and their definitions. It also defines and implements the spatial reference objects for projected and geographic coordinate systems.
- **ESRI.ArcGIS.Geoprocessing**
  This implements the geoprocessing framework as well as the core geoprocessing tools.
- **ESRI.ArcGIS.esriSystem**
  This library contains components that expose services used by other libraries in ArcGIS; hence it controls all the other libraries.
- **ESRI.ArcGIS.DataSourcesFiles**
  Contains workspaces and workspace factories for vector data formats
- **ESRI.ArcGIS.DataSourcesRaster**
  This is similar to the one above except that it contains workspaces and workspace factories for file raster data formats and not vector formats
- **ESRI.ArcGIS.Carto**
  This library is responsible for the display of data on the map layout or through servers in a client server environment.

Having added the references to the required ESRI object libraries the COM class is created and then the code is written. The COM class is where the code is written and it is the one that is compiled into a dynamic link library (.dll) before the tool can be executed.

5.5.5 The functionality of the geoprocessing function tool

The function tool developed here calculates a new value for a selected pixel on a raster dataset and edits this value by replacing it with the newly calculated value. This tool is developed in order to aid the Cellular Automata process. It is written in such a way that it can be accessed as a geoprocessing tool through ArcToolbox and can be used for any CA process; however it requires minimum editing before it can be reused. The editing that is required is to change the equation that calculates the new pixel value. The purpose of creating a COM class is that the code can be accessible and reused in another code is also explored in the design of this tool. Consequently this aids the flexibility of the developed tool.

This section explains the function of the geoprocessing tool that is created. The inputs of this tool are listed below and explained based on the CA fire model in chapter 4, using the equation of how to calculate new cell states:

- **Input Raster Dataset**
  The input raster dataset used in this case is the raster that contains the rate of spread values for the whole study area.
- **Event start point coordinates**
  The start point contains are the XY coordinates of the location where the fire started in UTM (WGS84) coordinate system.
- **Time interval**
  The time interval Δt, is the time required to cross the cell with the highest rate of spread in the cells neighbourhood.
- **Iteration number**
  The spread of a fire through a surface depends on multiple calculations of the new cell value in different time intervals. These re-calculations are performed as iterations of the model. The number of the specific iteration is stored within the model and is retrieved here.

The steps followed in creating the function tool are thus described:

- **Get input raster dataset**
  The input raster dataset is accessed and decoded so that it can be read by the code.
- **Get XY coordinates of the event (fire) start location**
  The XY coordinates of the fire start point are retrieved.

- **Determine the location in terms of pixel coordinates**

  The location of the start point is given in terms of map XY coordinates but in order to define the neighbourhood of the cell the coordinates of the start point are required in pixel coordinates (r,c). The definition of the neighbourhood will be explained in the next step. The conversion to pixel coordinates is explained below.

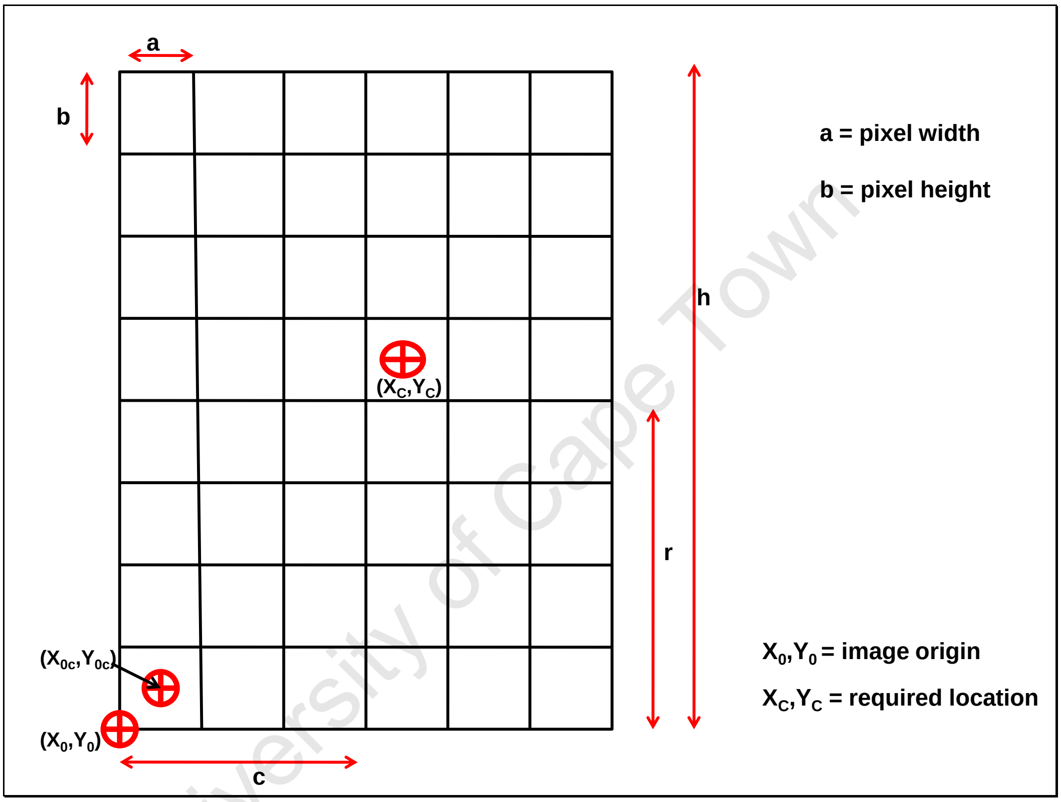


Figure 5-7 Conversion of start cell coordinates from Cartesian to pixel coordinates

The first step is to determine the origin of the image with respect to map coordinates, (X_{0C}, Y_{0C}). The origin in this case is required as the centre of the first pixel in the bottom left of the image (see Figure 5-7). The map coordinates of bottom left corner of that pixel (X_O, Y_O) can be retrieved in the code through one of the methods made available by the imported ESRI libraries. These coordinates are then used to acquire the required location as follows:

$$X_{OC} = X_O + (a/2) \qquad \textbf{5-1}$$

$$Y_{OC} = Y_O + (b/2) \tag{5-2}$$

A raster is always rectangular in shape but in most cases the pixels with no data values are given the same colour as the map space background hence making the raster image to appear to have a distinct shape (see Figure 5-9). This is why it is possible to acquire the coordinates of the bottom left extent of the raster; and is done so as to simplify the calculations that require extents of raster dataset. The following equations are then applied. The column (c) in which the coordinates falls is calculated as follows:

$$c = \frac{(X_c - X_0)}{a} \tag{5-3}$$

The calculation for the row in which the start cell falls, is as follows:

$$r_c = \frac{(Y_c - Y_0)}{b} \tag{5-4}$$

And finally:

$$r = (h - r_c - 1) \tag{5-5}$$

The final equation to determine the row (r) accounts for the fact that the pixel coordinates has an origin that begins on the top left side of the image and not the bottom left as with the map Cartesian coordinate system (see Figure 5-8). It is worth mentioning that the start coordinates that are provided as input will not always necessarily be the coordinates of the centre of a cell but as long as they fall within a particular pixel they will be converted to coordinates of the pixel they fall within. This is achieved by rounding the values of (r) and (c) up or down appropriately.

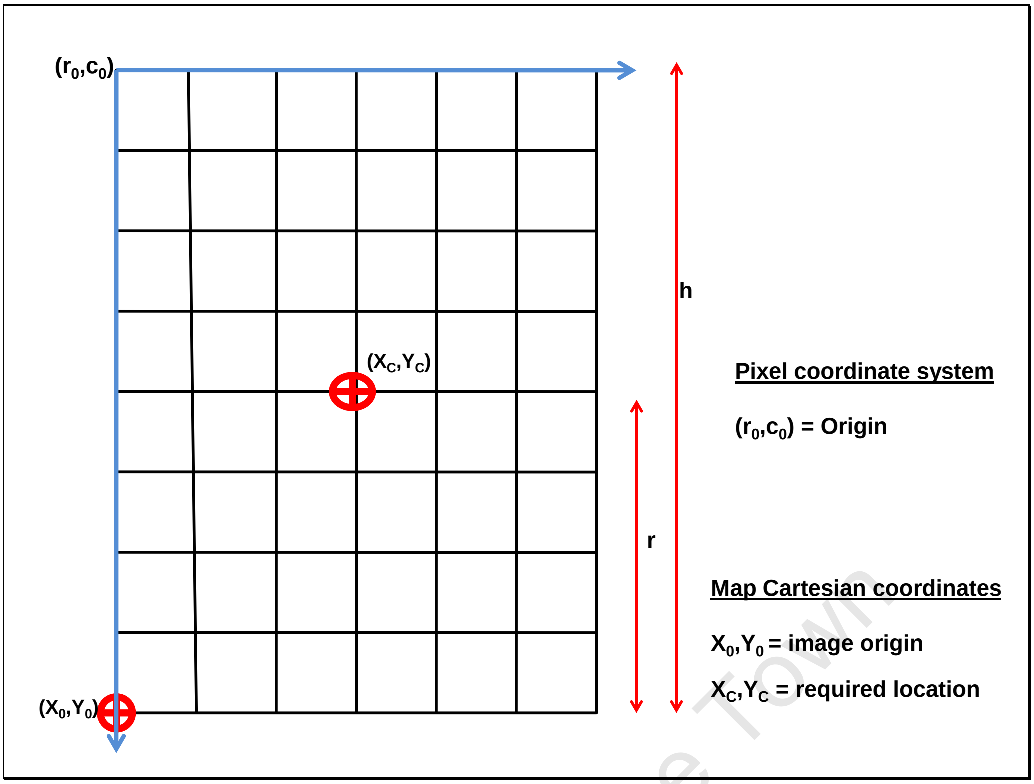


Figure 5-8 The pixel coordinate system (drawn in blue) superimposed on the map Cartesian coordinate system

- **Define the Moore neighbourhood of the cell centre as a pixel block**

  Once the Cartesian coordinates of the start location have been converted to pixel coordinates, the Moore neighbourhood of the selected pixel, which consists of the 8 pixels directly surrounding the cell, is defined. This neighbourhood containing only the directly connected pixels is typically defined as having a width of 3 and height of 3 pixels; this includes the centre pixel. The following Figure 5-9 presented summarises this discussion.

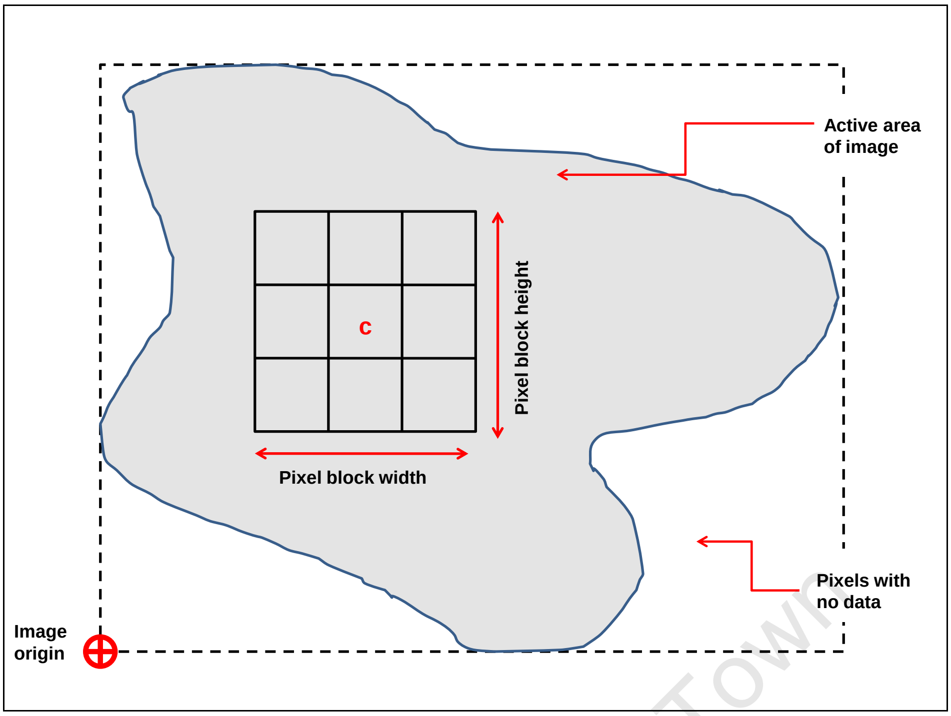


Figure 5-9 Illustration showing the rectangular shape of a raster dataset, inactive and active pixels and the definition of the size of a pixel block.

- **Access the pixel values of the cells in the neighbourhoods and store them in an array**

  The pixel block, containing the neighbourhood of the centre cell is then read from the image band and the pixel values of these cells are then retrieved and stored in a temporary array.

- **Perform the calculation of the new pixel value using the values in the array**

  The pixel values stored in the temporary array are retrieved and used to calculate the new value of the cell using the state equation, equation 4-27, presented in chapter 4.

  The components of this equation are explained in chapter 4, section 4.5.9 and are used to determine the parameters of the geoprocessing tool in discussion.

- **Write back the new pixel value into the original raster**

  When the new value for the centre pixel has been calculated this value is then written back to the centre cell in the input raster. The output raster has been described to be of derived data type; hence the input dataset which has now been edited or updated with the new pixel value is returned as the output dataset and as a result, is made available for access to other ModelBuilder processes as input, to complete the model. This updated pixel value introduces the dynamic component of the modelling process and it is used to calculation the state of a pixel at a specific time instant.

The fire spread model using cellular automata is described in chapter 4. From this discussion it is clear that the spread of fire from cell to cell is an iterative process of several igniting and extinguishing cells, hence the model has to perform iterations to show this. The tool described above is involved in the iteration process.

A reminder of the CA process followed in this model is provided to clarify the discussion below. In the first instance, after ignition only one cell is active and fire spreads to the neighbours. At the second time step this burning cell has burned out and ignites the neighbouring cells. The neighbours themselves now become focus centre cells; this means that the tool above has to be applied to all this newly burning cells. Two options of how to implement this in the model were explored.

The first option is using the model to perform these iterations and not the developed geoprocessing function tool. This involves iterating using a list of cell value written to raster datasets, where the model that calculates the new cell value produces new data sets that have the new cell values; this depends on how many burning cells there are. These cells with the new values are then merged together at the end to provide one output raster. This model was unable to deal with the large capacity of datasets that were being created due to limitations in computer resources.

As a result, a second option was sought. The option was to increase the functionality of the developed geoprocessing function tool such that it is able to perform internal iterations between the cell centres and update the input dataset with the new pixel value. This approach works very well and avoids the problem experienced due to limited computer memory. As a result, the developed geoprocessing function tool has the capacity to include multiple start points of the fire resulting from new ignition of more cell centres.

The process of fire growth includes two kinds of iterations. There is an inner iteration where the values for the new centre cells are calculated and the outer iteration where the model is iterated through different time intervals. The tool solves the problem of inner iterations and the entire model then has to iterate over different time intervals to show how the fire will spread. The inner iteration is responsible for changing the pixel values in the updated raster grid. Care is taken when moving to an overlapping region that the old pixel value is used instead of the newly calculated one. If left unattended this problem would lead to inaccurate, accumulating, pixel value results. This is avoided by temporarily saving the new values to an array and only writing them back to the raster cells once all the new values had been calculated. The overlapping regions of the centre cells are shown in the figure below Figure 5-10.

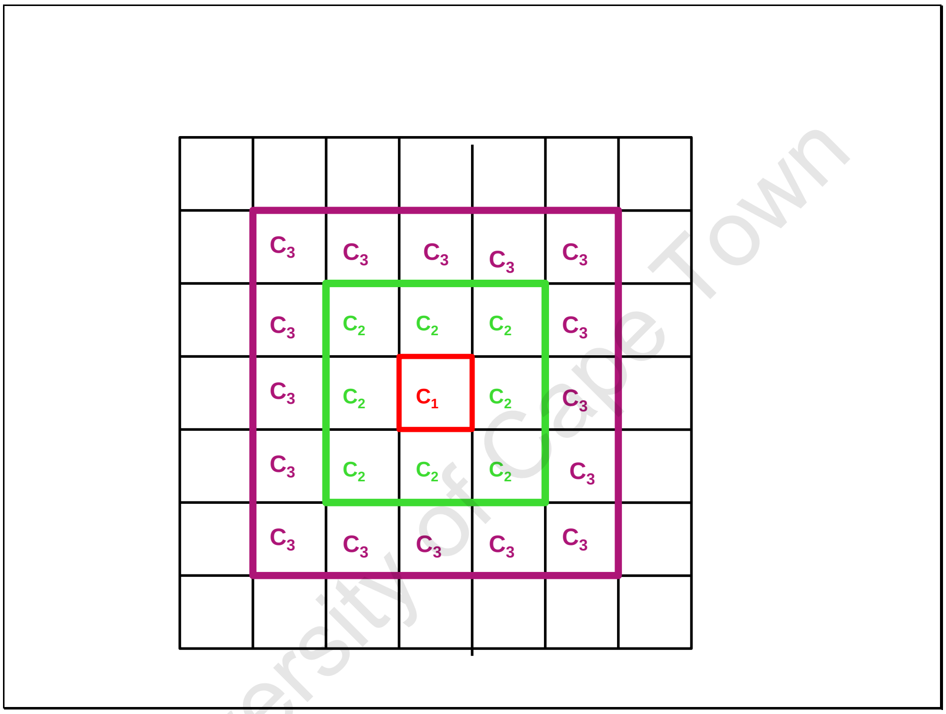


Figure 5-10 The number of possibly active cell centres increasing with the number of iterations showing the first (C_1) and second (C_2) and third (C_3) iterations. An active cell can alos become a neighbour to another cell i.e in top right cell C2 is a center cell but it is alos a neighbour cell to the next cell on its immediate right hence this would create the over calculation if the value of the first C1 is written back to the cell before the second C2 is caluculated.

Although some cells burn out and become inactive at the end of a particular iteration they are considered in the calculation and given no data values on the map for consistency.

5.6 Visualisation

Once all the calculations have been carried out, the next task is to implement the visualisation of results. In order to aid visualisation of growth models, animation of the acquired results are performed. There are a number of ways to perform animations in ArcGIS. The methods that are suitable for this type of study are performing animations through time. These animations can be performed on feature layers, raster catalog layers.

From observation, it is common practice that vector based fire models display fire fronts in vector format and the raster based models display the results of a fire in raster format. According to this study the growth of a fire is shown in two ways. Firstly, as the growth of a region of fire showing explicitly what happens within the fire area by displaying fire behaviour characteristics exhibited by the burning fire pixels. As mentioned in chapter 4, for a burning cell, it is important to know how hot a fire is burning and how long the cell has been burning. The second method is by displaying the approximated burning fire front. In GIS terms, the first method displays animations of fire area through time in raster format, whereas the second method displays the animation of a fire front through time in vector format. These methods are discussed separately below.

5.6.1 Animation of fire area through time

The animation of fire area through time is achieved through the use of raster layers. This method is straightforward because the spread of fire is modelled in grid raster space.

The raster layers are stored in a raster catalog layer for the animation to be possible. The raster catalog layer must be stored in a geodatabase; therefore the geodatabase that is discussed in section 5.4.1 is used to store this raster catalog.

