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TITLE

GIS Based Modelling for Fuel Reduction Using Controlled Burn in Australia. Case Study: Logan City, QLD

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Master Thesis 30 Credits, in Geographical Information Sciences

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Abstract:

Bushfire problem is a long-lasting problem which is a big threat and environmental problem in Australia. Planning to control bushfire is very important for Australian Environment. One of the most effective methods to fight bushfire disasters is planning for controlled burns in order to reduce the risk of unwanted bushfire events. Controlled Burn management is very important for Australian environment authorities.

This research aims to investigate different approaches to build up spatial model to aid decision makers have a rational justifications for planning controlled burns or prescribed burns in long term. This includes finding out suitable model for scoring blocks designated as bushfire prescribed burns blocks. The target of this research is to investigate suitability criteria related to prescribed burn management and use them to design a model for analysing geospatial suitability for bushfire prescribed burns. In the process of this research, first it is tried to find out how prescribed burn programs work, what characteristics a burn plan has and how different criteria may contribute in forming suitability for performing a prescribed burn. Then a model is developed for this purpose. This model should give decision makers a very good logic how a prescribed burn could be recommended as for short term or long term planning. Different needs and perceptions for planning prescribed burns have been investigated and considered in the model. The developed model then has been tested in a pilot area within Australia and the results are debated, validated and justified.

Results show that this study has represented a good agreement between the real block preference proposed by Parks Branch experts at Logan City Council and model outcomes. The created model and tool for prioritizing blocks could be used as a good basis for long term decision making based on a user friendly adjustment interface.

1 Introduction

1.1 Bushfire as a Disaster in Australian Context

'Bushfire' is a general term used to describe a fire in vegetation. Bushfires have been responsible for some of the most unforgettable natural disasters in Australia, such as the Ash Wednesday fires in Victoria and South Australia on 16 February 1983 and wildfire on "Black Friday," 1939. (The Black Saturday Bushfires is the name given to the bushfires which started on the 7th of February 2009 in Victoria, Australia). Fire should not be regarded as unnatural or catastrophic, but rather as a recurring aspect of the Australian environment. Across Australia, major bushfires are estimated to have cost $2.5 billion in the period from 1967 to 1999, corresponding to average annual cost of $77 million (Gentle *et al.*, 2001). There have been over 700 deaths caused by bushfire since the first recorded death in 1850 (Blong, 2005).

They had not lived long enough were the words that Judge *Leonard Stretton* used to describe the people who lived and worked in the forests of south-eastern Australia when they were engulfed by a holocaust wildfire on "Black Friday," 1939. The judge, who conducted an immediate royal commission into the causes of the fires, was not commenting on the youthfulness of the dead: he was lamenting the environmental knowledge of both victims and survivors. He was regretting the innocence of European immigrants in a land whose natural rhythms they did not yet understand. He was depicting the fragility and brevity of a human lifetime in forests where life cycles and fire regimes had the periodicity and ferocity of centuries. He was indicting a whole society (Griffiths, 2009).

While bushfire activity in Australia is prevalent in most landscapes that carry fuel (e.g. grasslands, forests, scrub and heath lands), the two predominant bushfire types in Australia are grassland fires and forest fires. Common to both are sources of ignition and factors such as weather conditions that affect the intensity of a bushfire. Bushfires are ignited either naturally by lightning, or by human activity. Across the Australian continent, lightning is the predominant ignition source of fires, being responsible for just over 50% of all ignitions. In the southern states, where most asset loss occurs, natural causes account for approximately 30% of ignitions (Middelmann, 2007).

As stated by (Marsden-Smedley, 2009), projections from climate change models suggest that in the next few decades across much of south eastern Australia there will be major increases in the level of fire threat through increases in the incidence of high fire danger conditions (although smaller increases in fire threat are predicted in southern Tasmania (Lucas *et al.*, 2007).

In 2009, Queensland, Australia, experienced one of its worst bushfire seasons on record and at one point fire-fighters attended 4491 vegetation fires across the state over a 36-day period. In many cases homes and lives were at risk and residents were faced with the decision to stay with their property or leave the area early ("PREPARE.ACT.SURVIVE," 2014).

1.2 Planned Burning:

As mentioned before, in Australian usage, ‘bushfire’ is a general term used to describe a fire in vegetation. Fires lit purposefully for fuel reduction or land management purposes are often more accurately referred to as ‘prescribed fires’ ("Australasian Fire Authorities Council," 2014)

Broadly, planned burning is the controlled use of fire on vegetation within selected areas, and has two major purposes:

1- Fuel management: mostly the reduction of amounts of flammable leaf litter, bark and coarse debris on the near ground (Fuller, 1997). This would be done to reduce overall fuel-hazard rating to low or moderate and minimize impacts to community and ecological values
2- Ecological reasons: Habitat manipulation, such as promoting the germination of seeds from soil seed bank. Control of alien vegetation (weeds, although fires also facilitates invasions by alien weeds) and silvicultural purposes (Fuller, 1997).

It is necessary to distinguish between ‘Fuel reduction burns’ and ‘ecological burns’. Ecological burns do not contribute with Disaster management and Fire Risk Control and solely relate to impacts of the fire on ecology. With ecological burn, Prescribed burning can be used to establish a particular fire regime (i.e. different intervals, intensities, or patchiness) thought to be beneficial to certain flora or fauna (Altangerel *et al.*, 2013). Planned burning can assist with the maintenance of ecological values by providing a range of fire types, seasons, frequencies, ages, sizes and intensities (Marsden-Smedley, 2009).

But “Fuel Reduction Burns” is targeted to reduce the amount of flammable vegetation, it can also play an important role in wildfire risk management. It can be directed to reduce the intensity, size, and occurrence of large wildfires, and facilitate fire suppression.(Bradstock *et al.*, 1998) A stated aim of ‘Fuel Reduction Burns’ is to minimise the area burnt by wildfires, and in particular large scale, high intensity wildfires. These high intensity wildfires are responsible for the majority of the threats to public health and safety; extremely expensive to suppress; and frequently result in threats to ecological values through their lack of fire regime variability and the small proportion of the landscape left unburnt (Marsden-Smedley, 2009).

The cost of a bushfire is often related to the assets lost or insurance claim value of the event, but real costs include the social and environmental costs as well as the economic losses. The costs of two fires of similar size can vary significantly depending upon the exposure of assets and the population density and socioeconomic profiles of the areas in the paths of the fires (Middelmann, 2007).

For the period from 1967 to 1999, the total economic cost of major bushfires has been estimated at $2.5 billion, contributing about 7% to the annual cost of natural disasters and an average annual cost of $77 million (Gentle *et al.*, 2001).

From 1850 to 2001, 696 lives have been lost in bushfires across Australia (Blong, 2005).
However, there has been a decline in the number of lives lost in bushfires over the past 20 years (Ellis *et al.*, 2004).

1.3 Problem Context

According to Cheney (1996), Reduced to the most basic outline, most decision makers who take a responsible attitude towards fire management have three platforms in their fire management policies. These are:

- to manage fire so that damage to forest, environmental and economic values is minimised;

- to manage fires so that as far as possible they are prevented from spreading to other lands; and,
- to provide fire suppression on a least cost plus loss basis.

The issue of relativeness of fuel reduction and effective fire management aims mentioned above has been debated by many scientists. McArthur (1962) has done some good research in different fire management policies in vegetation or fuel management context, especially with regards to spotting phenomena of fires in eucalypt forest and come to the conclusion that any fire management system based only on fire breaks would not meet the policy objectives outlined above. In his opinion fire management needed to become fuel management. In his work in Control Burning in Eucalypt Forests, (McArthur, 1962), set out the benefits of reducing the quantity of fuel available for combustion:

- the intensity of a fire burning under any set of meteorological conditions is reduced;
- the rate of spread of the fire is reduced;
- the difficulty of constructing effective control lines is reduced, so any fire becomes easier to control; and,
- the likelihood of fires starting is reduced.