5.6.2 Animation of fire front through time

The animation of fire fronts through time requires the use of vector layers. The output of the fire simulation, CA model is raster datasets. These raster datasets that are produced by the model must be converted to vector format, more specifically polygons. Consequently this method is not as straightforward as the first method. The conversion of raster dataset showing the behaviour of the fire to fire front polygons is outlined below.

The assumption made is that fire spreads as far as the centre of a cell it occupies. The burning cells are, without considering how hot or how long they have been burning, extracted from the raster. These extracted cells are then converted to points; where the points occupy the centre of the burning cell. These points are then joined to create the fire front polygons. The conversion to polygons and not polylines is made so as to enable shading of the area of for verification purposes and to aid better display of the fire area.

Another option is to create a smooth surface that does not have hard edges in order to show a more realistic representation of the fire area. As a result, instead of converting the points directly to polygons, a convex hull of the points is calculated as used as the fire front. A convex hull is a minimum convex surface that aggregates the points within a set of points (Worboys and Duckham, 2004). The concept of convex hulls is illustrated through the use of these graphics Figure 5-11. ArcGIS has a built in function to calculate and generate convex hulls. Smoothing if over done can result in inaccurate representation of results; this is further demonstrated in the chapter on analysis of results, chapter 7.

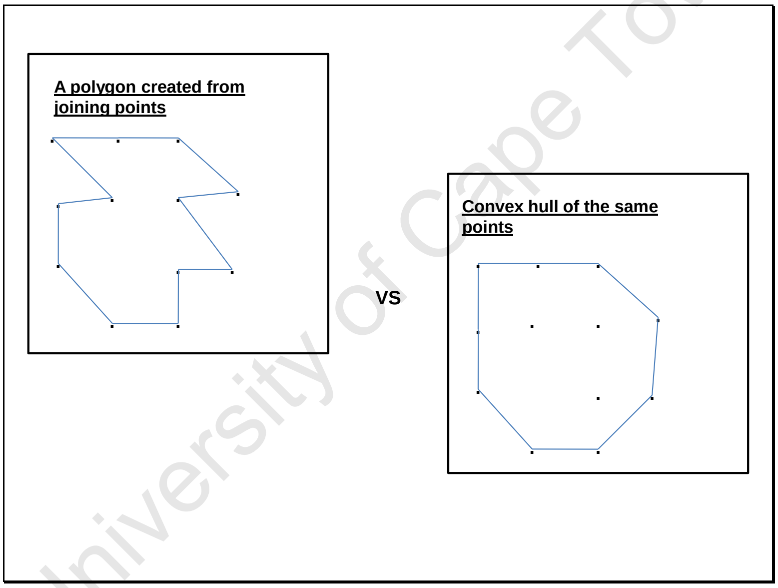


Figure 5-11 The comparison of delineating the fire area by 1) connection of points to form a polygon (on the left), and 2)connection using a convex hull (on the right)

5.7 Discussion

The previous chapter gave a theoretical description of the methods that are employed in this study to develop a fully integrated fire model. The fire model calculates the predictive fire behaviour characteristics as well as predicting and simulating the spread of a fire through a surface once an ignition event has occurred.

This chapter deals with the implementation of the theoretical model, proposed in chapter 4, in a GIS environment, more specifically using ArcGIS. The ModelBuilder environment is proposed as the suitable modelling environment for implementing environmental models in this case fire modelling. Within the ModelBuilder environment, it has been indicated that core geoprocessing tools can be used to model the spread of fire through the Cellular Automata technique. Although these tools can be used to develop a CA model, the result is computer intensive hence it is not a very practical process.

The limited ability of the geoprocessing tools in terms of CA modelling however lead to the exploration of how to enhance geoprocessing functionality within the ArcGIS environment, and implementation thereof, to simplify the process. ArcGIS provides functionality for developers to extent or build over the basic properties that are provided, through the ArcObjects components which can be used with most programming and scripting languages and compiled for re-use in other programming sessions. The custom geoprocessing function tools are thus developed to supplement the basic functions that are provided with ArcGIS and the predictive fire spread model completed.

The next chapter explores the data that is used in predicting the behaviour and spread of wildfires. The data acquisition and preparation of this data for use in the developed model are thus explored.

6 DATA ACQUISITION AND PREPARATION

6.1 Introduction

One major concern in spatial modelling is the accuracy of the model which depends on the quality of the input data used in the model. A general consensus is that the reliability and efficiency of a model depends on the input data, hence the reliability and validity of input data must be verified as it will help improve the accuracy of the model output (Clarke et al, 2002;Skidmore, 2002;Brimicombe, 2003;Wainwright and Mulligan, 2004)

Rothermel (1972) stated that one of the major steps in building a predictive fire model is making a decision about what data is perceived to be the most appropriate to include in predictive model.

This chapter discusses issues relating to data in building environmental (in this case fire) models. These are organised to constitute the three main sections of this chapter. In the first section, the identification of data to be used in the model is discussed. The second section deals with the acquisition, access and description, of the selected data. The final section discusses the preparation of the data into formats that are suitable for the modelling process in ArcGIS. Figure 6-1 below, gives a summary of this chapter which describes data acquisition and preparation.

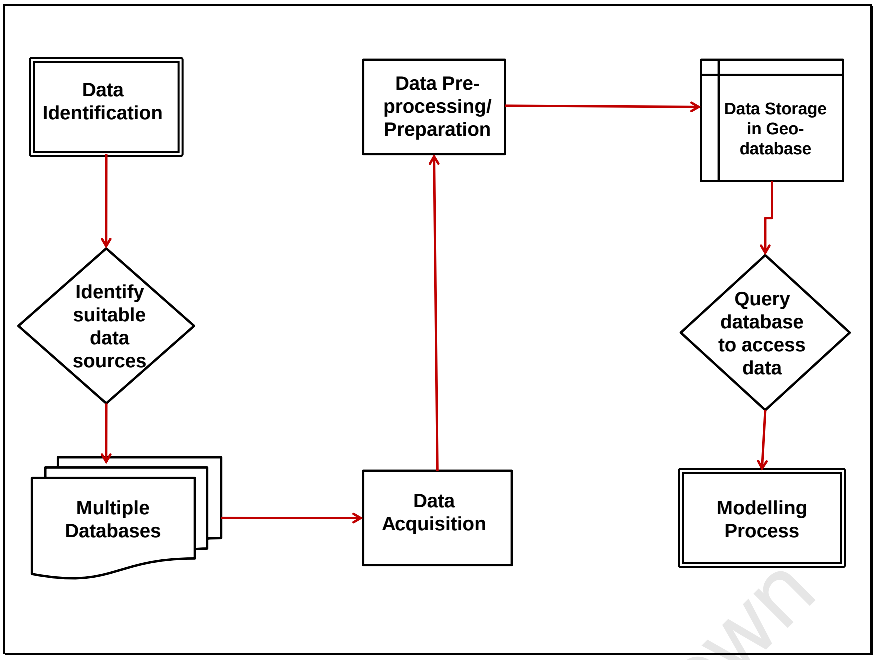


Figure 6-1 Summary of work flow processes involved in data acquisition and data preparation

6.2 Identification of Required Data

The Identification of data required in a specific model is performed through the investigation of data that is generally required in most wildfire models; this includes factors that affect the behaviour and spread of wildfires. The list is then narrowed down to data that is readily available for the study area, and eventually data that is required for the selected modelling processes is identified. Once the data has been identified it is then grouped into categories depending on the phenomenon it represents. The purpose of data grouping is to narrow down the search for possible data vendors. A typical example to illustrate this is weather data such as wind speed and relative humidity, which both describe the weather patterns that are experienced by an area, and hence this data is are grouped under weather variables. When looking for data sources it is most likely that the data provider who supplies wind speed also provides all data relating to weather conditions.

A table showing all the data that is required for modelling fire behaviour and fire spread as well the groupings is provided in Table 6-1.

Table 6-1 The table showing the data required for fire modelling and the purposes for which the data is used

DATA GROUP	RAW DATA ELEMENT	DERIVED DATA	PURPOSE OF USE
Weather	Relative humidity		Calculation of fire Intensity (FI)
	Wind Speed		Calculation of fire intensity and rate of spread (ROS)
	Wind direction		Predictive fire propagation simulation
Topography	Digital elevation model (DEM)	Slope	Calculation of FI
Vegetation	Fuel load		Calculation of FI and ROS
	Satellite images	Fuel moisture	Calculation of FI and ROS
Natural environment	Water bodies (rivers, lakes, dams)		Used to delineate fire breaks
Infrastructure	Roads, airstrips,		Fire breaks
	Rest camps, picnic spots, public access gates		To indicate human activity
Previous Fires	Fire scars, start and end location, fire dates		Validation of predictive model results

6.3 Data Acquisition

When data has been grouped, the next stage is to identify the data vendors. The choice of data vendors is based on the credibility of the organisation where the purpose is to control the reliability of the data used as input in the model. The credibility of the organisation supplying data is judged based on its record of supplying data and also whether metadata is provided for the data being sourced. Consequently, the credibility of a data vendor and data supplier is measured in accordance with the South Africa Spatial Data Infrastructure (SDI) Act (No. 54 of 2003). A summary of the stipulations of the SDI Act in terms of data capture, supply and access is provided in the following subsection. International data vendors and suppliers are selected based on the credibility of the organisation (such as NASA)

6.3.1 SDI Act (no. 54, 2003)

The SDI Act (no. 54 of 2003) stipulates conditions relating to supply and handling of data. The purpose of the SDI Act is to facilitate the capture, and regulate sharing and transfer of spatial data. Amongst other functions, the Act also helps to avoid duplication of datasets, protects copyrights of data custodians and promotes management and maintenance of data.

It is the obligation of the data custodian[7] to supply metadata for any piece of data that they produce. In this context, metadata refers to the information that describes the characteristics of spatial data, such as the content, quality and condition of the data. The quality of the data refers to the level at which the data meets the required standards according to the SDI Act or the needs of the users. This includes information about the completeness, accuracy of the data and when it was produced or last updated. The data custodian may appoint a data vendor[8] to supply the spatial data or derivatives thereof; however they are still accountable for the data in its original, unmodified form. Whenever this data is supplied, whether by the creator or the supplier being the custodian or vendor respectively, it must be accompanied by the metadata.

The Act also makes provisions for data access agreements between the data user and data custodian or data vendor, depending on who the supplier is, at their own discretion. The terms of the agreement must stipulate the duration of the agreement, legal protection of the copyright and any other conditions deemed necessary by the supplier. (Government of Republic of South Africa, 2004)

6.3.2 Data acquisition based on SDI Act guidelines

A number of different data sources were identified based on the data groupings discussed in section 6.2. In the aforementioned section, the criterion for data source selection was mainly the credibility of the source following the SDI Act which is discussed in section 6.3.1. Examples of such sources include the Department of Land Affairs' Chief Directorate of Surveys and Mapping (CDSM), South African Biodiversity Institute (SANBI). International sources include the United States Geological Surveys (USGS) and the US National Space Agency (NASA).

A number of data access policies were encountered and all of them had the same purpose, which is to protect both parties involved in data sharing and transfer, but most favour the data custodian and supplier. Data policies protect the data custodian by indemnifying them in

[7] According to the SDI Act above, a data custodian is a person or organization that produces, maintains and distributes spatial data

[8] A data vendor is a person or organization that supplies spatial data on behalf of the data custodian.

cases where inconsistencies found in data have the potential to cause harmful consequences to the data user. The policies also address copyright issues such as requiring the user to correctly credit the data custodian, as well as the concern of the data custodian in connection with the way the user utilises the data. The data management and access policies generally affect the availability of data. There are cases, such as the Kruger National Park scientific services, where the data custodian required the user to sign an agreement stating clearly the purposes for which the data will be used. A declaration that no other use of data will be carried out outside the terms agreed on has to be signed before the data could be provided to the user.

The following sections identify the data custodians from which data is acquired followed by a description of the acquired data. A table summarising the metadata and data custodians is presented at the end of the discussions.

6.3.3 Data Description, Custodians, and Vendors

6.3.3.1 Weather data

Weather data is used for the calculation of fire intensity and fire rate of spread and is required on a frequent basis. Most fire behaviour models give daily forecast of fire danger; hence they require forecasts of weather data at least once daily. Weather data forecasts are available twice daily from the South African Weather Services. It is possible to get forecasts for seven days at a time and this data is available for a distribution of weather stations throughout the country.

The data can be requested and supplied electronically without any direct contact with the organisation. No data user agreement needs to be signed but the user is required to register and provide details, both personal and pertaining to their organisation. After registration, the data user applies for data through the SAWS website. It takes at most four days for SAWS to process a data request and this data will be sent through email in the form of a Microsoft Excel spreadsheet with the format displayed in Table 6-2. The fact that it takes up to four days to process a data request at SAWS is a major limitation for this predictive model; thus will be discussed in the chapter about limitations.

Table 6-2 Example showing format of weather data table provided by SAWS

Weather Station	Relative humidity	Time
Skukuza	43.2	14:00

The Kruger National Park also operates weather stations within the park and this data is also available in the tabular format illustrated in Table 6-2 above.

6.3.3.2 Topographic data

Slope is required for the calculation of fire intensity. The slope can be deduced from the elevation of an area and for the purpose of this research the elevation information is derived from a digital elevation model (DEM). The Chief Directorate of Surveys and Mapping (CDSM) aims to provide a DEM for the entire South Africa at an interval of 25 meters (25m). This data is available for different map grid blocks in the form of tab delimited ASCII files. However, the elevation model provided by CDSM is not complete for the whole country including parts of the study area.

An alternative source of the elevation model is provided at a lower resolution of 90 meters by the NASA Shuttle Radar Topography Mission (SRTM) for the entire African continent. The SRTM was a joint mission between NASA and the US National Imagery and Mapping Agency (NIMA) that produced topographic data for approximately 80% of the earth's land surface between 60˚ north and 56˚ south, latitudes, using the radar interferometry technique. The accuracy at which this elevation model was produced is declared to be better than 16 meters in height, at 90 % confidence level, but is not explicitly known for the study area.

The SRTM DEM is available in two different formats namely the ArcGRID format, an ESRI proprietary format, and tiff, 32 bit floating point grid format. It is available in the Geographic coordinate system, WGS84 datum or the NAD83 (horizontal) and NAVD88 (vertical) datums. This data is available online at a fee, on the USGS Earth Resource Observation and Science website, http://edcsns17.cr.usgs.gov/srtmbil/ (USGS, SRTM), but was acquired through the UCT GIS research facility, who are custodians of GIS data at UCT.

6.3.3.3 Vegetation data

Vegetation is important to fire models in the form of fuel load measurements and fuel moisture. As mentioned in chapter 4 it is possible to measure fuel loads using remote sensing efforts but this is beyond the scope of this study to do so. Therefore the fuel load data was acquired through ground measurements conducted in the study area, by resident fire ecologists in the Kruger National Park. The process of acquiring fuel load measurements is described in chapter 4. The grass fuel loads are measured using a disc pasture meter at 10 meter intervals and the coordinates of the location of the pasture meter are recorded by means of GPS. This data is made available by the Kruger National Park Scientific services in the form of a Microsoft Excel spreadsheet with the following format.

Table 6-3 Table layout for fuel loads measurements

Site name	Longitude	Latitude	Fuel load (kJ/ha)
Satara	-24.26298167	31.71771	4680

The vegetation (fuel) moisture content is also measured. This is measured through the use of remote sensing, hence satellite imagery is required. The NDVI and NDWI are used to estimate fuel moisture content, using the red, near infra red (NIR) and short wave infra-red (SWIR) bands of satellite images. The options of satellite imagery that were explored are discussed noting the reasons why they were rejected, and finally the chosen satellite imagery is presented with a discussion on why it was chosen.

- **Advanced Very High Resolution Radiometer (AVHRR) NDVI Images**

  The AVHRR sensors are carried on the NOAA (National Oceanographic and Atmospheric Administration) polar orbiting satellites and provide coverage of the whole earth at all channels, with a swath width of 2399km. The sensor has 5 channels that are sensitive to the visible part of the electro-magnetic spectrum as well as NIR and thermal infra-red, a description of these spectral bands is provided in Appendix A (USDA, nd).

  The NDVI is one of the data products derived from the AVHRR. Calculations for NDVI are performed at NASA by the Global Inventory Monitoring and Modelling

Studies group (GIMMS). The calculation of NDVI uses AVHRR channels 1 (red) and 2 (NIR).

The AVHRR NDVI data for Africa is available at Famine Early Warning System Network (FEWS net) data dissemination service website http://earlywarning.usgs.gov/, a USGS/USAID initiative for identifying areas in need of aid. This initiative focuses mainly on areas that are affected by natural disasters such as drought and floods among others. The FEWS net acquires data directly from GIMMS and has an extensive data archive dating as far back as 1981. The data is updated every ten days and is available at a resolution of 8 kilometres. The data is available in Albers equal area conic projection using the Clarke 1866 ellipsoid. The SPOT Vegetation NDVI is used to calibrate the AVHRR NDVI product (FEWS net, nd).

The images that include the study areas are those that cover Southern Africa. These images are available as 8-bit (byte) data files and have pixel values ranging from 0 to 255. To obtain the NDVI values the pixels must be divided by 250, which will result in the NDVI pixel values ranging from 0 to 1. There are however, other non vegetation pixels, with the following values: water, 1.0200, masked areas, 1.0160 and missing data, 1.0120. Although 8 bit images have pixel values ranging from 0 to 255, the data is divided by 250 because only pixel values ranging from 0 to 250 represent vegetated land. This is why NDVI values greater than one, are found for areas that do not have vegetation (FEWS net, nd). The projection details for the images are given in Appendix B. An NDVI image of Southern Africa has been provided in Figure 6-2 to show the data as received from the FEWS net but has been edited to highlight the study area. The image is displayed in false colour where green represents high NDVI and brown indicates low NDVI values.

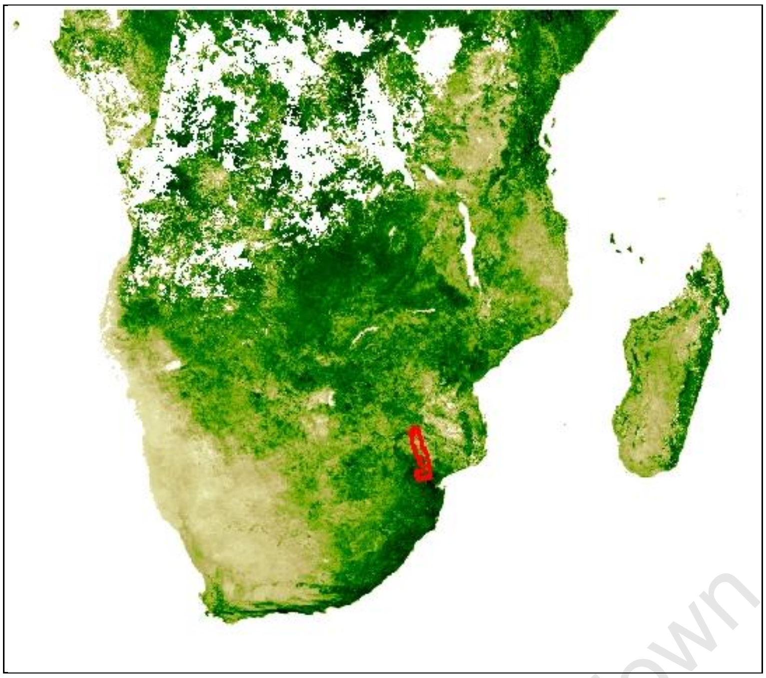


Figure 6-2. Edited NDVI image available from FEWS net, showing the study area boundary in red

This NDVI data is free and no data access agreements are required as long as the FEWS net is properly credited. Although AVHRR NDVI data has a low resolution, it is often preferred over more desirable products such as LANDSAT and SPOT, which have higher resolutions, due to the fact that it is free and available at a higher temporal resolution of ten days.