As such we can have a good scientific background that 'Fuel Reduction Burns' can contribute in Disaster Risk management in Australia and could efficiently address the three mentioned fire management policies. Constraints such as the cost of implementing prescribed burning and shortage of trained personnel can limit the use of fire (Cleaves *et al*., 2000). Limited resources for planning risk reduction practices in regards to fuel reduction highlights finding a good tool for helping planners in relevant authorities to have good decision aid model to find most appropriate burn areas supported by a very robust and sound scientific background. Using GIS could be a very good approach to deal with planning aspects of burn blocks (burn blocks are selected areas chosen by authorities and considered as potential pieces of land suggested for performing controlled burn on). Selection and justification of best decision be made to choose most suitable and economic blocks for burning both in short term and long term point of view were always a big concern for decision makers.

1.4 Problem Statement

Resources for prescribed fire are frequently insufficient to manage public lands for all conservation and resource management objectives, necessitating prioritization of the application of fire across the landscape within any given year (J K Hiers *et al.*, 2003).

In their works J Kevin Hiers *et al.* (2003), mentioned that there are, fewer tools that prioritize management actions at the landscape scale in a spatially explicit manner (McCarter *et al.*, 1998), and existing tools are frequently too complicated or information-intensive to gather widespread acceptance among land managers. Considering the above mentioned need, the problem extent which is going to be subject of this thesis is to investigate different approaches to build up spatial model or models to aid decision makers have a rational justifications for planning fuel reduction prescribed burns either in long term or short term. With this aim the following problem statements and investigation topics are considered in this thesis:

1- Investigate criteria related to prescribed burn management and their usability to design a model for analysing long term geospatial suitability of bushfire prescribed burns.
2- Finding out suitable model for scoring blocks designated as fuel reduction bushfire prescribed burns blocks in long term
3- Investigating different needs and perceptions for planning prescribed burns
4- Testing model in a pilot area

In this thesis it is tried to include both natural fire behaviour related factors and burn implementation factors as well. Assumption is that there is an uncertainty among many proposed burn blocks for prioritization. It is an assumption that the blocks are already chosen by environmental specialists site visits considered as potentially suitable for burns. Therefore the tool or model acts as a decision support tool for validating their suitability by some scientific and justifiable criteria for burn.

1.5 Research Objective and research questions

The objective of this thesis is to create a GIS based Fuel load reduction prescribed burn management system that serves as a decision support system for planners and decision makers to choose best blocks for implementation of prescribed burns in long term. The GIS based management system will consider the following facilities:

1- Considers justified and relevant weighted criteria for prescribed burns
2- Integrates information needed for planned burns in a spatial database system
3- Uses selected criteria to create a spatial model or a combination of spatial models to aid better planning of prescribed burns and
4- Applies the model in a pilot area to investigate and validate the results

Consequently the research questions are:

1- Why using a multi-criteria analysis is a good methodology for analysing blocks readiness for burn?
2- Which characteristics makes a block suitable for burning? Are these characteristics spatial?
3- How could the characteristics be modelled in Decision Support System GIS model?
4- How could short term and long term GIS models be developed?
5- What data is necessary to be integrated and structured in the system to assist planners to have most suitable database for producing burn plans

1.6 Development methodology

The Development Model in *figure 1.1* demonstrates the flow of work of this project in order to develop GIS based Fuel load reduction prescribed burn management suitability model. The research model has been divided into five different modules and each module needs several tasks to complete. These five modules are elaborated below.

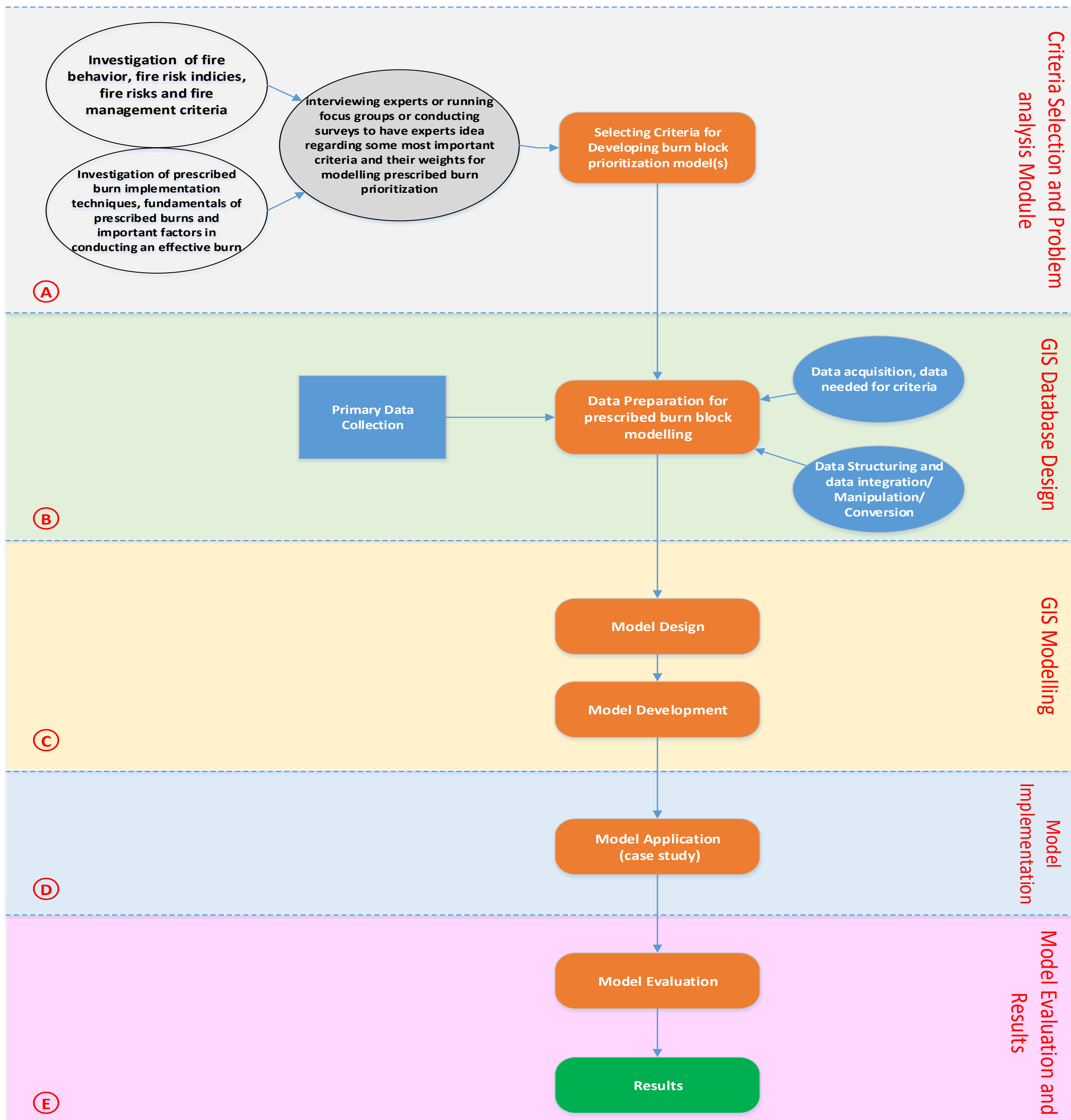


Figure 1-1- Research Development Model

A. ***Criterion Selection and Problem Analysis Module:*** Analysis of different aspect of fire control and fire behaviour is in the first module. In this module, different criteria related to fire control fire behaviour and prescribed burn implementation are studied. In this part several criteria for consideration of multi-criteria analysis with GIS model is going to be studied and the corresponding importance weight for them are debated. Research methodology used in this section is investigating literature and methods for determining weights and possibly, using experts' ideas by interviews or small surveys or running focus groups in a stakeholder organization to find out the most relevant and the most important criteria. The questionnaire for this survey is designed after analysing different factors and the selected factors are included in survey for final validation and importance weighting. Many implementation and fire related factors are analysed in this section and it is investigated how to consider existing fire risk indicators as a means of evaluating the burn readiness of blocks.

B. ***GIS Database Design:*** After finalizing the criteria and setting the related importance weights for each of them, the next task involved creating a GIS database, which is very important task of for best developing the entire project. It deals with the compilation and development of the spatial as well as non-spatial data according to the user requirements. It includes data collection which is followed by the data processing such as data integration, manipulation or conversion. Data received was some corporate data from Logan City Council. Such data has been already generated by Council's IT department as a reference for corporate and staff usage. Each criteria may need different database preparation activity.

C. GIS Modelling: The next task includes model design and development. The design and development relies upon the output and on the needs and requirements needed for planning purposes which comes from analysis and study done in initial module. The model will consider all the components which will be used to plan and prioritize burn blocks. This model should be able to work as a basis for having a sound and robust decision on which blocks are most suitable to be burnt in long term and short term point of view. And once model is designed and GIS database work is ready for it, the model is ready to develop. Based on the designed model for the tool, ESRI's ArcGIS as well as spatial analyst extension are the core software needed to build up the model. For further usage, the model is going to be developed on model builder platform to make the procedures more automated and easy to repeat.

D. ***Model Implementation:*** The next task includes model testing Logan City, south of Queensland. The case study is an administration area within Australia that all the criteria data has been prepared and acquired for. It is very important to have model results for that case to evaluate it and come to conclusions. Model design process is based on planning needs and implementation requirements.

E. ***Evaluation & Results***: This module involves the evaluation of the results taken from the model and the feedback in form of interviews and open discussions received the stakeholders, users or planners.

2 Study Area

The model is tested in Logan City region burn blocks. Logan City Council (LCC) area which is an independent local government adjacent to the Queensland state capital city of Brisbane.

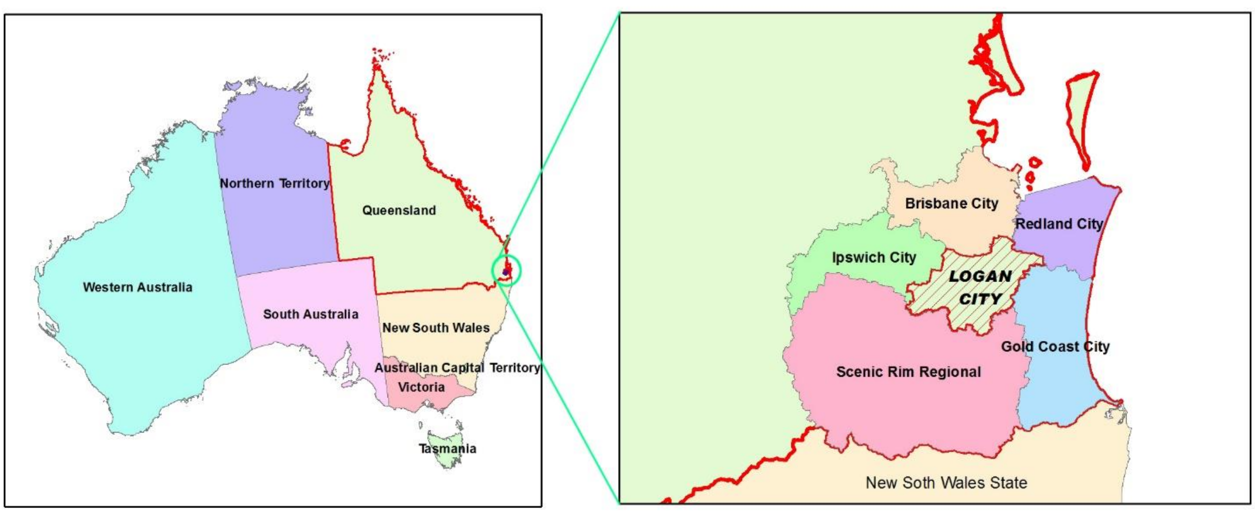


Figure 2-1-Logan City Geographical Location

2.1 Location

Logan City is located in South East Queensland, midway between Brisbane and the Gold Coast, with its centre approximately 23 km south of Brisbane. It has an area of approximately 933 km^2 and shares borders with five other local governments: Brisbane City Council, Ipswich City

Council, Scenic Rim Regional Council, Gold Coast City Council and Redland City Council ("Bushfire Risk Management Study Report," 2012).

2.2 Topography

The topography of Logan is generally flat in urban and residential areas with ridge lines to the west, north and east. The ridges lead down into flat and primarily rural land surrounding Logan River which flows south west to north east to through Logan (Logan City Council, 2013). The topography of Logan generally ranges from mountainous areas to flat or undulating areas ("Bushfire Risk Management Study Report," 2012).

2.3 Climate

Logan City is situated inland from the Queensland coast at approximately 27.6° south latitude and consequently has a moist sub-tropical climate. Rainfall is seasonal with the heaviest rain occurring during the summer months. The most extreme rainfall events are generally associated with tropical cyclones. The average annual rainfall is 1027mm. Temperatures rarely exceed 35°C or fall below 10°C for extended periods. The mean maximum and minimum annual temperatures are 25.6°C and 13.9°C respectively ("Bushfire Risk Management Study Report," 2012).

2.4 Vegetation

Logan City has a diverse range of natural vegetation types including significant examples of habitats that remain largely undisturbed by development. Extensive areas of the city, however, have had vegetation types greatly modified as a result of residential and industrial development and other areas have been cleared to make way for crops and grazing as well as for urban development. Approximately 27 per cent of the city area is given over to reserves, national parks, forest reserves and military land. Much of the previously continuous open forest and woodland vegetated tracts have been fragmented into a mosaic landscape by both peri-urban expansion and the need for infrastructure corridors ("Bushfire Risk Management Study Report," 2012).

2.5 Population

In 2010, Logan City had a population of 282,673 (Australian Bureau of Statistics, 2010). The most densely-populated neighbourhood (as per 2010 Census) was the Jimboomba - Logan Village area with 45,120 people, followed by Browns Plains with 31,245 residents. The median age for the city's residents is 31 years, 25.2 per cent of the population is under 15 years of age, and 5.9 per cent of the population is over 65 years. The Local Government Reform Commission predicts a population in excess of 382,388 by the year 2026. Note: These statistics change seasonally as advised by the Australian Bureau of Statistics ("Bushfire Risk Management Study Report," 2012).

2.6 Transport

Logan City is heavily reliant on transport links. Major South East arterial roads - including the Mount Lindesay Highway, the Logan Motorway, and the Pacific Highway/M1 Motorway - link the city to the rest of South East Queensland. All freight into and out of the city is carried by road. The city is supported by a range of bus services including commuter and school buses and specialised coach services ("Bushfire Risk Management Study Report," 2012).