- **MODIS Terra and Aqua**

  Another satellite data option that is explored is the use of MODIS terra and aqua satellite images. These images are considered in order to provide calculations of an alternative measure of fuel moisture content which is NDWI, as well as delineation of fire affected areas. The detection of fire areas in this case is the main product and the same image will be used to get NDWI as will be demonstrated later in this section.

  MODIS is an acronym for Moderate Resolution Imaging Spectro-radiometer which is the primary sensor aboard NASA's Terra and Aqua satellites. The terra satellite traverses the earth from north to south, across the equator in the morning whilst the Aqua passes over the equator from south to north in the afternoon. These satellites have a temporal resolution of two days which implies that they cover the entire earth's surface in two days. MODIS has 36 spectral bands and the specifications are provided in Appendix A of this document (Maccherone, nd).

One of the main products of MODIS is the detection of fire anomalies. The channels that are used to detect and characterise fire are listed below:

Table 6-4. MODIS Channels used for active fire detection and Characterization (MODIS science team, 2006)

CHANNEL	CENTRAL WAVELENGTH (μm)	PURPOSE
1	0.65	Sun glint and coastal false alarm rejection; cloud masking.
2	0.86	Bright surface, sun glint, coastal false alarm rejection; cloud masking.
7	2.1	Sun glint and coastal false alarm rejection.
21	3.96	High-range channel for fire detection and characterization.
22	3.96	Low-range channel for fire detection and characterization.
31	11.0	Fire detection, cloud masking.
32	12.0	Cloud masking.

The verification of the images acquired through the Terra MODIS is done by NASA through the use of Advanced Spatial Thermal Emission and Reflection Radiometer (ASTER) imagery. The validation of MODIS satellite imagery is an extensive process which is beyond the scope of this research; however a brief summary of the process follows. The 1km pixel MODIS grid corresponding to a fire anomaly is overlaid with a high resolution ASTER image as illustrated in Figure 6-3 below. The red rectangles represent pixels of high fire detection confidence by MODIS and the blue shows low level of confidence. These are compared to the corresponding location in the ASTER image to verify the fire detection. In some cases discrepancies are found between MODIS and ASTER as illustrated again in Figure 6-3. For this particular case a pixel (see hatched pixel) has been identified by MODIS as just cloud cover, yet ASTER is able to identify the underlying condition which is then corrected in MODIS (MODIS Scientific Team, 2002).

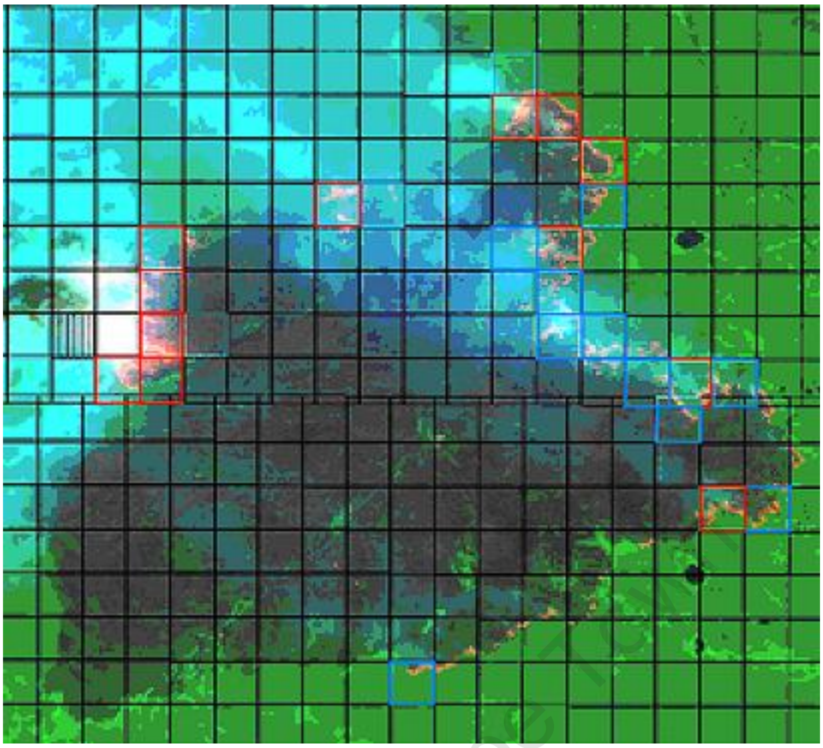


Figure 6-3 Validation of MODIS fire products by comparison with high resolution ASTER images, with red pixels indicating the detection of fires at high confidence level, and blue representing nominal confidence level of fire detection (MODIS Science Team, 2002)

The MODIS Rapid Response system produces near real time images of active fire occurrences for different parts of the world including the Kruger National Park. Near real time as well as historic images for each of these regions are available on the website, http://rapidfire.sci.gsfc.nasa.gov. These ortho-rectified images are available in three spatial resolutions: 250m, 500m and 1km. The 250m images are preferred in this study because they have a relatively high spatial resolution, hence show more detail.

The MODIS rapid response system produces true colour images as well as 721 false colour images. The true colour images use the MODIS 1(Red), 4 (Green) and 3 (Blue), band combination assigned to the red, green and blue channels of the digital image respectively. The 721 images use the MODIS bands 7 (Short Wave Infra-Red), 2 (Near Infra-Red), 1 (Red), assigned to the red, green and blue channels of the digital image (MODIS, nd).

The images are downloadable for free on the rapid response website in jpeg or GEOTIFF format. Each jpeg image comes with a world file which provides geo-referencing information to aid GIS display purposes. Metadata is available for each image showing the time the image was recorded by the satellite. The projection details of the different subsets are also available upon download. The Kruger National Park MODIS images are available in Transverse Mercator Projection, UTM zone -36 (36˚ S), using the WGS84 ellipsoid.

A sample of a MODIS image showing fire conditions is provided in Figure 6-4**Error! Reference source not found.**. The red polygons on the image indicate a thermal anomaly, in this case fire activity. The image has been edited to show the outline of the Kruger National Park; shown in blue.

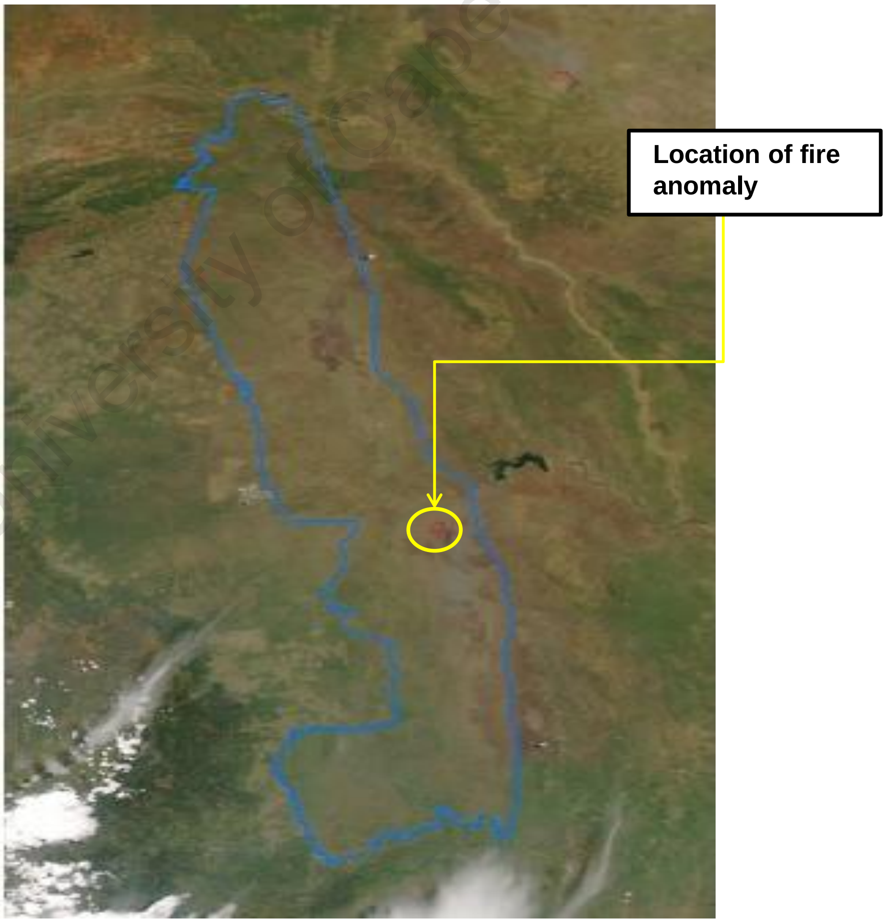


Figure 6-4 A True colour AQUA MODIS picture for 8 Dec 2006 with the Kruger National Park boundary (courtesy, MODIS Rapid Response)

As mentioned earlier, the MODIS images can be used to generate NDWI and NDVI as an alternative to the low resolution AVHRR NDVI datasets. Beginning on the 20 May 2008, MODIS has been producing daily NDVI images in addition to the true colour and 721 images mentioned above. MODIS generated indices are a better option because the images used to generate them are usually available on a daily basis and they have a higher spatial resolution. The 721 MODIS imagery made available by the rapid response system can be used for this purpose as it is made of all the necessary spectral bands; SWIR, NIR and Red band. It must be noted that MODIS also produces NDVI calculations but these are not available for South Africa and NDWI is the preferred index over NDVI.

6.3.3.4 Other Data

This section refers to all the data that is not used to calculate fire behaviour parameters but are important to fire modelling.

- **Water Bodies**

  Water bodies are not directly used in the calculation of fire behaviour variables. They have a number of reasons why they are important. Water bodies are used in suppression attempts for collection of water to extinguish unwanted fires; hence it is important to know where they are located. Water bodies also have the capability of acting as fire breaks because water does not burn.

  The South African Biodiversity Institute (SANBI) has data about the rivers for the whole of South Africa. This data is available online through the biodiversity GIS unit at http://bgis.sanbi.org, a GIS data clearing house for SANBI, free of charge. Data from this site is protected by SANBI data policy, which requires the user to register their details on the website before data can be downloaded. Data can alternatively be requested at SANBI and will be sent on disk to the user.

  The rivers shapefile was produced by the Council of Scientific and Industrial Research (CSIR) in February 2004, hence SANBI are the data vendors. The shapefile was created at a scale of 1: 50 000 and was created using the WGS84 reference ellipsoid, no projection details are given.

CDSM produces and supply more data about water, such as bore holes, dams and community taps as 1: 50 000 shapefiles. These shapefiles are available at no charge and no data policy agreements are required.

- **Infrastructure**

Information about roads and access to the study area is required to show human activity. Roads can also be used as fire breaks and to indicate discontinuities in fuel as will be described in the data preparation section.

Roads data is available through the Kruger Scientific services and data policy agreement is required. The Kruger data agreement requires the user to state exactly the purposes for which data is required and to sign a declaration that the data will not be misused or used for any other purposes except the ones agreed upon. Roads shapefiles can also be acquired at CDSM on the same terms as the rivers shapefile.

Having described the data and discussed the data acquisition, a summary of the metadata is thus provided:

Table 6-5. Summary of metadata for all the acquired datasets

DATA SET	FORMAT	SCALE/RESOLUTION	PROJECTION	TEMPORAL RESOLUTION	DATA CUSTODIAN/VENDOR
Weather					
Wind speed (m/s)	Microsoft Excel table	Available for selected towns	--	Daily	SAWS
Wind direction(˚)	Microsoft Excel table	Available for selected towns	--	Daily	SAWS
Relative humidity (%)	Microsoft excel table	Available for selected towns	--	Daily	
Topography					
DEM	**1. ArcGRID**, TIFF (32 bit)	90m contour interval	WGS 84 ellipsoid/ NAD 83 (horizontal) and NAVD88 (vertical)	Production period (2000 – 2003)	NASA (SRTM)
	2 .crt file, **ASCII (.txt file)**	25m contour interval	Not Specified	Not specified	CDSM
Vegetation					
Vegetation Coverage shapefile	ESRI shapefile (polygon)	--	Universal Transverse Mercator, central meridian: -33, WGS84 ellipsoid)	Last updated 1990/06/01	Kruger NP Scientific Services
Fuel loads	Microsoft excel table	10m	--	Before every fire season	Kruger NP Scientific Services
Satellite imagery					
AVHRR NDVI image	WinDisp, **BIL**	8km	Albers equal area conic projection, Clarke 1866 ellipsoid	10 days	FEWS net
MODIS 721 image	Jpeg Image file (.jpg), world file (.jgw)	250m resolution	Universal Transverse Mercator, central meridian: -33 reference ellipsoid:WGS84 ellipsoid	Daily	MODIS rapid response
Fire Occurrence					
Fire Scar shapefile	ESRI shapefile (Vector-polygon)	-	-	Annually (end of fire season)	Kruger NP Scientific Services
Other					
Rivers	ESRI shapefile (Vector - line)	1: 50 000	WGS84 reference ellipsoid No projection specified	Last updated 2004	SANBI
Water points	ESRI shapefile (Vector - point)	1:50 000	Not Specified	Last updated	CDSM
Infrastructure (Buildings etc.)	ESRI shapefile (Vector)	1:50 000	Not Specified		Kruger NP Scientific Services
SA towns	database file(.dbf)		--	-	ENPAT

6.4 SavFIRE Test Data

The test data used to validate the model is acquired from the SavFIRE project that is underway in the Kruger National Park. SavFIRE is an acronym for Savanna Fire Ignition Research Experiment. The purpose of SavFIRE project is to investigate the effects of fire that starts from point ignitions against perimeter fire ignitions in the Kruger National Park. The project began in 2006 and will run until 2010 where a number of point ignitions and perimeter ignitions will be applied to areas ranging in size from 500, 1000, 2000 and 4000 hectares in different parts of the national park with different vegetation types. In one year similar vegetation will be burnt in those different size areas. This project was initiated as a result of the changed fire management program that incorporated the effects of fire burning not only as a result of lightning ignitions but as a result of arson fire caused by trans-migrants illegally traversing the park. This resulted in the incorporation of controlled burns as a result of point ignitions along with perimeter ignitions. An assumption made was that point ignition will result in larger fires that will burn longer through the designated area. It was further assumed that as a result, this will lead to changes in fire intensities and generally different fire behaviour which will positively influence biodiversity in the ecosystem. The purpose of the SavFIRE project is to verify these assumptions that had been made by fire management (Govender, 2006).

A summary of the conditions in which the controlled fires will be carried out according to the SavFIRE team is provided in Table 6-6.

Table 6-6 Experimental controlled burn conditions for SavFIRE project

2006 – MOPANE VELD	
AREAS = 500 ha & 2000ha	**REPLICATIONS** = 2
POINT IGNITIONS	**PERIMETER IGNITIONS**
SEASON: End of winter before spring rains – October.	**SEASON**: End of winter before spring rains – October.
GRASS FUEL LOAD: ≥4000 kg/ha	**GRASS FUEL LOAD**: ≥4000 kg/ha
GRASS FUEL MOISTURE: Fully cured <20%	**GRASS FUEL MOISTURE**: Fully cured <20%
AIR TEMPERATURE: Initiation of Fire = ±25 ^{0}C	**AIR TEMPERATURE:** Initiation of Fire = ±25 ^{0}C
RELATIVE HUMIDITY: Initiation of Fire = ±40 %	**RELATIVE HUMIDITY**: Initiation of Fire = ±40 %
WIND SPEED: Initiation of Fire = ±10 km/h	**WIND SPEED:** Initiation of Fire = ±10 km/h
FIRE DANGER INDEX: Initiation of Fire = ±50	**FIRE DANGER INDEX:** Initiation of Fire = ±50
2007 – MOPANE VELD	
AREAS = 500, 1000, 2000 and 3000 ha **REPLICATIONS** = 1 of each area	
POINT IGNITIONS	**PERIMETER IGNITIONS**
Similar season, fuel and atmospheric conditions	

2008 – KNOPPIESDORING VELD	
AREAS = 500, 1000, 2000 and 3000 ha **REPLICATIONS** = 1 of each area	
POINT IGNITIONS	**PERIMETER IGNITIONS**
Similar season, fuel and atmospheric conditions	
2009 – ROOIBOS VELD	
AREAS = 500, 1000, 2000 and 3000 ha **REPLICATIONS** = 1 of each area	
POINT IGNITIONS	**PERIMETER IGNITIONS**
Similar season, fuel and atmospheric conditions	

The areas within the Kruger NP in which the experiments are being carried out are as shown on the vegetation map in Figure 6-5 below.

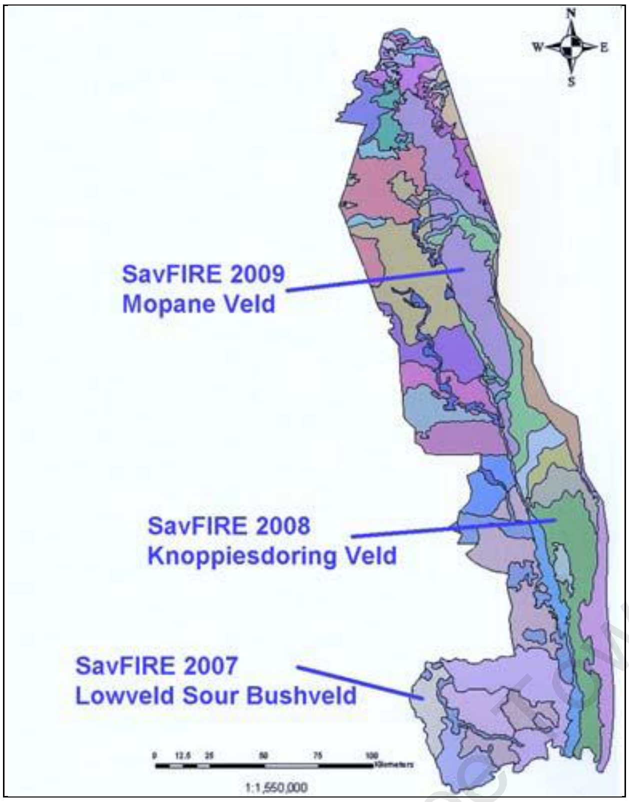


Figure 6-5 The location of the different major vegetation types in which the SavFIRE burning trial will be conducted in the Kruger National Park (SavFIRE, 2007)

6.4.1 Measuring procedures carried out in the SavFIRE project

Defined steps are performed with regards to carrying out measurements for the purpose of controlled burns. Measurements are carried out **before** the burn period, **during** the controlled burn and **after** the fire stopped burning. The measurements and procedures followed in these three periods are discussed in the following subsections.