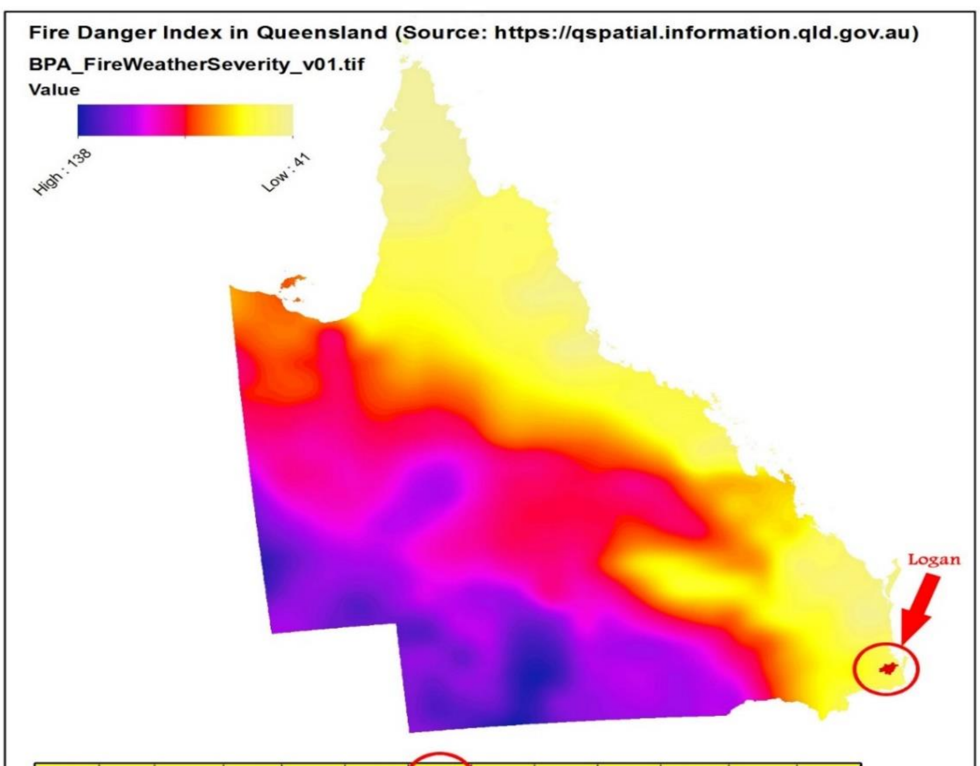
Passenger rail services within Logan City are provided by Queensland Rail through the TransLink network on the Gold Coast line. The interstate rail line between Queensland and New South Wales runs roughly north to south through some suburbs within Logan.. This rail line provides passenger and extensive rail freight services between the two states. There are no seaports or airport facilities in the city ("Bushfire Risk Management Study Report," 2012).

2.7 Infrastructure

Power supply is drawn from the state grid via a number of sub-stations at Belmont, Loganlea and Greenbank. More than 50 major transmission lines (275 kV) are located within the city, operated by Powerlink Queensland. Distribution of power is undertaken by Energex and retail entities who maintain some 1800km of power lines carrying a range of voltages (240V – 11kV), generally on wooden poles ("Bushfire Risk Management Study Report," 2012).

2.8 Bushfire in Logan

The (A G McArthur, 1973) Forest Fire Danger Index (FDI) which is the best known, most widely used and thoroughly tested fire weather index adopted by fire agencies in Australia and Australian regulatory Instruments (such as AS3959 - Australian standard AS 3959-2009 Construction of buildings in bushfire-prone areas 2009), is a reference for Fire Danger Rating.(J Leonard *et al.*, 2014). Fire Danger Index is defined as the chance of a fire starting, its rate of spread, its intensity and the difficulty of its suppression, by various combinations of air temperature, relative humidity, wind speed and both the long and short term drought effects in worst case scenario.("Bushfre Assessment Report, Bellvista II, Caloundra West," January 2010). According to Bushfire hazard area/ Bushfire prone area ("Bushfire hazard area - Bushfire prone area - inputs - Queensland," 2014) database, Average Fire Danger Index in Logan City is found out to be 54.5 which is fairly average for this region (ArcGIS Zonal Statistics Analysis done on the map for Logan city extent, Figure 2-2).



LOCALITY	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	VARIETY	MAJORITY	MINORITY	MEDIAN
Logan CC	1532739	957961875	52	58	6	54.54294	1.168214	83600094	7	54	58	54

Figure 2-2-Fire danger Index in Queensland

In comparison extreme fire danger indices happening in western Queensland rather than Northern and Coastal Queensland this value is rather mild. Again, in contrast to significantly impacted bushfire prone states of New South Wales, Victoria, South Australia and Western Australia, Logan does not immediately rate as very considerably lower than the rates cited for those states which is in average 80-100 ("Bushfre Assessment Report, Bellvista II, Caloundra West," January 2010). According to Granger *et al.* (2001), analysis in their report on natural hazards, the risks of bushfire in South East Queensland, is a low overall risk of bushfire damage in urban areas, however, the risk in rural areas and rural fringe areas is moderate to significant.

Logan City is not immune to the risk of severe bushfires, especially in the extensive peri-urban residential communities which are adjacent to large tracts of native bushland and have a large urban/bushland matrix. Logan has both large land areas and urban/peri-urban populations that could be potentially impacted by bushfire risk and if left unchecked or unmanaged the risk situation could escalate. In addition climate change predictions for South East Queensland could escalate the role of bushfire as a major risk element.("Bushfire Risk Management Study Report," 2012)
Low (2011), believes the study of Low Choy *et al.* (2008), Williams *et al.* (2009) and Bradstock *et al.* (1998) have indicated that fire risk will increase mainly in the sclerophyll forests of eastern Queensland. As Logan is largely within a dissected sclerophyll landscape it is highly probable that bushfire risk will increase ("Bushfire Risk Management Study Report," 2012).
In a study of natural resource management issues impacting the peri-urban areas of South East Queensland, Low Choy *et al.* (2008) state that where settlement has extended into densely vegetated areas, bushfire risk is becoming an increasing management issue. In addition, the recent analytical research by ("State-wide Natural Hazard Risk Assessment. Report 3: Current exposure of property addresses to natural hazards.," March 2011) found that 25,198 residences within Logan were within 100 metres of natural forest ("Bushfire Risk Management Study Report," 2012).

This result illustrates the extensive urban/bushland interface zone within Logan (often termed the I-Zone) is the third largest local government in terms of number of residences adjacent to bushland in the State (Risk Frontiers, May 2011.) . Only the local government areas of Sunshine Coast Regional Council and Gold Coast Regional Council have a larger number of residences contained in the urban/bushland interface zone ("Bushfire Risk Management Study Report," 2012).

For Logan, this research indicates that large numbers of properties/residences are at medium/high risk from bushfire impacts and that mitigation may be required to minimise impacts. It is predicted that future climate change will only increase the potential risk of bushfire impacts in the extensive peri-urban and urban/bushland interface zone. ("Bushfire Risk Management Study Report," 2012)

Gillen *et al.* (2006), emphasise the high potential risk to both assets and people with the expansion of rural residential living in South East Queensland and also highlight the challenges that local government and current planning systems face in dealing with such a large potential 'risk landscape' ("Bushfire Risk Management Study Report," 2012).

Figure 2-3-Results from an intense bushfire in the Carbrook area of Logan

("Bushfire Risk Management Study Report," 2012)

3 Problem analysis

3.1 Fundamentals of controlled burns

3.1.1 Preparation for implementation of a prescribed burn

Prescribed or controlled burn implementation point of view is done by municipalities, city council authorities or state governments in Australia. The circumstances under which a successful prescribed burn could be achieved are not a few. Many of these conditions are somewhat short term conditions that could affect better reduction of fuel in the area.

According to (D. o. E. a. N. R. Government of South Australia, 2011) the critical aspects influencing the success or failure of fuel reduction burning includes the blocks burn's:

- Location relative to assets being protected and/or ignition sources
- Size and width
- Coverage
- Proportion of the landscape treated
- Fuel moisture and content
- Intensity needed
- Frequency needed
- Weather condition
- Wind direction and speed
- Canopy and topography

For purpose of successful prescribed burn, first the block must be selected for burn purposes. *This thesis gives a comprehensive solution to blocks' initial selection and long term planning.* Then a routine monitoring process initiates for the selected block(s). A practical condition happens when most of the criteria stated above are favourable. Even some other case factors like cloud positioning and sun light coverage are determinant in starting and choosing a pattern for burning.

In the second prep ration phase, urban areas around the blocks are secured in different ways from giving notifications to inhabitants or even giving temporary evacuation notice. The burn plans and burn maps for the block is prepared. (Figure 3.2 and 3.3) The fire techniques or ignition techniques used for blocks depends on different factors including positioning of the block, wind direction (for purpose of smoke drift towards urban areas and fire spread), topography, fuel moisture content and fuel type and load.

The most common ignition patterns used during planned burning are (Marsden-Smedley J.B *et al.*, 2013):

- Back fire ignition;
- Flank fire ignition;
- Headfire ignition;
- Spot fire ignition and;
- Perimeter fire ignition.

Figure 3.1 shows one of these many techniques used for a prescribed burn.

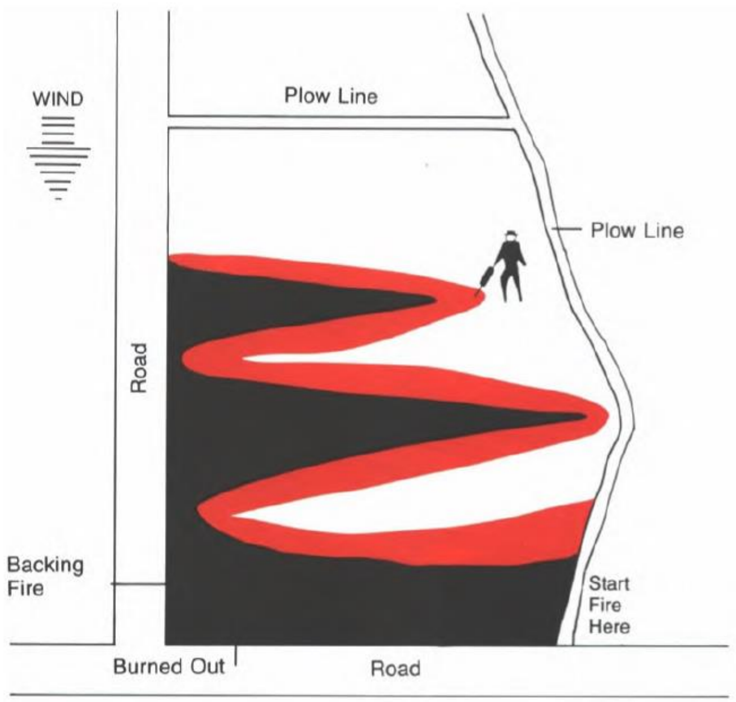


Figure 3-1-Strip headfiring: a method of prescribed burn (Wade et al., 1989)

Postharvest Prescribed Burning Unit Plan

Prepared by ____ Signature ____ Date ____ Permit no. ____
State ____ County ____ District ____ Comp't ____
Burning Unit No. ____ S ____ T ____ R ____ Gross acres ____ Net acres ____
Landowner ____ Address & phone no. ____
Person responsible & how to contact day & night ____
(Draw map on back or attach)

A. **Description of Area:**
1. Natural stand or plantation ____ Stand age ____ Harvest date ____
2. Clearcut ____ Harvest method ____ Pine basal area removed ____
3. Organic soil ____ Hardwood basal area ____ Hardwoods utilized ____
4. Unmerchantable trees felled ____ Snags felled ____ Debris evenly distributed ____
5. Debris (light, medium or heavy) ____ Brush (light, medium or heavy) ____
6. Herbaceous fuels (light, medium, heavy) ____ Herbaceous fuels continuous ____
7. Herbicide used ____ Date applied ____ / ____ / ____
8. Drum chopped ____ Single or Double Pass ____ Date Completed ____ / ____ / ____
9. Windrowed and/or piled ____ Date piled ____ / ____ / ____ Piled when wet ____
10. Pile or windrow dimensions: Ht. ____ Width (dia.) ____
11. Windrow break interval ____

B. **Preburn Factors and Desired Fire Intensity:**
1. Areas to exclude: ____
2. Chains to plow (see map): Exterior ____ Interior ____ Total ____
3. Chains to fire (see map): Exterior ____ Interior ____ Total ____
4. Equipment needs ____
5. Crew size ____ Type of fire ____ Type of ignition ____
6. Ignition procedure (see map): ____
7. No. of hours to complete ____ Tons/acre to consume ____ Litter to leave (in.) ____
8. Special precautions: ____
9. Notify: ____
10. Regulations that apply ____
11. Passed screening system? ____ List smoke-sensitive areas, critical targets & locate on map: ____

C. **Weather Factors:**

Weather Factors	Desired Range	Predicted	Actual
1. Surface wind (speed & dir.)	____	____	____
2. Transport wind (speed & dir.)	____	____	____
3. Mixing height	____	____	____
4. Dispersion Index (or comparable)	____	____	____
5. Relative humidity (%)	____	____	____
6. Temperature (oF)	____	____	____
7. Fine-Fuel moisture (%)	____	____	____
8. 10-hr. fuel moisture (%)	____	____	____
9. Days since rain ____ Amount	____		____
10. Burning Index ____ Drought Index	____	____	____
11. Best month to burn	____	Dates burned ____	
12. Time of day to start	____	Time set ____	

D. **Summary of Burn:**
1. Type fire & ignition ____
2. All piles, windrows & logging decks ignited ____
3. % of area burned ____ Did area between piles burn? ____
4. Spotting frequency ____ Distance ____ firebrand material ____

E. **Evaluation Immediately After Burn:**
1. Any escapes: Number ____ Adjacent to burn area? ____ Acres involved ____
2. Hours to burnout: Active flaming ____ Smoldering ____ Total hours ____
3. % understory veg. consumed ____ Depth of litter remaining (in.) ____
4. % material < 3" dia. consumed ____ Did piled debris burn down? ____
5. Objectives met ____
6. Adverse publicity ____
7. Smoke problems ____
8. Remarks ____

F. **Future Evaluation** (Date, signature and remarks) ____

36 ____

Figure 3-2- A raw burn plan form (Wade et al., 1989)

Fire plan should be prepared before and approved by authorities. Figure 3.2 shows the form used by authorities as a template for preparation of a fire plan document. Also, the fire map should be carefully prepared based on different topological factors, ignition methods, etc. (Figure 3.3).