6.4.1.1 Measurements before the controlled fire

- **Measurements of fuel load**

  Fuel load measurements as it has already been mentioned in the previous sections are carried out with the use of a disc pasture meter at 10 m intervals within the veld assessment area. A sample of the veld condition before the fire is shown in Figure 6-6

Figure 6-6 An example of the veld condition before the start of the fire (courtesy of SavFIRE, 2007)

- **Measurement of climate conditions**
  Measurements of the prevailing climate conditions before the fire starts are obtained from the weather monitoring stations within the national park. The locations of these weather stations are within the camps and GPS coordinates are known.

6.4.1.2 Measurements during the controlled fire

- **Date and time**
  The date and time at which the fire was started and completed are recorded
- **Changing weather conditions**
  The prevailing weather conditions from the stationary weather stations are supplemented as the fire progresses by readings taken from automatic hand held weather kits. Measurements of air temperature, relative humidity, wind speed and wind directions are recorded as in the illustration provided in Figure 6-7.

Figure 6-7 Measurements of prevailing weather conditions carried out using mobile, handheld weather kits (courtesy of SavFIRE, 2007)

- **Fire behaviour characteristics**

  Measurements of fire intensity, flame length and the fire danger index (FDI) are also recorded in order to provide information on the general behaviour of the fires.

6.4.1.3 Measurements after the controlled fire

- **Fuel loads after the fire**

  The condition of the veld after the fire is documented and compared with the measurements taken before the fire. This gives an indication of how much fuel was burnt and how much is left after the fire. This information is crucial to fire managers. The same measurement technique as before the fire is used (see Figure 6-8).

Figure 6-8 Veld condition after a controlled fire (courtesy of SavFIRE, 2007)

- **General veld condition**
  Aerial photographs are taken after all the fires to provide fire management with a general perspective of the area that has been treated with controlled burns.

6.4.2 Data received from the SavFIRE project

Due to the complexity and size of the SavFIRE project the Kruger National Park provide data measurements for the test fires that were performed in 2008. Efforts to acquire any other data from the previous years were unsuccessful as this data still has to be analysed by the SavFIRE team on conclusion of the project in 2010. Consequently, they require first preference in data analysis before it can be released for public use. This issue has been discussed in chapter 1 in the subsection on limitations.

6.5 Data Pre-processing

This section describes the data preparation tasks that were performed. The data used in this project is acquired from different sources in different formats. Some of the data is available in formats that are ready to use in the ArcGIS software whereas some raw data is not suitable for use in ArcGIS. Consequently, some of the data had to be prepared for use in ArcGIS by changing or modifying their format where appropriate. The data preparation activities performed, include the reduction of data volumes where necessary and preparing data files to formats that can be read by ArcGIS.

6.5.1 Weather data

Weather data does not come with spatial reference, therefore in order to acquire suitable data the weather stations that fall within the study area need to be identified, thus a list of weather stations within the national park was acquired from the Kruger National Park. The weather sites are usually in towns therefore the SA towns' database file was acquired from the UCT GIS research facility. This data table is produced by Environmental Potential Atlas (ENPAT). The data in the tables is imported to Microsoft access (.dbf) to form part of the personal geo-database that stores the data for this project. The weather stations are distributed as illustrated in Figure 6-9. The towns are displayed in ArcMap based on their x-y coordinates, specified in the town's table acquired from ENPAT. The wind speed and relative humidity tables are joined in ArcMap to the towns' layer as a means of geo-referencing the weather data for use in the model. The town name is used as the joining attribute.

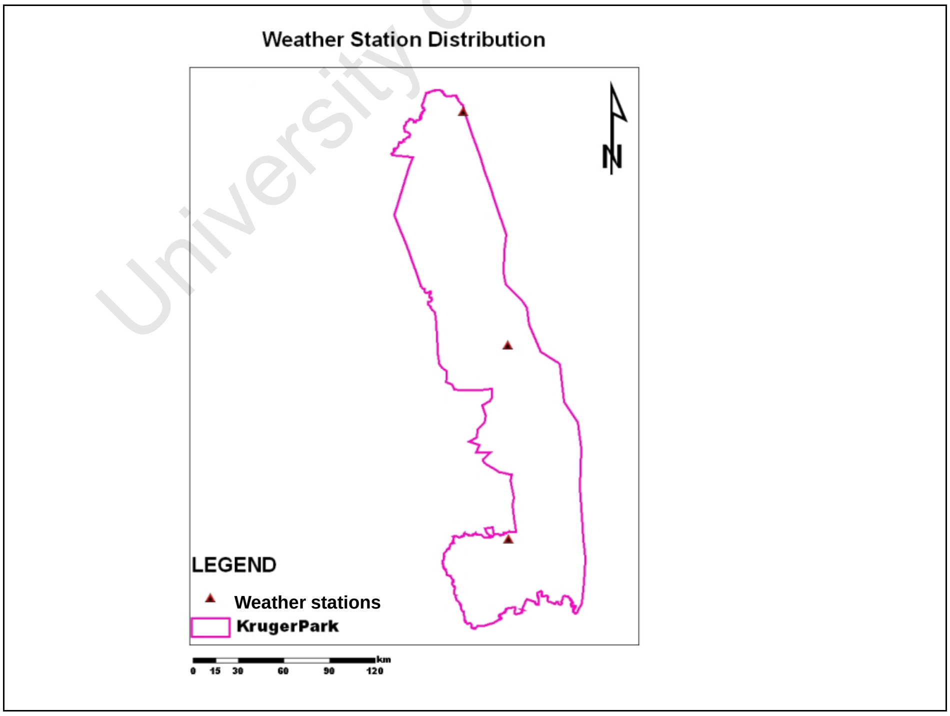


Figure 6-9 Location of weather stations within the national park

The weather data is then appended to the appropriated towns and interpolated to the study area. At this point the weather data has been attached to towns, as point data. The weather data is required not only for discrete points but for the entire park as a continuous surface. This is made possible by interpolating measurements between the points. Among ArcGIS surface interpolation functions available Inverse Distance Weighting (IDW) and Kriging are the most preferred.

IDW is a deterministic interpolation method based on the surrounding measurements. IDW assumes that the weight of the variable being measured decreases with increasing distance from the measurement. Kriging is a statistical method; it is based on the statistical relationship between measurements. Kriging also provides a measure of how accurate the predicted interpolation is. Both methods use the following equation

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \quad \textbf{6-1}$$

Where: $Z(s_i)$ = the measured value at the i^{th} location.

λ_i = an unknown weight for the measured value at the i^{th} location.

s_0 = the prediction location.

N = the number of measured values.

The difference is that in IDW, the weights (λ_i) are based only on the distance from the measured locations to the predicted location, whilst in Kriging the weights are based on the distance as well as the spatial relationship between the measurements. Kriging is more appropriate if there is known to be a spatially correlated distance between the measurements (ESRI, 2008). In this model both models produce similar results and either could be used, however IDW was chosen because of simplicity of use. The result of the interpolation process using IDW is shown in Figure 6-10.

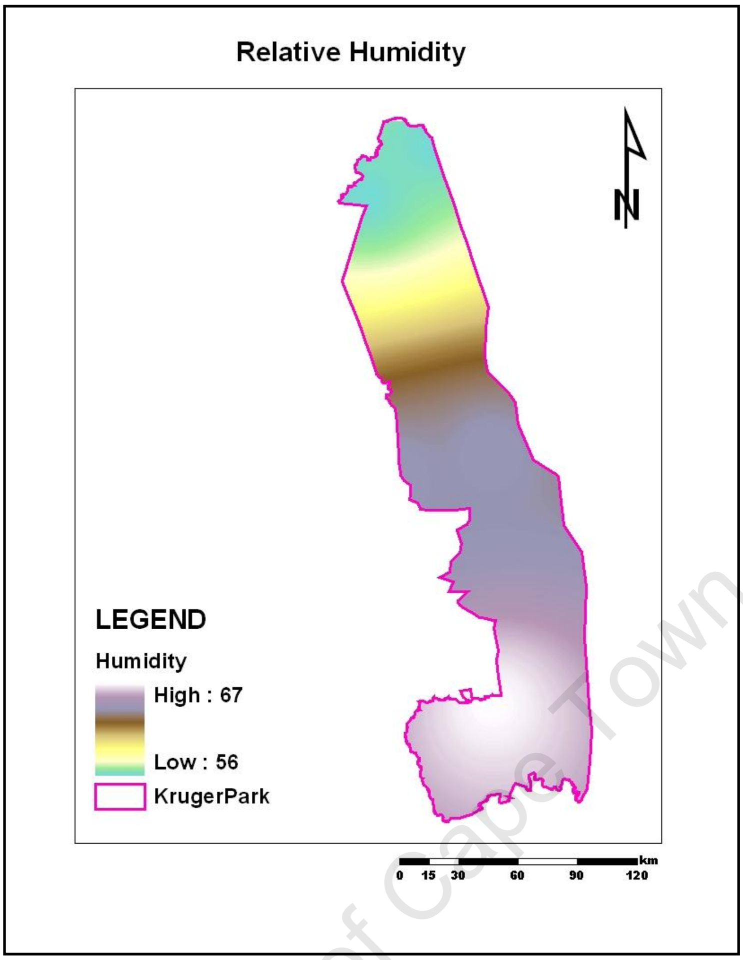


Figure 6-10. Interpolated relative humidity measurements performed by IDW

6.5.2 Fuel load measurements

The fuel load is measured physically at discrete locations within the Veld Condition Assessment VCA sites in the study area. A shape-file that shows the location of VCA sites was acquired from the Kruger national park. The fuel-load measurements are received in a Microsoft excel table and are imported to the Microsoft access project database for easy access and management. From the database, the fuel load measurements table is joined to the VCA sites shape-files to provide means of geo-referencing the fuel load measurements in ArcMap as illustrated in Figure 6-11.

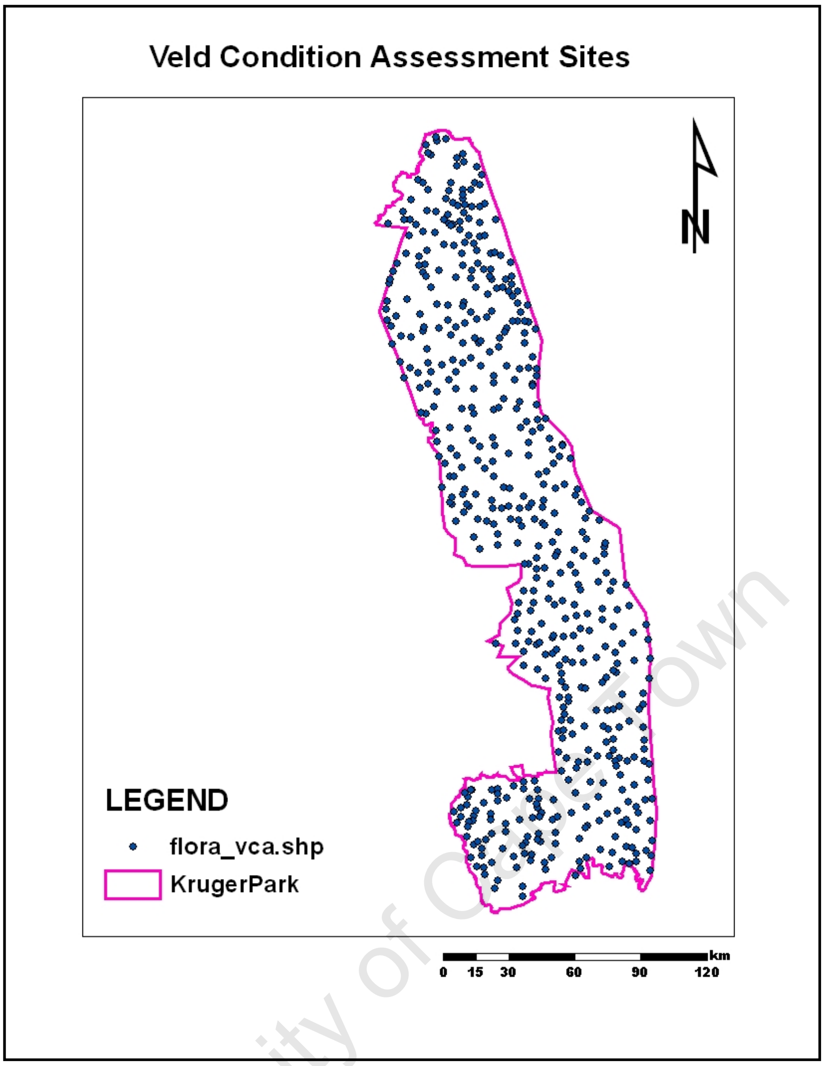


Figure 6-11: Distribution of VCA sites within the study area

As with weather data, the fuel load is required as a continuous surface. The same technique of IDW was used in this step. The fuel loads are interpolated from the points from which they were measured to a distance of 10 m around these locations. This is based on the fact that fuel load measurements are taken within a distance of 10 m from each other. Roads and rivers need to be accounted for in this layer and these are included as barriers for the interpolation process; therefore no fuel loads are encountered along these features.

6.5.3 Satellite imagery

The AVHRR NDVI images covered the whole of Southern Africa. In order to reduce the anticipated problem of long computation time the layer was clipped to cover only the study area. These images also need to be projected in ArcMap, the projection details are given separately and the projection had to be done by manually typing in the correct parameters in ArcCatalogue.

A summary of the pre-processing tasks performed is given in Table 6-7 below:

Table 6-7 A summary of data pre-processing tasks performed

DATASET	DATA PRE-PROCESSING TASK
Weather data tables (humidity, wind speed etc)	Import as database tables (.dbf), join to towns.dbf table, and display as x-y data
AVHRR NDVI image	Clip to size of Kruger National Park, projection
Roads layers	Merge to create one layer, projection
MODIS images	Projection

6.6 Discussion

This chapter describes the different kinds of data that are required for input into the fire model. The data is acquired from different sources and needs to be prepared before it can be used in the model. The major advantage of selecting data that has metadata provided is that it simplifies the pre-processing tasks such as re-projection. The acquired data is thus stored in the file geodatabase that is discussed in chapter 5 and is thus easily accessible for use in the modelling process.

The next chapter discusses the results of the modelling processes, results are presented and qualitative analysis of the results is discussed.

7 EVALUATION OF FIRE MODEL: RESULTS AND ANALYSIS

7.1 Introduction

A fire modelling methodology for surface fires on heterogeneous landscapes is proposed in chapter 4 and is implemented as a fully embedded model in the GIS environment (using ESRI ArcGIS) in chapter 5. Fire behaviour is modelled through the fire intensity, which is then used to predict the fire danger index (FDI) that an area exhibits, based on environmental factors, namely meteorological conditions, topographic conditions and the condition of vegetation. The spread of fire is then predicted based on the rate at which a fire will spread in case of an ignition incident. The spread of fire in this model considers the case where fire results from point ignitions as opposed to line ignitions. The rate of fire spread model is a physical-statistical model that considers the transfer of heat as well as environmental conditions. It also takes into consideration the fire intensity, flame length and flame height. The predictive fire spread model is developed using the cellular automata technique. Although a cellular automaton is a raster grid modelling method, the final results of the propagation of the fire front in this model are presented in vector format.

This chapter presents the results of the two fire models that are proposed in this study. The results of the fire behaviour model are presented first. These include the predicted fire intensity and the fire danger index. Secondly the results of the predictive fire spread model are presented and finally a quantitative analysis of the results is presented.

As mentioned in chapter 6, the data used to test the fire model is acquired from the SavFIRE experiments of controlled burns that were carried out in the Kruger National Park. As the SavFIRE experiments consist of fires that result from point ignitions and line ignitions, whereas this study only considers point ignition fires, a limited amount of data is available. Hence other controlled burns that were administered by the park’s fire management as a means of rangeland control were also used to test the model presented. The data preparation methods, in all cases, are discussed in chapter 6.

7.2 Predictive Fire behaviour model results

The calculations for the fire behaviour parameters, namely: fire intensity, flame length and fire danger rate of spread, use well known equations whose effectiveness has been proven in the Kruger National Park. The verification of the values and the reliability of these equations is beyond the scope of this study as they have been verified in previous fire ecology studies by fire ecology researchers, Trollope et al (2002) and Higgins et al (2008). The burning index calculated in this study is a measure of the fire danger index and an illustration of the output of this model, which shows the changing spatial pattern form season to season, is shown in Figure 7-1 below.

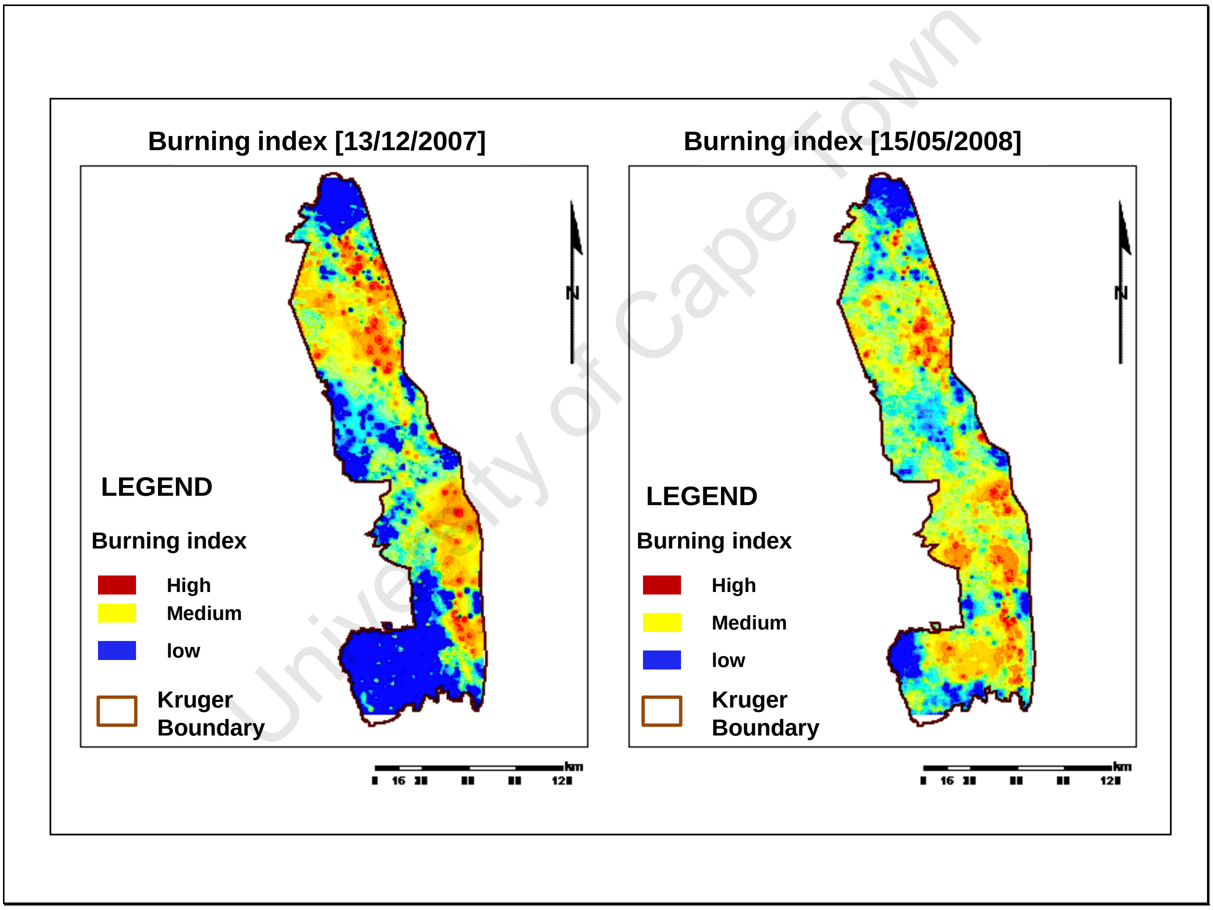


Figure 7-1: An illustration of the calculation of the burning index which is a unit-less measure of the fire danger index. The image shows calculations of burning index in winter and in summer with higher burning index values experienced in the winter (fire season).