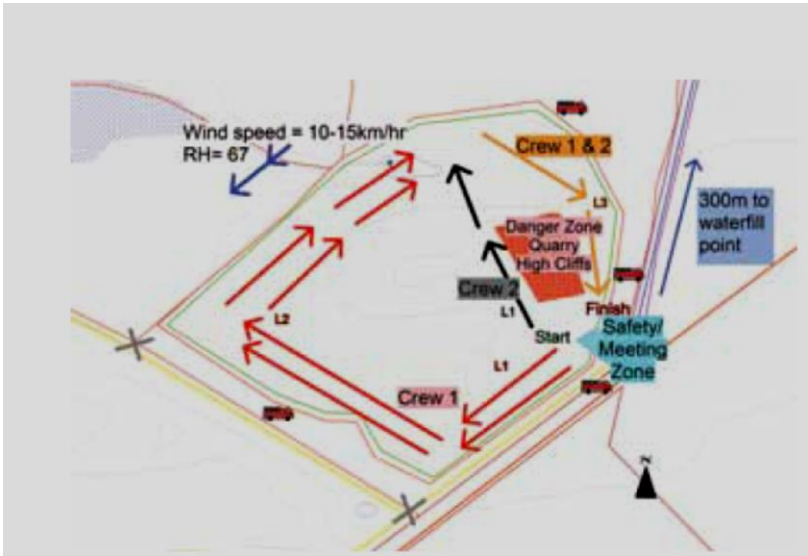


Figure 3-3- A sample burn illustration map (Marsden-Smedley J.B et al., 2013).

3.1.2 Implementation of a prescribed burn

Fuel moisture is one of the factors that should be checked before and during the burn process. If the fuel is very moist the fire will not go on and if the fuel moisture is too dry, fire control may be very difficult. The fuel moisture examination is done regularly at site using a fuel moisture meter device and by eye examination (Figure 3.4 a & c). The wind direction and speed also should be monitored before and during the burn. The readings are done by teams staying at the block during the day that the prescribed burn is intended to be done. Readings are filled out in a form and the burn process will not commence unless all the current criteria are in the favourable conditions. Ignition start is done by a device named driptorch (Figure 3.4 d and Figure 3.5); this device is designed to spread fire by means of fuel drops in a very safe and slow mechanism. The fire spread is closely controlled by a fire fighter and water pump and hose car (Figure 3.4 b & 3.5). In case the fire is dangerously spreading or is going wild, it will be immediately distinguished by means of water jet. (Figure3.4 b). After the burning process the fire fighters will examine the site closely and make sure that there is no fire spreading or remaining by using this water pump car.

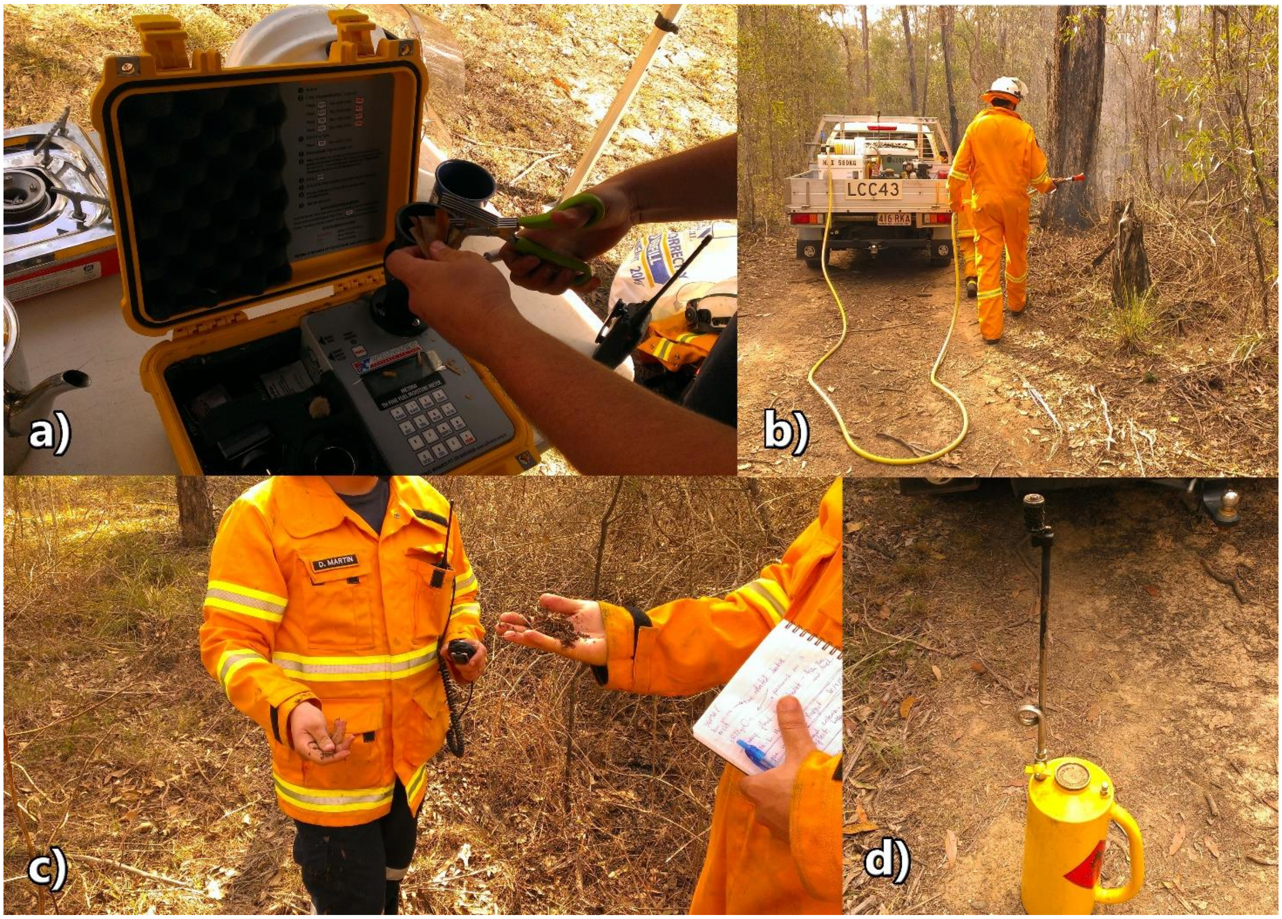


*Figure 3-4- **a)** moisture meter; **b)** extinguishing process by means of a pump car and water hose; **c)** eye examination of the fuel moisture; **d)** driptorch*

Figure 3-5- ignition process by means of a driptorch (left), during burn fire control process by fire fighters (right) (Kay, 2014)

3.2 Assumptions and Criteria for selecting a prescribed burn site

The ultimate goal of this research as mentioned, is providing a GIS application that generates a prioritization list of prescribed burn blocks that could be useful reference for deciding about a particular burn site and good decision support for correct management of burn plans. To achieve the end result, several criteria should be determined as the key criteria for Multi Criteria Analysis in GIS modelling. The basic approach is inspired from the fire risk modelling approach done by (Zeng *et al.*, 2003) and (Sivrikaya *et al.*, 2014) researches. They have tried to model fire risk by GIS. In this research the approach is to use Multi-Criteria analysis modelling in GIS to find out readiness of the blocks for prescribed burn. Hence, the criteria selection for this study would be mainly based on how different factors would contribute in best block selection for a controlled burn in long term. It should be noted that criteria involved with a favourable controlled burn site selection have some similarities to criteria related to fire risk as they both involve in setting fire to start. Fire scientifically is a chemical reaction that needs three elements of oxygen, fuel and heat to happen. This is known as fire triangle (Hampshire Fire and Rescue Service, 2014). In natural disaster point of view, heat is caused naturally by sun or lightening but in fire control practices heat is manmade and caused artificially. As planned burns are controlled, naturally fire spread is under control so, it can be understood that some same criteria needed for considering fire risk intensity analysis in a Multi- Criteria GIS model, is needed for a controlled burn site selection model. If there is a higher risk in a place for natural fire, it could be a favourable condition for a controlled burn to take place because fire could be more easily applied to that place. This is the main reason fire risk criteria are considered as a criteria in selecting a suitable site for conducting prescribed burn (it will be discussed later in fire risk section). However it is necessary to look at some criteria effective on fire risk with controlled burn 'implementation' and 'safety' point of view as well. The more easily controlled burn could be implemented with a safe condition, the less cost would be imposed to planners and related authorities. So the core selection criteria is based on implementation and safety aspect of conducting a controlled burn. The second aspect that is taken into consideration, as described above, is the fire establishment factors which could be adopted from Fire Danger Rating Models.

Another assumption that has taken into account is that long term planning concept of prescribed burns is of interest in this study. As, described in *controlled burn fundamentals* section, it is inevitable that in short term, some deterministic factors like wind speed, wind direction, humidity, temperature and soil moisture is very important to start burning an area. For example, implementation-wise, if it is too windy or if the fuel moisture is high it is not easy to burn an area, this imposes higher costs. But these factors are somehow considered in short term. The reason why the short term factors are not considered, is because they are not relevant for long term strategies. Some of these factors, although very important in prescribed burn principles, are not easy to model for long term planning or they could not give us a good spatial perception in long term or they are considered for a unique burn. For example for wind speed or wind direction we should have a yearly estimation of average wind speed or wind direction which is practically too difficult to prepare and to put it into long term modelling. Assumption in this thesis is, if planners have an estimation where is the best place to burn based on static long term criteria, they could have a plan to put their priorities to that place and monitor the situation every now and then and when wind speed, wind direction, humidity, temperature and soil moisture were favourable they can initiate burning. Hence it is very important to keep in mind that criteria discussed in this thesis is rather long term, static, and more location-related rather than time dependant.

3.2.1 Slope

Topography is an important physiographic factor which is related to wind behaviour and hence, affects the fire proneness of the area. Fire travels most rapidly up slopes and least rapidly down slopes (Jaiswal *et al.*, 2002). A major portion of the forest in the study area (Logan City) is located on steep hills, which helps to spread a fire.

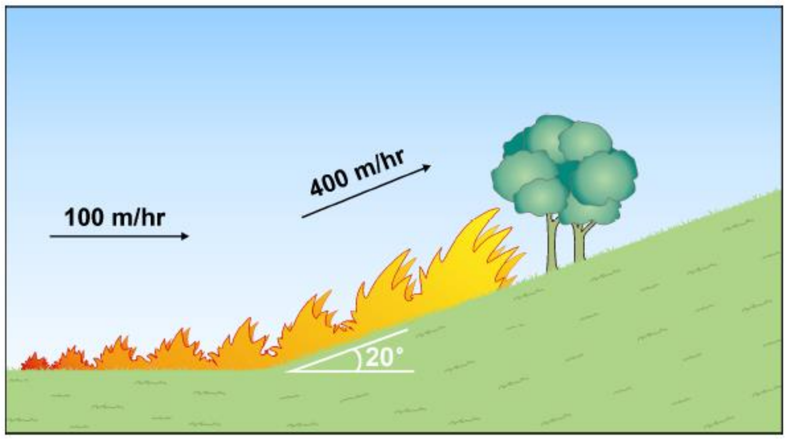
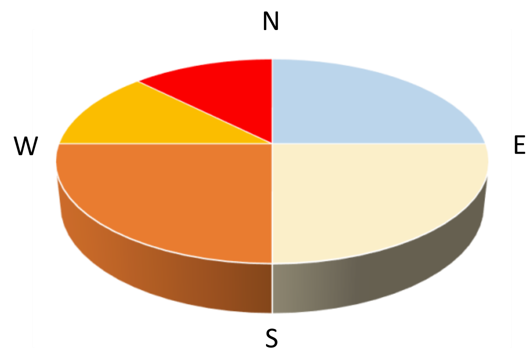


Figure 3-6-Slope in Bushfire development. Source: (Ripley Valley Rural Fire Brigadeand Brigade, 2014)

For every 10 degrees of slope, the fire will double its speed. For example, if a fire is travelling at 5 km per hour along flat ground and it hits a 10º slope it will double in speed to 10 km per hour up the hill. By increasing in speed, the fire also increases in intensity, becoming even hotter. The opposite applies to a fire travelling downhill. The flames reach less fuel, and less radiant heat pre-heats the fuel in front of the fire. For every 10 º of downhill slope, the fire will halve its speed. Fires tend to move more slowly as the slope decreases (Country Fire Authority 'CFA', 2012).
Considering the implementation point of view, many fire fighting and prescribed burn managers have an agreement that steeper areas are the most suitable places for prescribed burns.

3.2.2 Aspect

Aspect is also an important topographic factor in assessing potential bushfire behaviour. Type of fuel load and the amount of moisture in fuel load is directly related to the aspect of the land. According to Sivrikaya *et al.* (2014), south-facing areas suffer a greater water stress than the rest and, consequently, the probability of a fire event and fire sprawl increase. As Australia is in southern hemisphere, the contrary should work for our case of study. This means, roughly, northfacing areas have higher potentiality of sun exposure. Based on this, areas located in SE to SW aspects receive limited sunlight exposure and humid winds and often result in moist environments and vegetation of lower combustion value. Slopes receiving high quotas of sunlight and dry winds i.e. westerly to northerly aspects in our case study, often result in drier environments and vegetation of high combustion value (Travers, 2014). Aspect could be categorised according to different amounts of sunlight exposures for Australian geographical location:



Aspect	Direction	Sun Exposure	Colour
90-180	East to South	Very Low	
0-90	North to East	Low	
180-270	West to South	Moderate	
270-315	North-West to West	High	
315-360	North to North-West	Very High	

Figure 3-7-Image Different aspects and relations to sun exposure in Australia

In terms of controlled bushfire management, aspect could be very important because the places where receiving good amount of sunlight are better to burn in a controlled burn rather than places where there is not good amount of sunlight exposure because of having higher probability of better conditions such as fuel moisture, favourable temperature and favourable wind.

3.2.3 Elevation

With decreasing outside pressure all fires developed more slowly. Elevation could affect the development of fire with the increase of elevation there will be a decrease in oxygen amount and this cause the combustion happen more difficultly. This means higher elevations are not suitable to burn because it needs more effort to maintain fire and most probably fire will put off and do not spread by its own in a controlled burn. In implementation point of view usually higher elevations happen to be more difficult to access by fire team, has more difficult roads to access and this makes accessibility difficult. According Wieser *et al.* (1997), higher altitudes and fire burning rate for wood fire have and inverse linear relationship.

3.2.4 Fuel Type

Bushfire also is largely dependent on the amount and type of vegetation in the place of controlled burn. The amount of vegetation in an area is called "*Fuel type*".
Fuel is live and dead vegetation that accumulates over time. Dead leaves, twigs and bark build up as they fall from trees and shrubs, but some of this material is decomposed by insects, micro flora and fungi. Fuel can be characterised by type, size, quantity, arrangement and moisture content (Government of Western Australia, 2013).

Common types of fuels include:

- grass
- forest litter lying on the ground
- small shrubs and scrub
- trees, logs, stumps and bark and
- decomposing humus and duff (fine ground fuel)

(Government of Western Australia, 2013).

In prescribed burn practice the amount of fuel existing at the place is very important factor to choose a block for prescribed burn. Higher amount of fuel causes higher risks and demands more emphasis on applying fuel reduction controlled burns on that area. Although higher amount of fuel load means higher risk in bushfire hazard mapping, it should be considered as favourable for prescribed burn because both fuel reduction purposes and effective fire spread during a controlled burn. (Good fire spread in a controlled burn is not considered as dangerous or risky due to the controlled nature of the burns. In contrary it is considered as a favourable condition for fire fighters performing prescribed burns).