7.3 Predictive fire spread model results

7.3.1 Prediction of fire rate of spread

Before the simulation of the spread of a fire, calculations of the rate of spread are performed and these are updated every time a fire passes through a cell, this is explained in detail in chapters 4 and 5. When an actual controlled burn fire incident takes place, the initial rate of spread (at the start of a fire) is recorded. The initial observed rates of spread are required for comparison with the initial rate of spread that is calculated by this model in order to assess the accuracy of this spread model. This data is available for the SavFIRE experimental burns and was not provided for rangeland fire management burns. As a result, the rangeland fires are not included in the analysis of the rate of fire spread. Three SavFIRE point ignition burns were available and the comparison of the calculated rates is provided below.

Table 7-1: A comparison of the observed and calculated rates of spread

Fire	Observed Rate of Spread (m/s)	Predicted rate of spread (m/s)	Difference (m/s)
1	0.14	0.08	**0.06**
2	0.08	0.06	**0.02**
3	0.37	0.32	**0.05**

Although three fires provide insufficient information to draw definitive conclusions, the table above shows that there is good agreement between the observed fire rate of spread and the predicted values at the beginning of the fire.

Wind speed is one of the inputs used to calculate the rate of spread and amongst these inputs, it has been found to be the most variable. Consequently wind speed variations are expected to contribute largely to the discrepancies in the calculation of rate of spread. This is mainly because of the fact that the observations of wind speed are not necessarily made at the same time the fire rate of spread is recorded. The values of wind speed that are used in the predictive model do not completely coincide with the recorded time of rate of spread observations.

7.3.2 Fire area prediction

The fires presented in this section were chosen from fire experiments and rangeland fires that cover different ranges, with respect to the wind speeds and consequently different ranges with respect to the fire rates of spread. These cases also represent fires that burn over a wide range of areas, from small areas to large areas, and from a few hours to a number of days.

The simulations are performed to represent a fire that burned for a defined period of time within a fire incident, or in other cases the simulations run to cover the whole fire event from beginning to the time it extinguished. The fire areas calculated during these simulations are compared with the fire scars acquired from MODIS Terra and Aqua satellite images. The identification of the area that burnt or is actively burning is performed by overlaying the satellite images of the particular day, during which the fire burned, with the fire start locations that have been provided. The locations are converted to point (vector) shapefiles for display purposes as discussed in chapter 6. Every active fire image provided by MODIS records the time at which the image was taken in the metadata, which is useful in identifying the appropriate images for a specific fire event. An active fire event is shown by a red polygon in the satellite images and fire scars are made evident by the changes in vegetation that occur from a visual analysis of the images captured before and after a fire. In both cases these boundaries are digitised, following which the quantitative analysis is carried out.

The results of the simulation of fire propagation over a defined time period will be provided but cannot be quantified as such information was not observed during the fire. The results of the test fires are presented, and the ability of this model to correctly predict the area burned is performed by comparing the predicted area to the observed fire area. The cases investigated are discussed in the following subsections. In the case of each fire, two images are provided: one is the predicted fire area overlaid on a SPOT image that provides a background that shows the underlying ground conditions noting the landscape, whilst the other is the predicted fire area overlaid on a MODIS image that shows the predicted area with respect to a fire scar or live burn.

7.3.2.1 Fire 1: Moderate to high wind speed

The first case investigated is the ability of the model to predict the overall area burnt by a fire during the prevalence of moderate to high wind speeds.

Figure 7-2 and Figure 7-3, below show a fire burning under moderate to high wind speed, with wind predominantly blowing from the East South East (ESE) and South East (SE) directions. The first image, Figure 7-2 shows the predicted area (in yellow) with respect to the MODIS active fire that was used as the end of the simulation in this case. The second image shows the fire area with respect to the features on the ground. The simulation shows that the fire slowed down as it crossed the main feature that resembles a river valley.

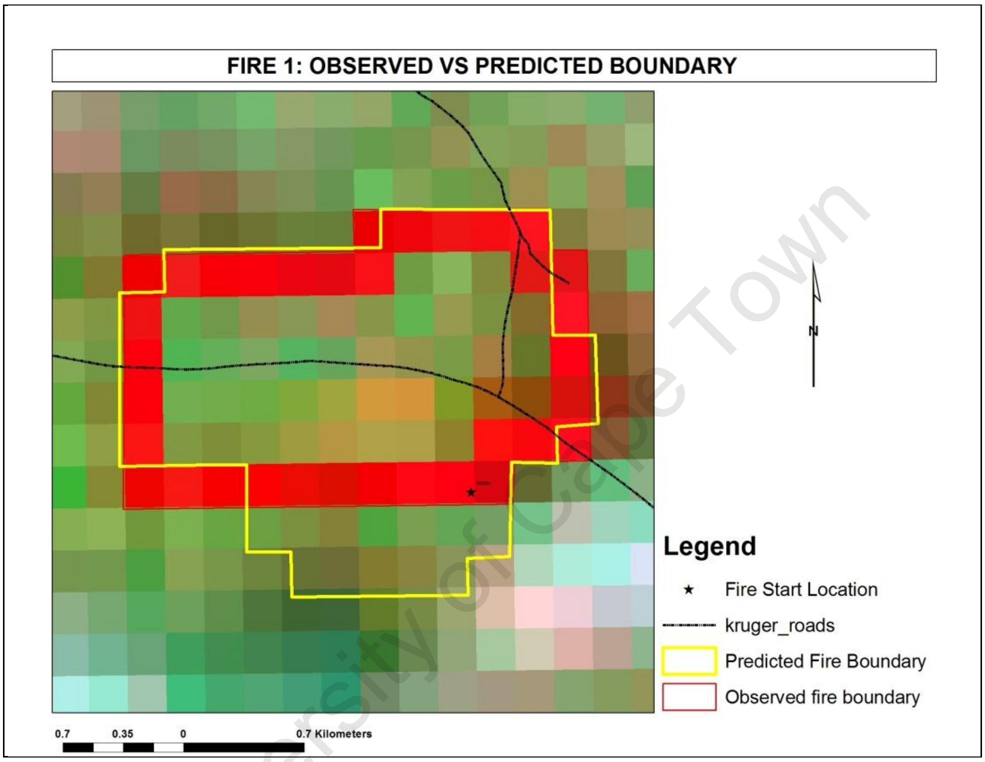


Figure 7-2 Fire 1: the predicted fire shown with the background of the observed boundary according to the MODIS image

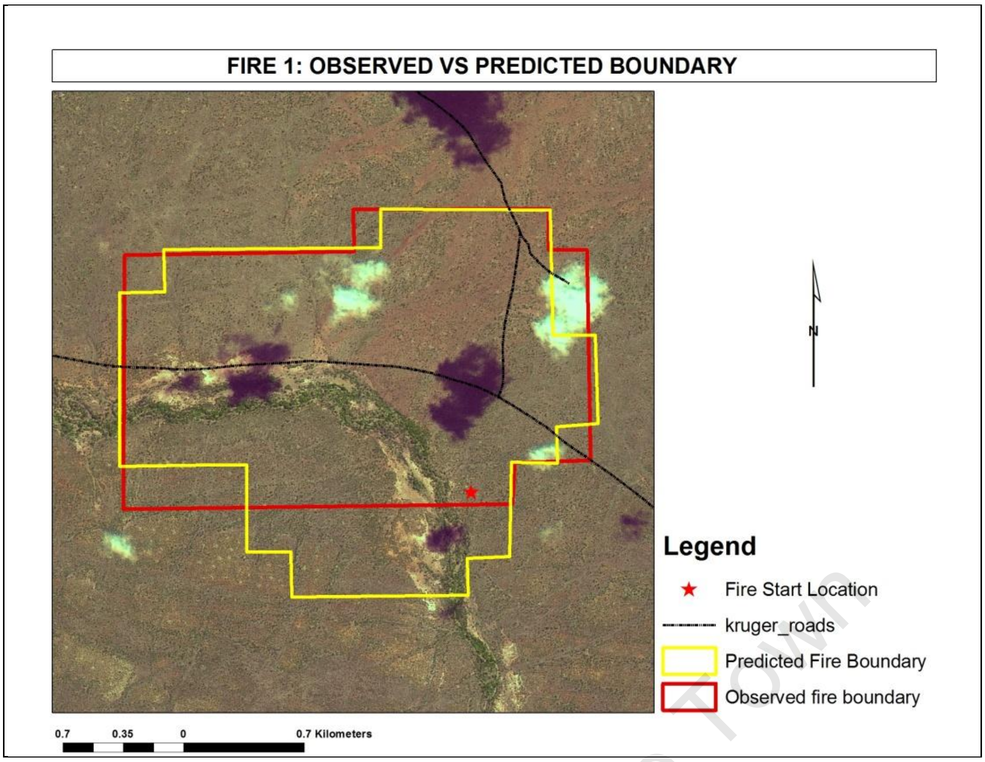


Figure 7-3 The fire spread prediction under moderate to high wind speeds; a major river valley is shown in the burned region

The prediction ability of the model in this case is good as most of the actual burnt area and the prediction area coincide and very little under-prediction of the area that burnt is experienced. The model does not over-predict by much either. Hence the conclusion is drawn that the model successfully predicted the fire area burnt in this case.

7.3.2.2 Fire 2: Moderate to low wind speed

The case presented here shows a fire burning under moderate to low wind speed with wind blowing from the south and south east under low fuel conditions.

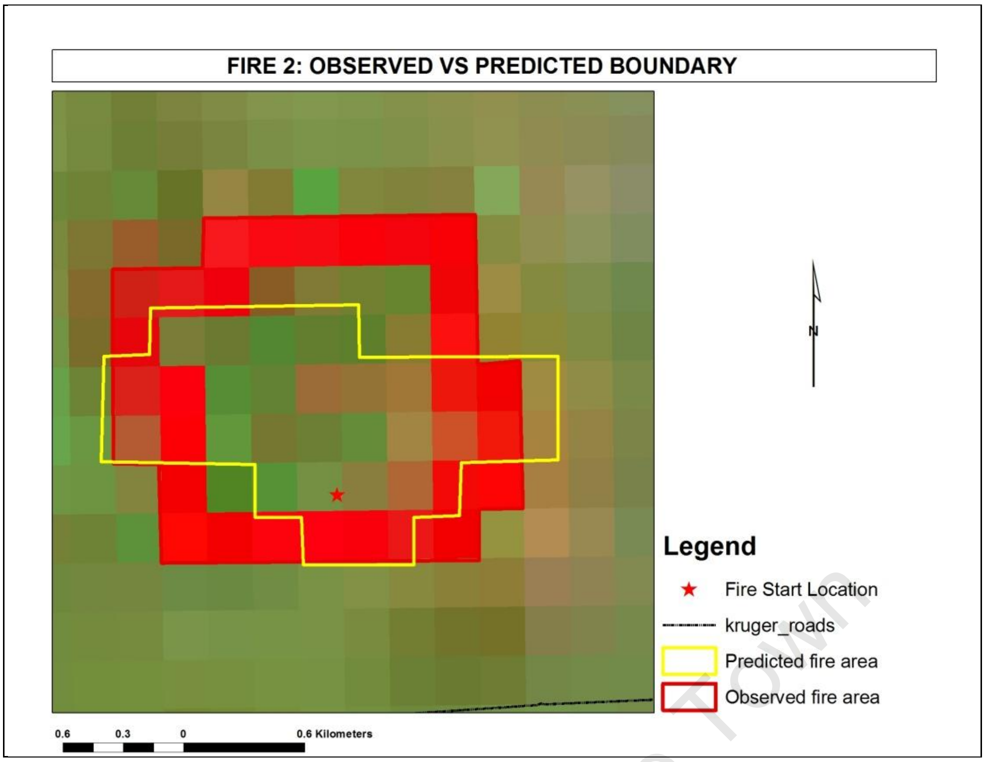


Figure 7-4 Fire 2: the predicted fire area (yellow), compared to the MODIS fire boundary (red)

Figure 7-4 shows the predicted fire area compared to the MODIS image showing the area that is affected by the active fire. The location where the fire started is also shown.

Figure 7-5 shows the same fire with a background of the landscape. In this case no major land features are visible in the fire area.

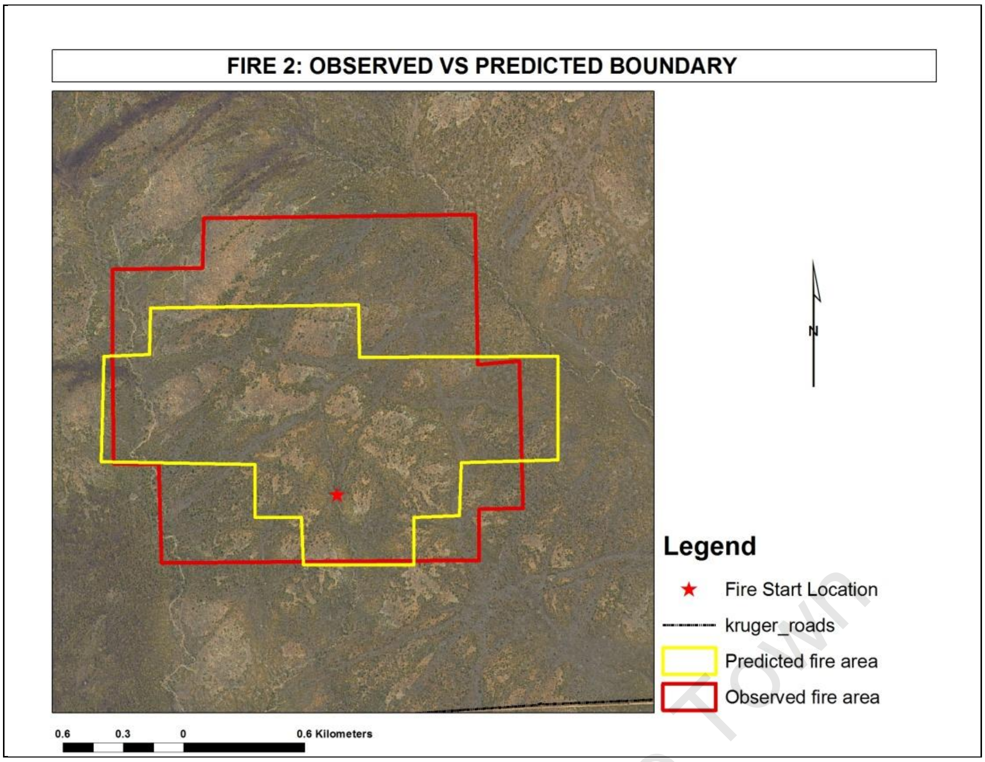


Figure 7-5 The predicted spread of fire burning under low wind speed in a small area

The model shows a considerable amount of under-prediction. Since there are no major land features in the area that is affected by the fire, the under-prediction of the model in this regard can be considered as a result of inadequate weather data. It is likely that the weather data used at the beginning of this simulation does not correspond with the actual weather conditions that prevailed at the time of the fire. It has been mentioned previously that the weather data is not necessarily updated (within the model) at the beginning of a fire incident but rather at a time when this information becomes available at the weather station.

7.3.2.3 Fire 3: High wind speed

This section demonstrates a fire burning under high wind speed conditions with wind blowing from the south, south west and south east directions. The fire burned for three days and the simulation below covers the whole duration of the fire incident from the time of ignition.

Figure 7-6 below shows the predicted fire area with reference to the fire scar that was acquired after the fire ceased burning. Since the simulation was run to cover the whole fire incident from ignition to completion, a fire scar is used to represent the area burned instead of the MODIS area of red pixels that indicate an active fire as was indicated by the two fires in the preceding sections.

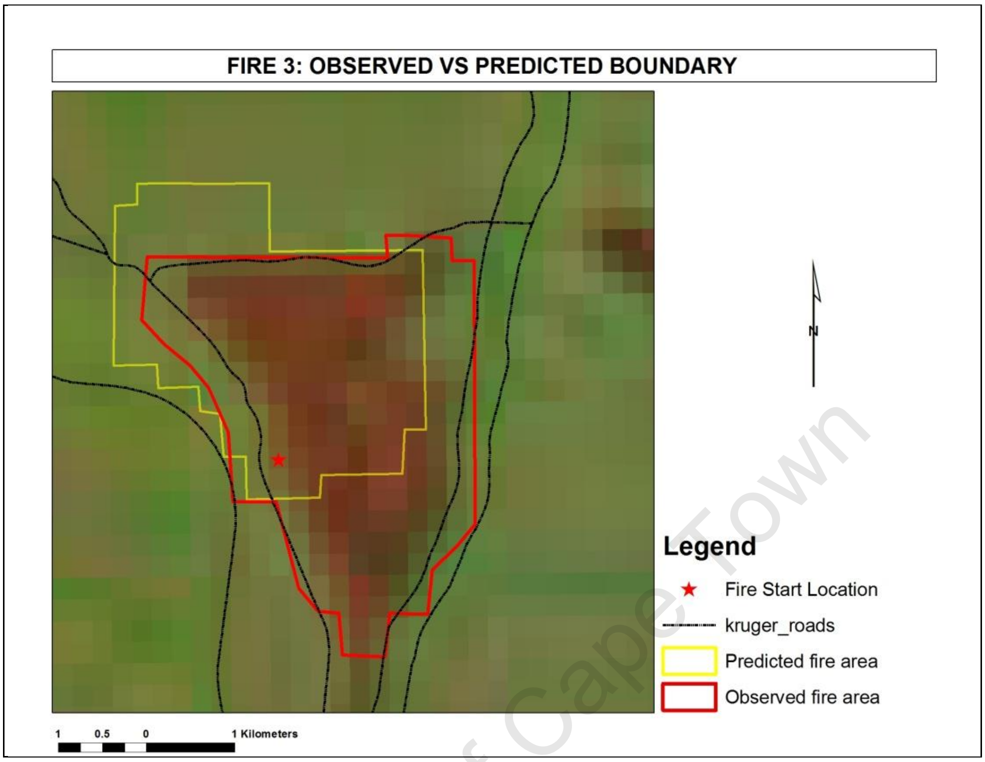


Figure 7-6 Fire 3: the predicted area compared to the burns scars that are represented by dark pixels in the background image

Figure 7-7 below provides an illustration of the area predicted to burn by the model compared to the actual area that burned, whilst showing the landscape in the background. The fire burned up to the enclosing roads on all sides in this case; hence the roads assumed the role of fire breaks. However in the predicted area, the fire continued to spread beyond the roads. This indicates that although the effect of roads is accounted for in the vegetation (fuel load) interpolation, the cell size of the satellite images that are used in calculation of fuel moisture content[9] seems to diminish this effect. The Fuel moisture content is calculated from MODIS satellite images that are re-sampled to a resolution of 50m whereas the width of the roads is much smaller. This was discussed as a possible limitation in chapters 1 and 6 and is evidently a limitation in this case.

[9] Fuel moisture content is measured by the use of the NDWI; this is discussed in chapter 3.

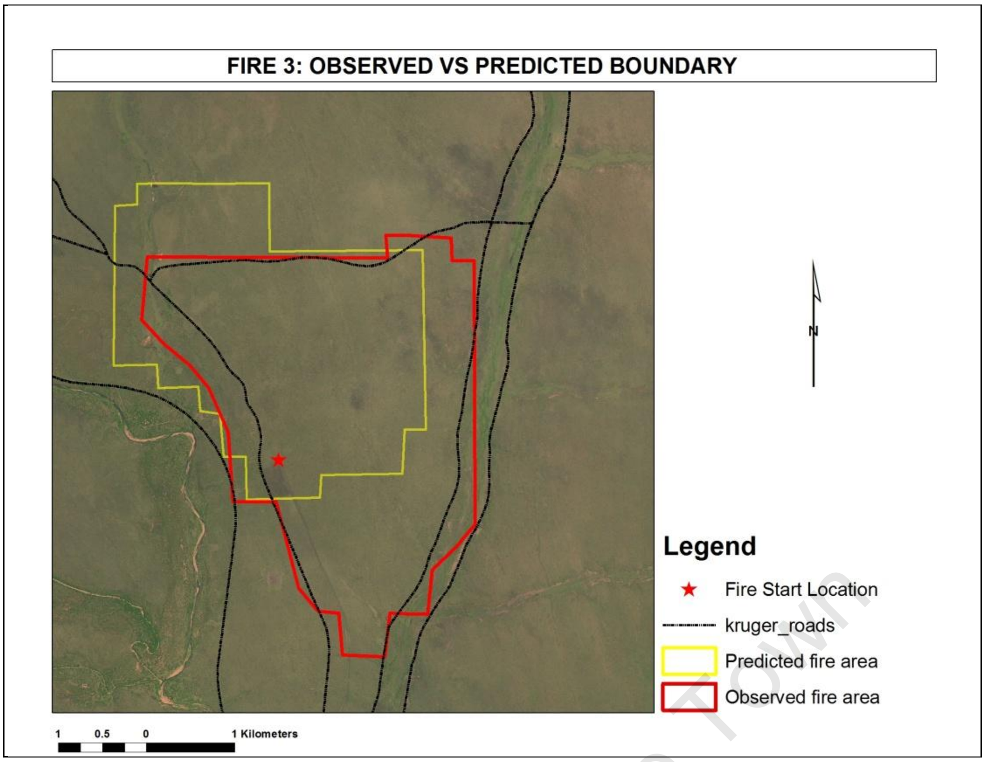


Figure 7-7 The spread of fire under high wind speed over more than one day

7.3.2.4 Fire 4: Moderate wind speed

The fire illustrated in this section burns under moderate wind speed, with wind blowing from the east and north easterly wind directions. The fire that is followed in this case, burned for more than one day but the simulation performed was allowed to run for one day. The purpose of this case is to investigate the ability of the model to predict fires that burned long under moderate wind conditions.

The resultant fire area after one day of burning is illustrated in Figure 7-8 and Figure 7-9 below. Figure 7-8 shows the fire scar as depicted by MODIS image as dark pixels; the bright red pixels represent the next fire day, as the simulation in this case did not run until the end of the fire.

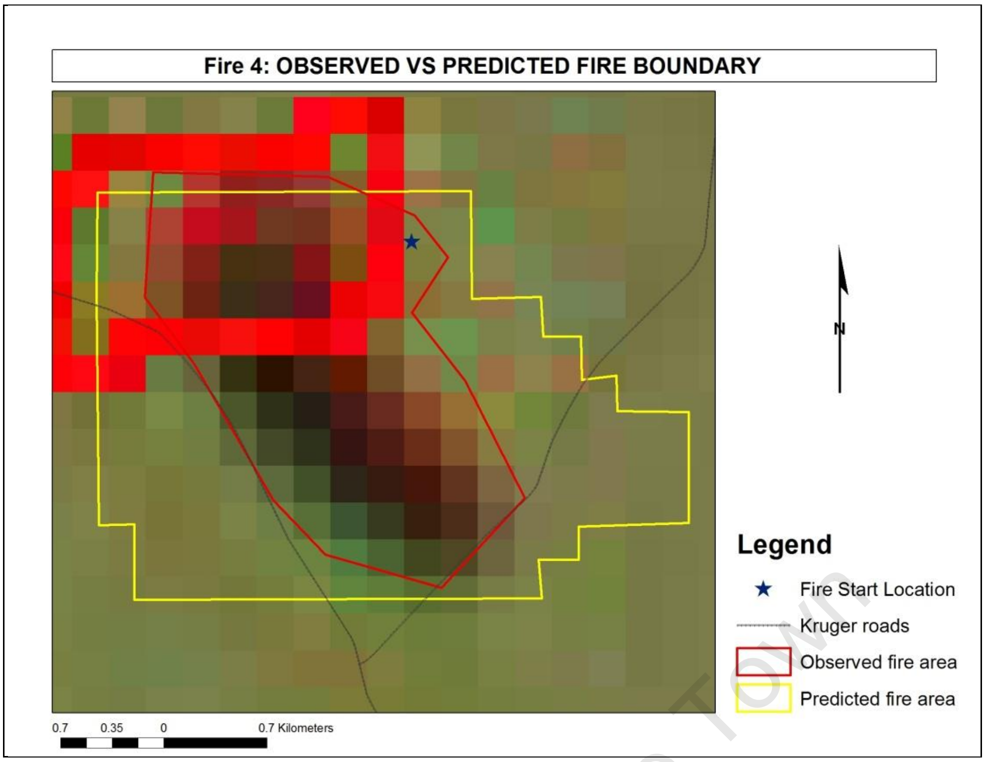


Figure 7-8 Fire 4: the comparison of the predicted fire area and the fire scar (dark pixels) after one day of burning while the fire continued to burn (the red pixels represent that the fire continued to burn, however these are not part of the analysis as only day 1 is considered in the simulation)

Figure 7-9 shows the predicted area with respect to the landscape and no major features were found within the fire area. The observed fire area is again restrained by the surrounding roads to the left and at the bottom of the image; the effect of roads is again not properly accredited by the predicted fire area.

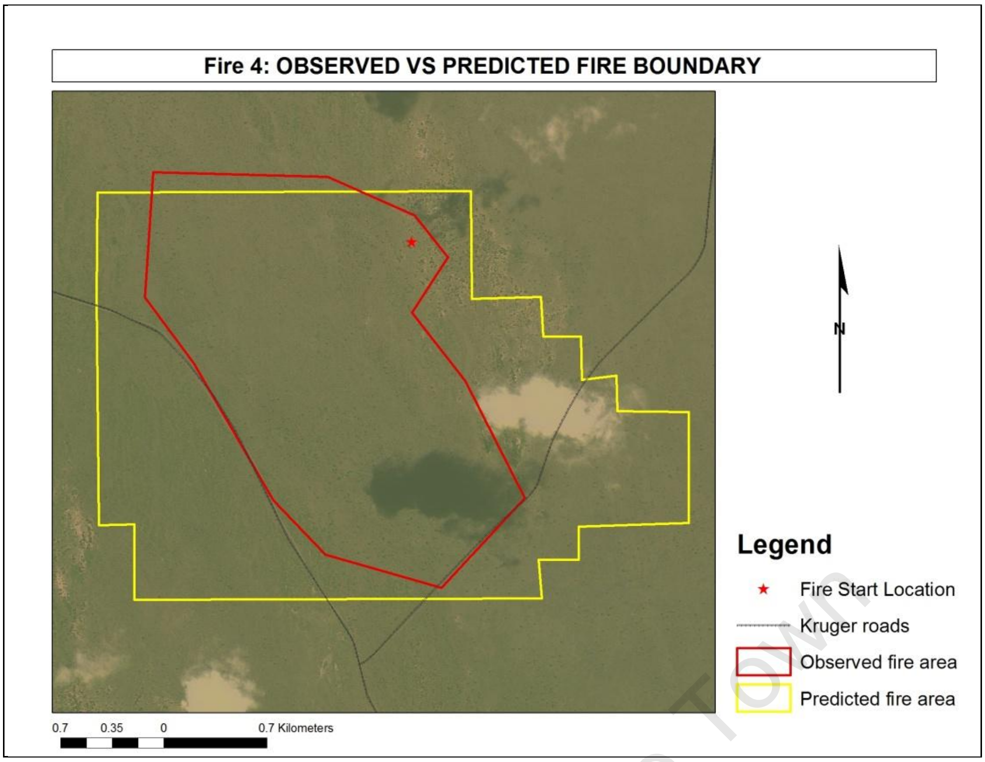


Figure 7-9 The spread of a fire burning under moderate wind speed, simulation run until one day into the fire

The model is able to correctly estimate the fire area, however, over-prediction is also experienced. Again this is attributed to the change in weather conditions over time although, in this particular case the weather conditions did not change dramatically. Hence, the model is able to correctly predict the fire area. The effect of roads is not properly demonstrated by the prediction, similar to section 7.3.2.3 above, although in this case the wind speed is relative low. A conclusion is made that the inability to show roads as a result of coarse satellite images, accounts for over-prediction. Human intervention efforts to stop the fire from breaching the road could have occurred, however such information is not supplied by the Kruger National Park.

7.3.2.5 Fire 5: Moderate wind speed

Figure 7-10 and Figure 7-11 below represent a case of a fire burning under moderate wind speed with wind blowing predominantly from West under a short simulation time span. The simulation of the spread of this fire was predicted from the start point into a few hours from ignition but not until the end of the fire.

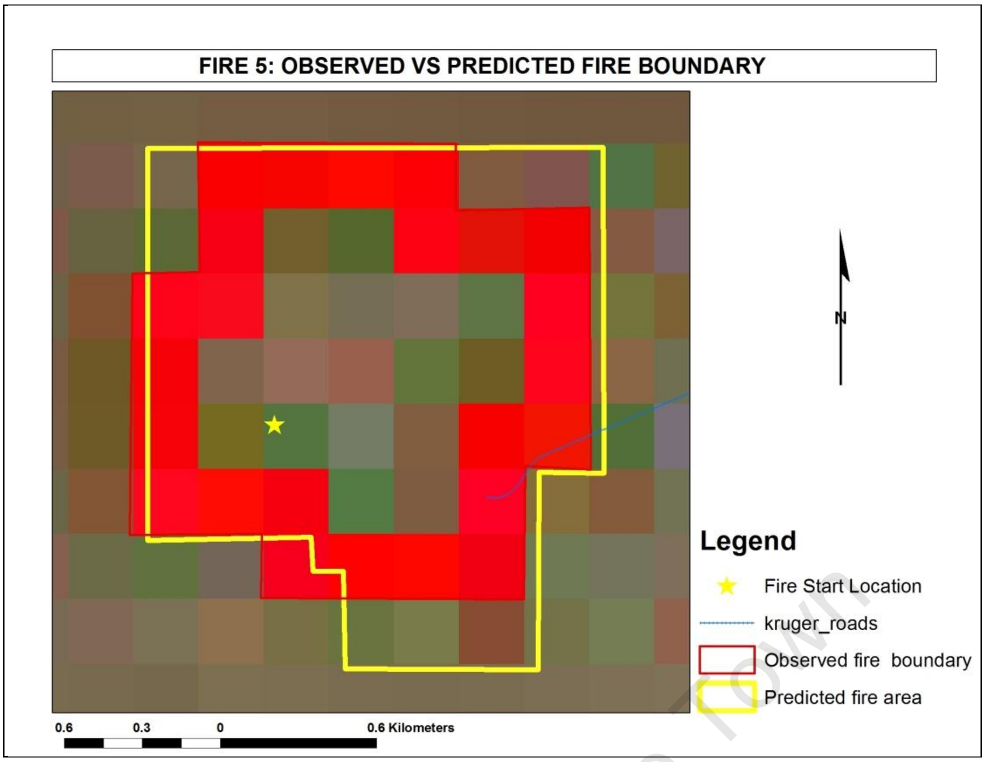


Figure 7-10 Fire 5: comparison of predicted fire area with active fire from MODIS

Figure 7-11 shows the underlying landscape on which the fire burns and the only major feature present is the river channel on the bottom right of the image. The predicted area recognises this feature as seen in the figure below.

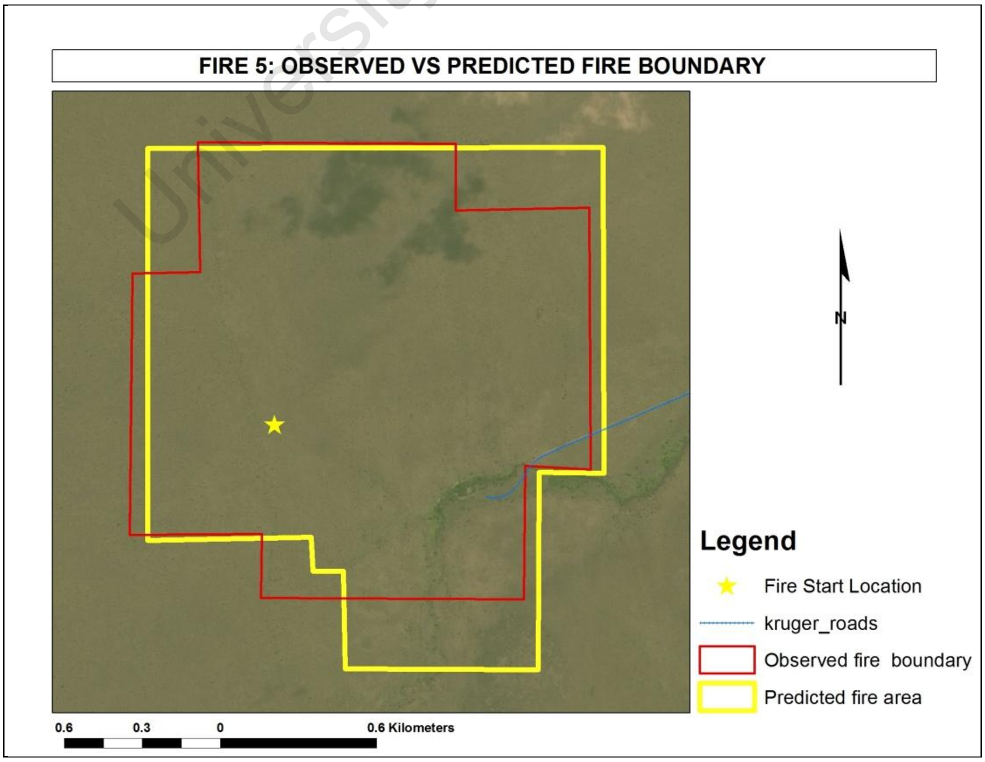


Figure 7-11 The spread of fire with moderate wind speed over short simulation distance

This case demonstrates the behaviour of fire under low wind speed and the amount of back spreading of the fire is considerably larger than in cases where the wind speed is relatively high as it has been presented in the previous cases. The model predicts the area burned by the fire very well, which is largely attributed to the fact that the fire has not been burning for long. Fires that have not been burning for long have not been exposed to variations in weather conditions which would result in modified influence on the fire due to weather variations. The fuel conditions exhibited by this area are more regular although the fuel conditions are not homogeneous.

7.3.2.6 Discussion of fire test cases

The behaviour of the model has been demonstrated through the test cases above, with respect to wind speed, wind direction, response to fire breaks, and fuel conditions.From visual inspection of the fire areas shown above, the ability of the model to predict the spreading of fire in all directions (not just the direction of the prevailing wind) has been successfully demonstrated in each of the cases presented. This is in accordance with the fact that in general, in Savanna ecosystems, back fires burn seven times slower than head fires in the presence of wind (Trollope et al, 2002). The next section provides qualitative analysis of the fire test cases.

7.3.3 Quantitative Analysis

The analysis of the predicted area by comparison with the actual fire area, to show the capability of the model was performed by the use of similarity analysis. Statistical similarity analysis is carried out when two data sets are compared against one another to show their agreement, resemblance, and conversely, their disagreement.

As mentioned in chapter 5, the result of the fire spread model, which shows the active fire area, is output in raster format but is then further processed by conversion to vector format to represent fire area polygons, for a more visually appealing representation of the fire front for visualisation purposes. Two methods of representing fire fronts were proposed in chapter 5; these are conversion from raster to vector without smoothing out the edges, and smoothing out the edges by defining a convex hull of the raster fire area. The results of the analysis process are described in terms of these two methods. Hence a choice of which one is most suitable will be made and presented.

Various methods of similarity analysis, also known as resemblance coefficients for qualitative analysis, exist but one that is commonly used for verification of ecological data (of which fire area modelling is a part), is Sorenson's similarity coefficient, discussed below (Romesburg, 2004; Perry et al, 1999).

7.3.3.1 Similarity Analysis: Sorenson coefficient

Sorenson's coefficient of resemblance performs comparison of two data sets that have a certain amount of overlap between them as illustrated by Figure 7-12. The coefficient tests for absence and presence of certain phenomena common to the sets by considering the elements included in the intersection, as well as the elements in either set that are not in the intersection.

In this case Sorenson's coefficient is used to test the ability of the fire model to predict the area burnt by a fire, by comparing the area that was predicted to burn with the area that actually burned. The equation (Equation 7-1) is presented below and its components are presented in terms of the fire model under investigation.

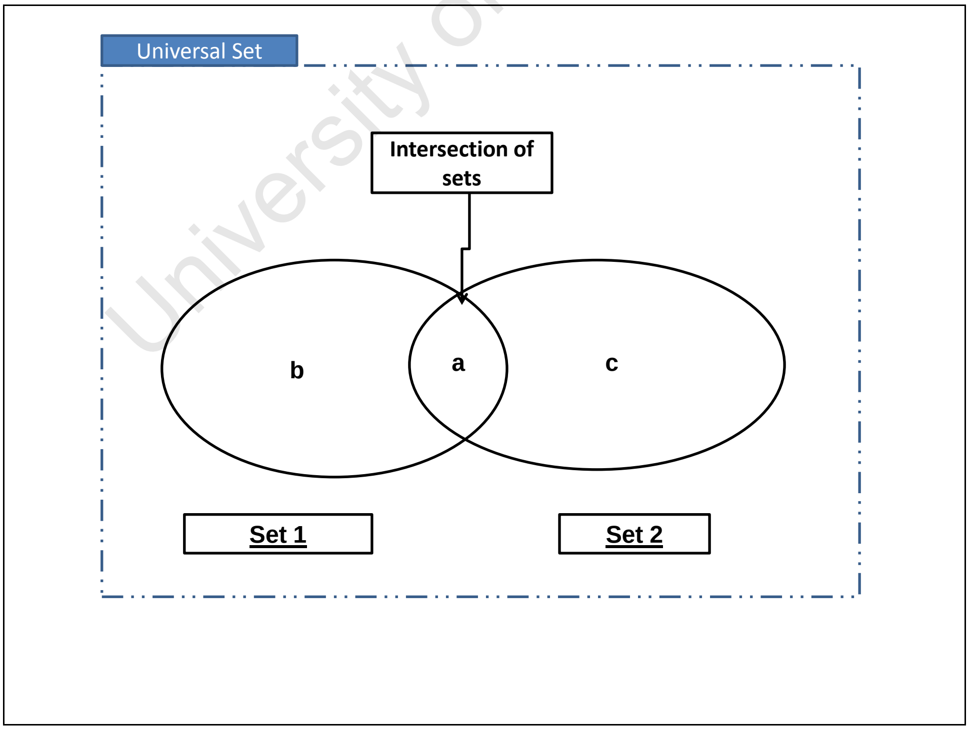


Figure 7-12: Two set representations that share a common trait between them. The two sets, 1 and 2, share an intersection of elements (a), and the non intersecting elements are (b) and (c), respectively

Calculation for Sorenson's similarity coefficient is as follows:

$$SC = \frac{2a}{(2a + b + c)} \qquad \text{7-1}$$

Where: a = Area detected to burn by both cases

b = Area predicted to burn but does not burn

c = Area burnt but not predicted

SC = Sorenson coefficient

The possible values of this equation range between 0 and 1. A value of 0 occurs when ***a*** equals 0, indicating that the intersection subset is empty, which means that no similarity between the two sets exists. A value of 1 occurs when ***b*** and ***c*** equal 0, meaning that the non intersecting subsets of either set are empty, therefore implying perfect similarity.
The illustrations of the results of these test cases are presented below followed by the Sorenson coefficient values of each case.

The diagrams, Figure 7-13 through Figure 7-17 below, show the component areas according to Sorenson's coefficient for fire areas (1 to 5), that have not been smoothed out. The blue areas show the area that are predicted to burn but do not actually burn (over-prediction), the green areas represent the areas that actually burned but were not predicted to burn (under-prediction), and the orange areas, labelled intersection area, represent areas that were predicted to burn and did actually burn (accurate predictions).

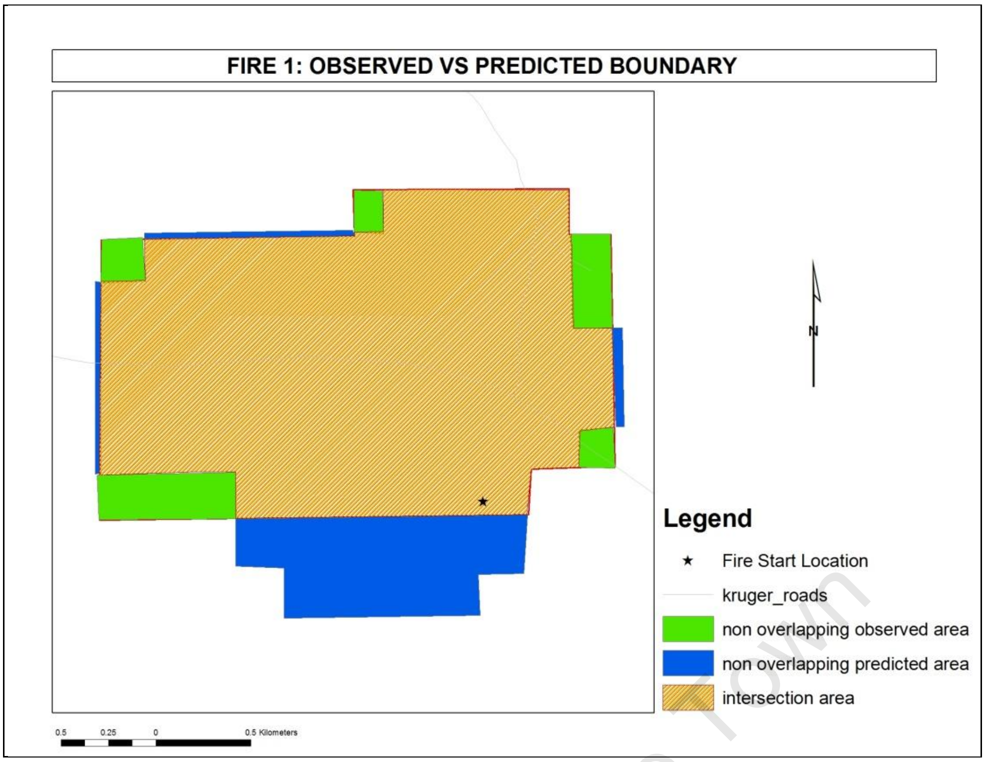


Figure 7-13 Fire 1: illustration of the components of Sorenson coefficient

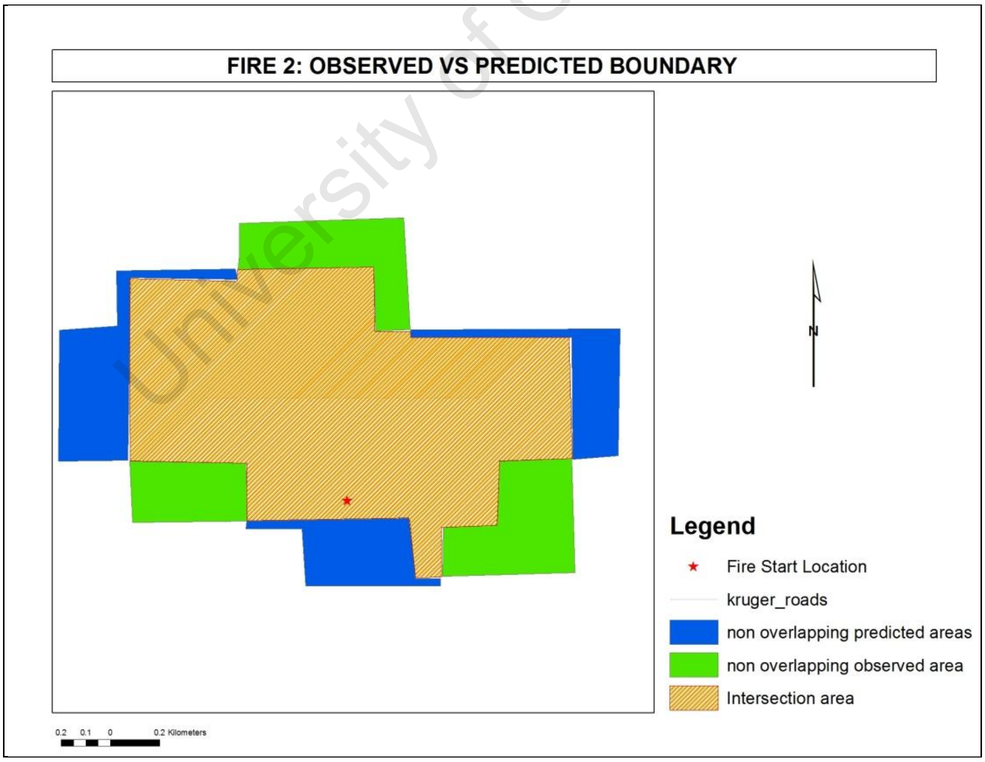


Figure 7-14 Fire 2: illustration of the components of Sorenson coefficient

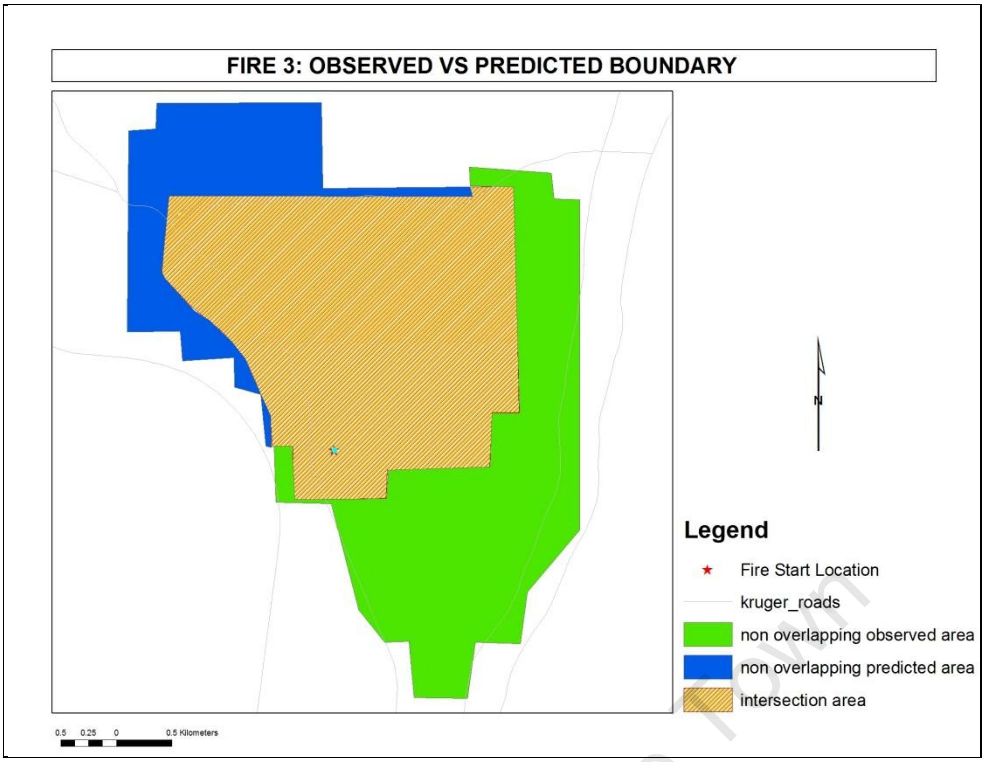


Figure 7-15 Fire 3: illustration of the components of Sorenson coefficient

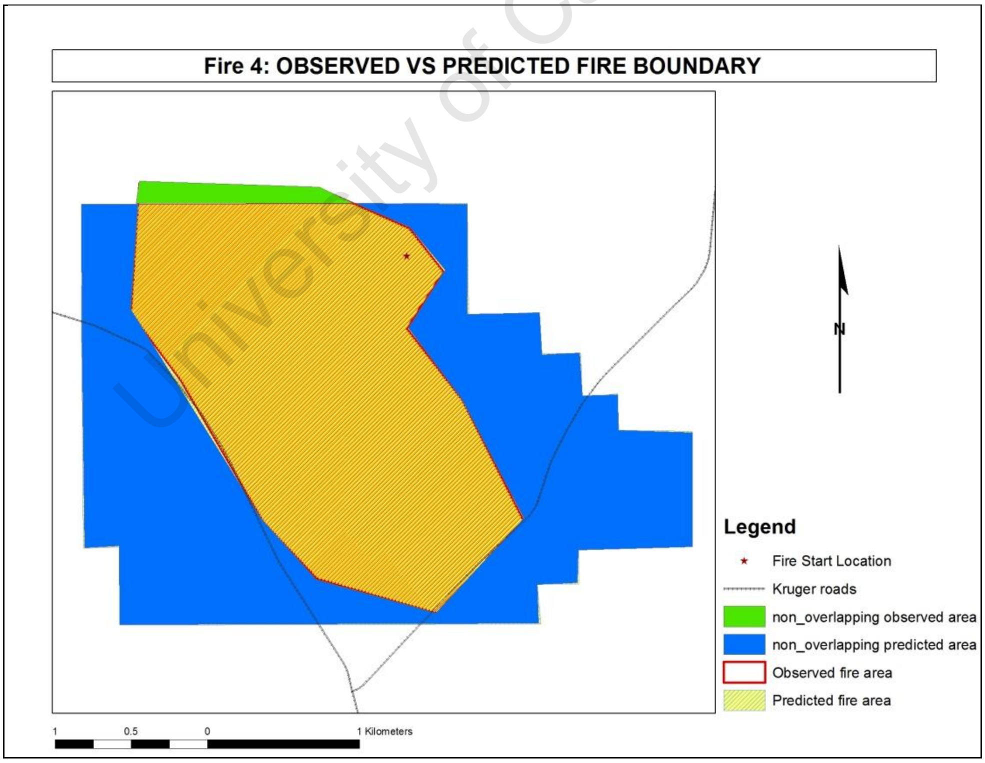


Figure 7-16 Fire 4: illustration of the components of Sorenson coefficient

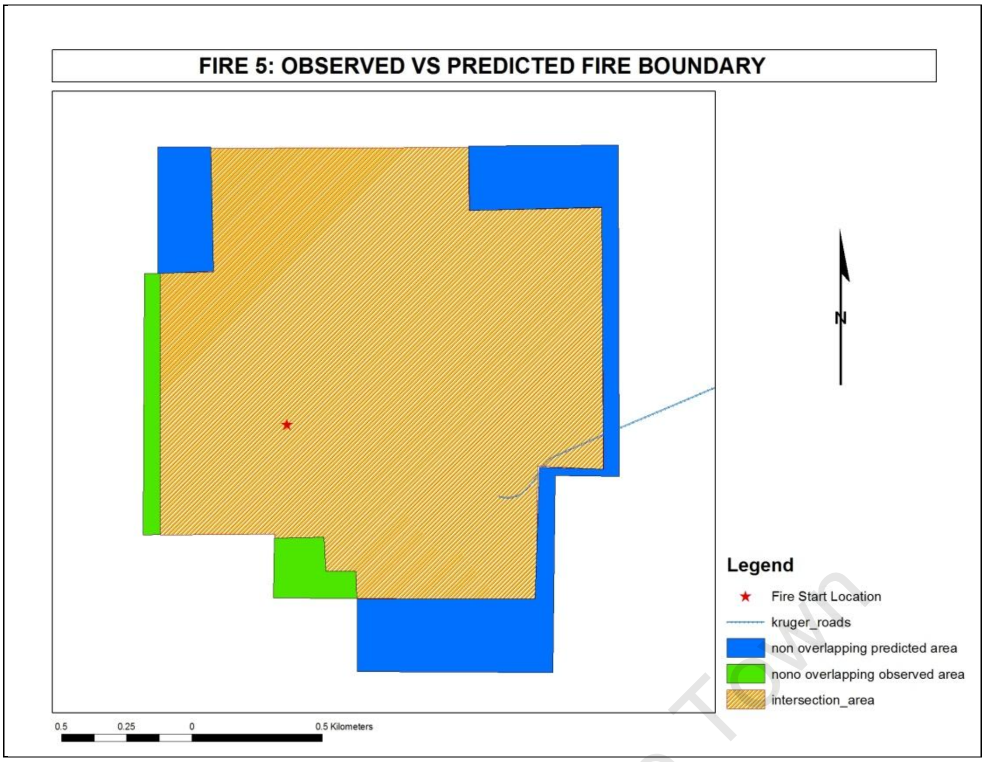


Figure 7-17 Fire 5: illustration of the components of Sorenson coefficient

The results of the comparison between observed and predicted fire area, for the fire test cases, where no smoothing is applied to the fire boundary polygons are presented in Table 7-2 below.

Table 7-2: Quantitative analysis of prediction results by Sorenson's Coefficient for Similarity Analysis without applying smoothing when converting raster area to vector polygon results

Fire	Observed area burnt (ha)	Predicted area burnt (ha)	A (ha)	B (ha)	C (ha)	SC
1	375.86	452.2	383.44	67.23	39.04	**0.88**
2	191.12	185	142.87	40.77	46.48	**0.77**
3	1165.21	885.23	676.46	214.9	487.8	**0.66**
4	438.48	886.31	439.32	438.32	15.27	**0.66**
5	258.1	296.6	243.8	51.9	13.72	**0.88**

The predictive capability of the model is generally good, with the worst prediction being 0.66 (66 %) and the best being 0.88 (88%). The worst case of prediction is experienced with fires that occur under high wind speeds, that burn over long periods hence being prone to considerable variations in prevailing weather conditions. The best prediction is experienced in small fires with moderate wind speeds, which are less likely to experience drastic weather changes.

Table 7-3 below shows the results acquired from the same method as above but with fire boundaries that have been smoothed out by defining a convex hull around the fire area which was initially in raster format. First, an illustration of the smoothing effect is represented by Figure 7-18. The colour scheme is similar to that of the non smoothed out fire areas presented in the preceding figures.

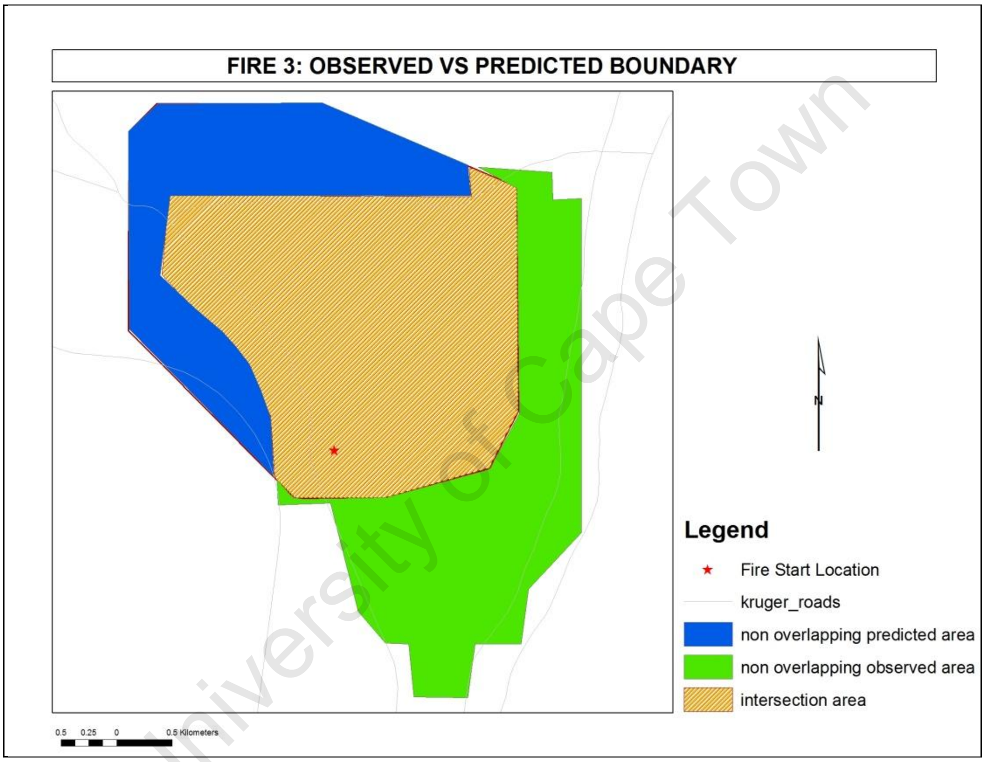


Figure 7-18 Fire 3: illustration of the components of Sorenson coefficient on a smoothed out fire area

Table 7-3 Quantitative analysis of prediction results by Sorenson's' Coefficient for Similarity Analysis with smoothing applied to image when converting raster area to vector results

Fire	Observed area burnt (ha)	Predicted area Burnt (ha)	A (ha)	B (ha)	C (ha)	SC
1	375.86	520.23	410.4	10.07	7.13	**0.98**
2	191.12	232.167	167.68	64.12	22.04	**0.80**
3	1165.21	1049.31	678.79	511.55	14.29	**0.72**
4	438.48	943.55	442.11	511.55	14.29	**0.63**
5	258.1	234.08	214.11	20.35	42.21	**0.87**

The same trend where large fires show the least prediction accuracy and small fires with low wind speeds showing the best prediction ability is again observed. The prediction accuracy of fires 4, 5 has decreased whereas the prediction for fires 1, 2 and 3 has improved. The smoothed out areas perform better with respect to Sorenson's coefficient in cases where the non smoothed out area under-predict the fire area and the reverse is observed when the non smoothed areas over-predict the fire area.

7.3.3.2 Comparison of predicted area burnt as a result of smoothing and no smoothing

Table 7-4 provided below shows the effect of smoothing the fire boundary compared to not smoothing.

Table 7-4 A comparison between the predicted fire area with and without smoothing

Fire	Observed Area burnt (ha)	Predicted Area burnt (ha)	Predicted Area with smoothing (ha)
1	375.86	452.2	520.23
2	191.12	185	232.167
3	1165.21	885.23	1049.31
4	438.48	886.31	943.55
5	258.1	296.6	234.08

The smoothed out areas are larger than the original prediction and this can be viewed as a distortion of the actual prediction ability of the model. Although the smoothing is applied in vector format, when it is compared to the original prediction which is in raster format, cells that are not burned are included when in fact they should not be, and hence leading to the conclusion that smoothing exaggerates the prediction capability of the model.

7.4 Propagation of fire fronts and animation

Another output of the fire model is an animation of the fire area with respect to time. Since animations cannot be shown in this text, a time-series illustration showing the fire fronts that result from simulating the fire progression over multiple time increments is presented below.

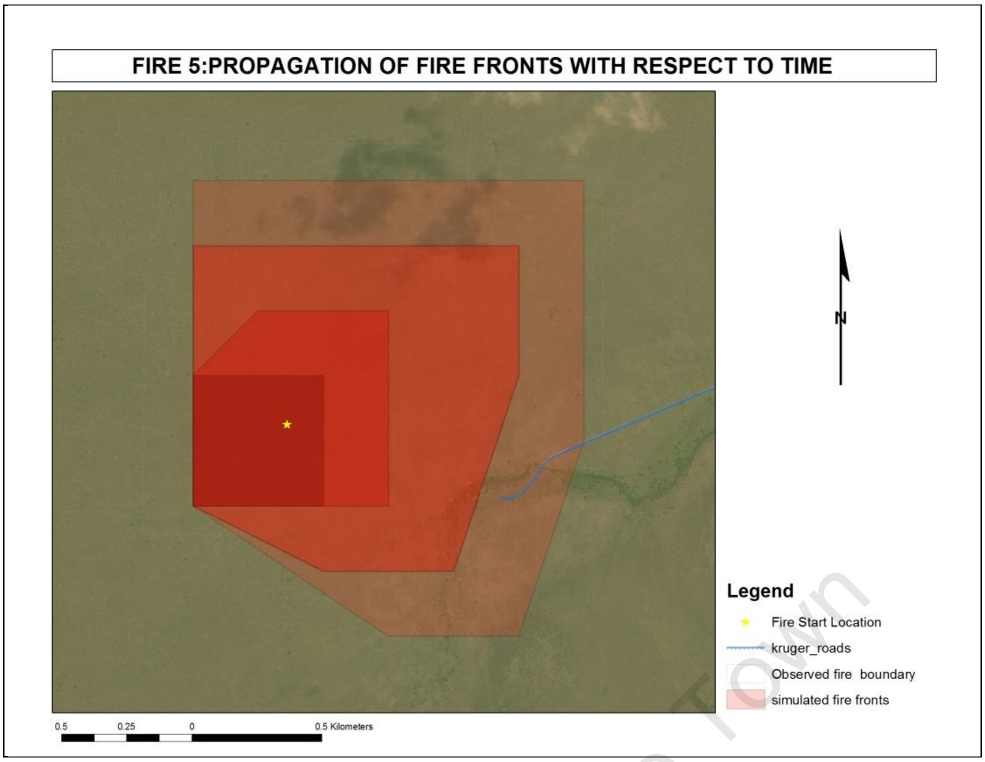


Figure 7-19 Fire propagation with respect to time with smoothing applied to the fire fronts

The fire fronts on which smoothing has been applied show a more elliptical shape of the fire spread. However as mentioned and illustrated in previous sections smoothing exaggerates the prediction ability of the model and may introduce erroneous predictions.

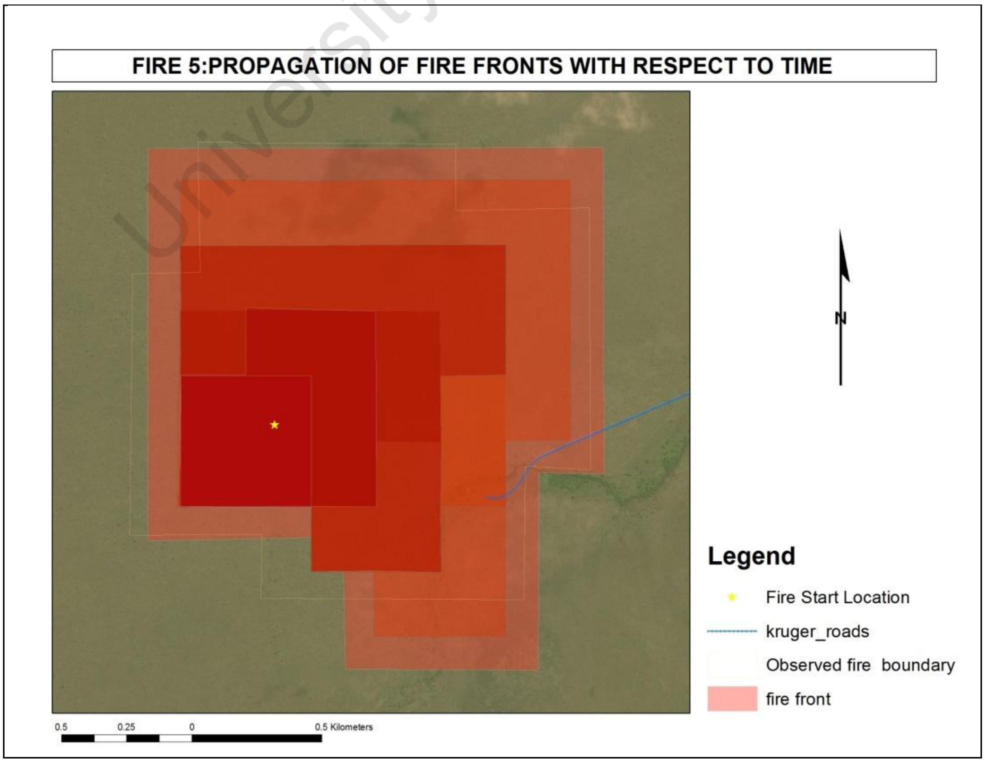


Figure 7-20 The predicted fire propagation without smoothing applied to the fire fronts

The fire areas presented in Figure 7-20 have not been smoothed hence they have sharp edges, although the results of the fire areas that have not been smoothed are not as visually appealing, they do not exaggerate the prediction ability of the model because they coincide with the states of the cell in the original results that are in raster format.

7.5 Discussion

The results of the fire model developed in this study are presented in this chapter and qualitative analysis of the results is provided. In general the model provides results with a good level of accuracy and has been found to be reliable. The accuracy of this model ranges with 66% being the lowest level of accuracy, and 88% being the highest level of accuracy achieved. The model is also found to perform best under moderate wind conditions and short ranges as opposed to high wind speeds and long range fires that burn for days.

The results of this model with respect to the prediction of the area affected by fire are satisfactory, although levels of over prediction are shown in cases of high wind speeds. This is not seen as a failure as most developed fire models exhibit this trend. Models that deal with prediction of potentially risky situations prefer to over-predict over too much under prediction for the obvious reason that it is better to be over-prepared than to be inadequately prepared (Yassemi et al, 2007).

The following chapter discusses the findings of this research, and conclusions are drawn based on the results, the accuracy achieved, and the entire modelling process.

8 CONCLUSIONS

8.1 Introduction

The previous chapter presented the results of the fire model developed in this study, a qualitative analysis of these results was performed and the model was thus evaluated. This chapter draws conclusions about this study based on the main research question, which is: what is the suitability of GIS for development of a fully integrated fire model. The performance of the model with respect to the sub objectives of the study is also considered on drawing conclusions.

The sub objectives of this study are presented in chapter 1 and reiterated below:

- develop a fire behaviour model that accounts for risk of fire occurrence
- develop a fire spread model that accounts for full spread of fire, not only in the (forward) wind direction
- visualisation of result of fire propagation with respect to time

8.2 The use of GIS for the development of a fully embedded fire model

Having reiterated the objectives of this research a discussion of the conclusions drawn based on the results and in accordance with the objectives of the study are presented. The suitability of the GIS environment to perform fire modelling tasks is also evaluated.

8.2.1 The fire behaviour (risk) model

The fire behaviour component of the model developed in this study is implemented by performing calculations of fire intensity and consequently the burning index. The determination of fire intensity and burning index is based on mathematical equations that form relationships between the factors that are most influential to the behaviour of wildfires. The implementation of this model is successfully performed using ArcGIS through the available spatial analyst geoprocessing tools, which are capable of performing mathematical operations on grid layers. The measurements for the factors that influence fire behaviour, which are obtained with respect to the ground, can easily be converted to grid format as input layers to the model calculations. As a result the implementation of this component of the fire model is successful.

8.2.2 The fire spread model

As demonstrated in chapter 7, by the results and quantitative analysis, the model is able to predict the spread of a fire successfully. The spread of fire in all directions and not only the prevailing wind direction is demonstrated to be successful as seen in the results presented in chapter 7. This is in line with the findings of Trollope et al (2002) who stated that the forward spread of fire is up to approximately seven times more in the direction of the wind than in the opposite direction, in the presence of wind.

The model did however show varying levels of reliability of predictions under different conditions[10]. The best predictions are experienced under moderate wind speed and the least reliable results achieved in very high wind speeds. The performance of the model is very successful for short simulation time periods less than 24 hours. The overall prediction accuracy is successful with success rates of between 66-88% of reliability.

This fire spread component of the fire model proved to be a lot more challenging to implement in ArcGIS ModelBuilder environment using available geo-processing tools. No readily available tool is capable of performing cellular automata operations hence a custom geoprocessing tool is developed to perform this task.

8.2.3 The suitability of GIS environment for implementation of embedded fire models

In chapter 2 the limitations regarding the use of GIS for development of fully embedded environmental models were outlined. The most notable disadvantages, drawn from the literature reviewed, are seen as the inability of GIS to model temporal process and the limited ability it has in terms of properly implementing existing environmental models. On the contrary, this research has proven these two statements to no longer be appropriate and has demonstrated the capabilities of GIS through geocomputation as discussed below.

[10] Conditions refer to conditions that influence the behaviour and spread of fires as discussed in chapter 2.

8.2.3.1 Ability to cope with temporal, dynamic processes

Environmental models, such as fire models, are dynamic processes that require frequent updating of input data and recalculation of parameters. The ability of ArcGIS through the chaining of processes that define calculations, in ModelBuilder, allows for the input data to be updated by the iteration of function processes. This iteration of processes is done in two ways: either a number of inputs are defined as input to one process one after another; or, the output of a function is reused as input to that similar process again at a changed state in order to derive different results. As demonstrated in chapter 5, this functionality of ArcGIS is explored in the building of the fire models hence demonstrating the ability of GIS to perform temporal processes.

8.2.3.2 Ability to perform complicated environmental modelling calculations and processes

The developed fire behaviour model is based on equations that were developed by fire ecology researchers and are considered to be complicated. The fire spread behaviour is able to successfully perform calculations for rate of spread, fire intensity, and flame length; which form part of the complex fire ecology calculations. These calculations as has been demonstrated in chapter 5 are performed through basic geoprocessing tools, hence this leads to the conclusion that GIS is able to implement and perform complicated fire modelling equations that are developed and used by fire researchers.

8.2.3.3 Fire propagation modelling through geocomputation

Enhanced programming abilities are possible through recent GIS software. Initially GIS had been criticised for offering programming only through basic macro languages, which could not cope with the complicated nature of environmental processes, such as propagation processes that include fire spread modelling, among others. With the possibility of using any COM[11] enabled programming language to enhance the basic GIS functionality offered, ArcGIS has made it possible to perform once impossible complicated spatial operations. This ability of GIS is used in the implementation of the fire spread model that is developed in this study. As discussed in chapter 5 a custom geoprocessing tool was developed to enable the implementation of the fire spread model. (It is worth mentioning that programming with GIS

[11] Programming with COM is discussed in chapter 5.

is not only available with ArcGIS but other proprietary and open source GIS software, although reference is made to ArcGIS as it is the software used in this study)

8.2.3.4 Visualisation of dynamic phenomena through animation

Upon completion of calculations and predicting the spread of fire, it is discussed in chapter 5 and demonstrated in chapter 7, that GIS provides for visualisation of dynamic results. This is demonstrated by animation of the propagation of fire through time.

Apart from all those aspects discussed above, another importance of GIS in fire modelling is that it provides the basic functionality of data management and visualisation of data in a spatially enabled environment.

The importance of using Modelbuilder to develop this fully integrated (embedded) fire model is that no data transfer (import or export) is required except for the basic input data. Results from the fire behaviour model are seamlessly transferred into the fire spread model. This is a most important factor that demonstrates that this model is an entirely embedded model. Having stated all these facts, it can thus be concluded that ArcGIS can be used to develop a fully integrated fire risk model.

8.3 Problems encountered: Limitations

A major challenge experienced by the model developed in this study, is the ability to properly account for the effect of small features such as narrow roads in a grid based modelling environment. This shows an effect on the accuracy of the model. From the test fires conducted, the model over-predicts fires that occurred in areas that were bounded by roads on either side, whereas the actual fires stopped when a road was encountered.

The model is tested on grid sizes of 250m (which is the lowest resolution of the satellite images used to calculate the fuel moisture content) and a resampled grid of 50m. The resampling does not improve the results by much because it is performed in such a way that the cell values do not change[12], on order not to introduce any biases. In order to account for roads in a grid, a cell size that allows the width of a road to be represented by one entire cell

[12] Resampling of input data is discussed in chapters 5 and 6.

should be used in the simulation. This also requires the resolution of the input satellite image (in this case), which is used to obtain the fuel moisture content, to match this resolution. Using a satellite image of this resolution will make it possible to identify and differentiate between a road and vegetation very close to the road, and therefore obtain different moisture value for these two features. Operating the model on such high resolution would require the use of powerful computers (although this is a hardware problem that can be accounted for and has no bearing on the model itself).

It is also known that the test fires used were range management fires, however it is not known whether this is a result of human influence along the road to prevent the spread of fire across the roads, meaning that the fire could have been intentionally stopped and the road width may have not played a role. Nonetheless appropriate resolution of input data is critical in order to improve the model accuracy.

9 RECOMMENDATIONS: FUTURE WORK

This chapter discusses the recommendations to improve the performance of the fire model developed in this study. The recommendations are made based on the limitations that hindered better performance of the model, as well as additional work that can be done to ensure better prediction ability.

9.1 Testing the model with more fire data

Due to data limitations, the proposed model is tested with five fire cases. Although these cases cover different fire conditions and reveal different fire behaviour with every different case, it would be beneficial to investigate the least successful cases further in order to determine a method of improving the prediction ability of the model in these cases.

9.2 Improvement of input data

The model clearly demonstrates the importance of wind in fire propagation. Apart from the fact that the chosen fire test cases provided most of the necessary information for modelling, these cases that are used to verify the performance of the model were selected mainly because of their proximity to the weather stations from which known measurements had been recorded. The input weather data needs to be provided at a denser resolution. The use of gridded weather data will be an added advantage but, if not possible the implementation of a verified weather prediction model will also be an advantage.

The use of coarse resolution satellite images has been discussed as a major limitation to this study in chapter 8; hence it is important to test this model with higher resolution input data in an effort to improve predictive ability in regions where barriers to fire, such as roads and rivers, exist.

9.3 Incorporation of a fire spotting model

The model assumes that fires propagate from one cell to the eight adjacent neighbours at a particular time instant. This is not the only way in which fires spread. Research has shown that under the prevalence of strong winds, when wind speed increases, and consequently the fire intensity increases, fire brands are transported in such a way that a cell that is not an immediate neighbour to the fire cell can also be ignited. This concept is called spotting

(Rothermel, 1983). It was beyond the scope of this project to investigate the concept of fire spotting. The implementation of a spotting model can improve the prediction ability of a model in cases of fire under high wind speeds, and reduce the under-prediction as seen in this model.

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APPENDICES

Appendix A: Spectral bands of satellite systems used

a) AVHRR Spectral band descriptions (NOAA, nd)

Channel (band)	**Description**	**Band width (micrometers)**
1	Visible (green) channel	0.58 – 0.68
2	Reflected Infrared channel	0.725 – 1.05
3	Hybrid reflected /Thermal infra red channel	3.55 – 3.92
4	Thermal infrared channel	10.3 – 11.3
5	Thermal infra red channel	11.5 – 12.5

b) <u>MODIS Spectral Band Descriptions (MODIS, nd)</u>

Primary Use of band	**Band**	**Bandwidth (nm)**
Land/Cloud/Aerosols Boundaries	1	620 - 670
	2	841 - 876
Land/Cloud/Aerosols Properties	3	459 - 479
	4	545 - 565
	5	1230 - 1250
	6	1628 - 1652
	7	2105 - 2155
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420
	9	438 - 448
	10	483 - 493
	11	526 - 536
	12	546 - 556
	13	662 - 672
	14	673 - 683
	15	743 - 753
	16	862 - 877
Atmospheric Water Vapour	17	890 - 920
	18	931 - 941
	19	915 - 965
Surface/Cloud Temperature	20	3660 – 3840
	21	3929 - 3989
	22	3929 - 3989
	23	4020 - 4080
Atmospheric Temperature	24	4433 - 4498
	25	4482 - 4549
Cirrus Clouds Water Vapour	26	1360 - 1390
	27	6535 - 6895
	28	7175 - 7475
Cloud Properties	29	8400 - 8700
Ozone	30	9580 - 9880
Surface/Cloud Temperature	31	10780 - 11280
	32	11770 - 12270
Cloud Top Altitude	33	13185 - 13485
	34	13485 - 13785
	35	13785 - 14085
	36	14085 - 14385

Appendix B: Projection details of satellite images

a) Projection details for Southern Africa, AVHRR, NDVI image (FEWS NET, 2007):

File format: BIL

COORDINATE SYSTEM DESCRIPTION (for all spatial extents):

Projection: ALBERS (Albers Equal Area Conic)

Units: METERS

Spheroid: CLARKE1866

Parameters:

1st standard parallel (dms): -19 00 0.000

2nd standard parallel (dms): 21 00 0.000

central meridian (dms): 20 00 0.000

latitude of projection's origin: 1 00 0.000

false easting (meters): 0.00000

false northing (meters): 0.00000

Pixel size (for all spatial extents):

x-direction: 8000 m

y-direction: 8000 m

Spatial parameters for **Southern Africa** window:

NROWS 530

NCOLS 640

Image coordinates (center of pixel) (x,y):

upper left (UL) -1452000, 12000

upper right (UR) 3660000, 12000

lower left (LL) -1452000, -4220000

lower right (LR) 3660000, -4220000