According to a current Commonwealth Scientific and Industrial Research Organisation (CSIRO) research regarding bushfire prone areas mapping, J Leonard *et al.* (2014), a twenty Vegetation Hazard Classes likely to have moderately consistent Potential Fuel Load has been identified for mapping fire risk. These twenty vegetation classes are as follows:

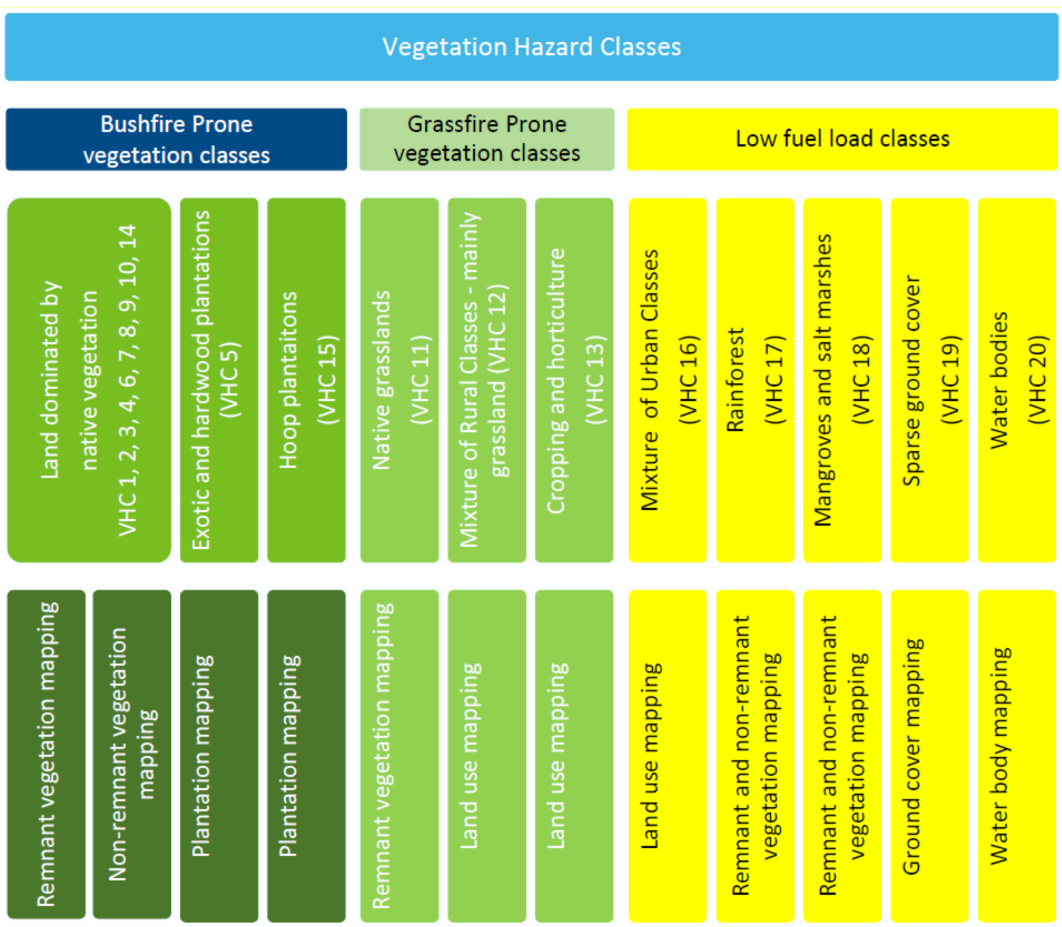


Figure 3-8-Overview of vegetation hazard classes and mapping inputs (J Leonard et al., 2014)

This classification could be considered as a useful input for determining fuel load in Queensland and Logan City area.

3.2.5 Proximity to urban areas

Bushfire risk to urban areas has been always of concern. When bushfire happens near urban areas precaution should be considered at highest level. According to J Leonard *et al.* (2014), bushfire impact mechanisms can affect people and property through flame attack, radiant heat exposure, ember attack, wind attack, smoke hazard and convective heat exposure (Ramsay *et al.*, 1987); (Blanchi *et al.*, 2008); (Blanchi *et al.*, 2014). Of these impact mechanisms, flame attack, radiant heat exposure and ember attack (Figure 3.10) are most relevant to land use planning and building decisions that seek to reduce the risks to life and property in new developments (Leonard and Blanchi 2012).

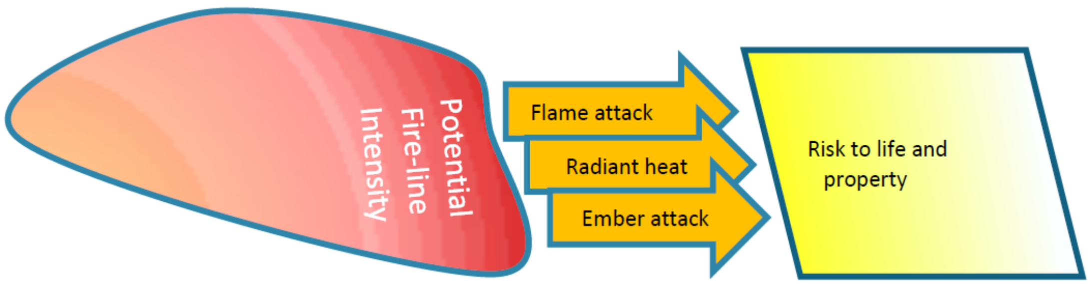


Figure 3-9- Significant impact mechanisms relevant to landscape scale planning decisions (J Leonard et al., 2014)

Flame contact is a short distance phenomenon compared to radiant heat and ember attack. The longest flames are generally those produced by the main fire front. Because flames naturally travel vertically, strong winds are needed to push the flames horizontally (Justin Leonard et al., 2012).

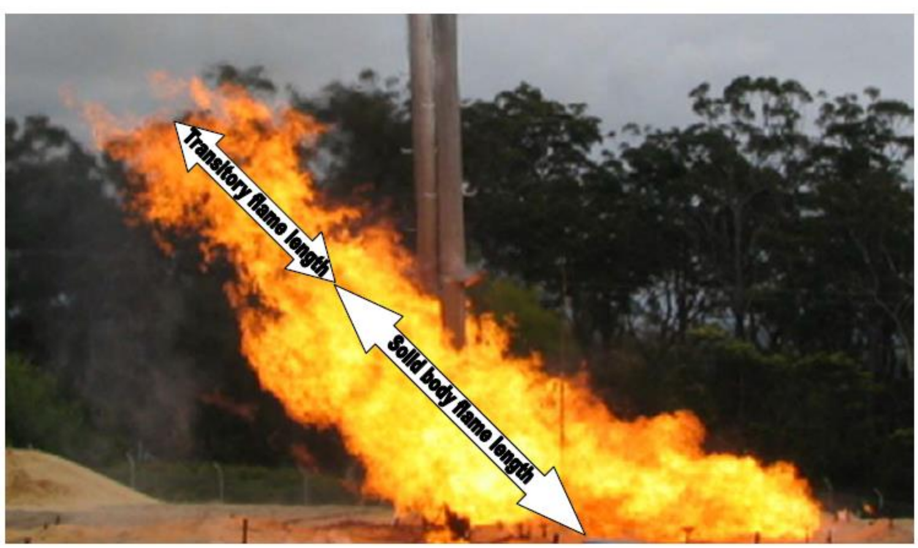


Figure 3-10-Flame body example- (Justin Leonard et al., 2012)

Radiant heat is the mechanism by which flames transfer some of their heat energy to the surrounding environment (Justin Leonard et al., 2012). Radiation impact on a house is synonymous with flame impact, as the flames themselves are the radiation (JE Leonard et al., 2004). According to J Leonard *et al.* (2014), a distance of approximately 100m would be required to avoid injury from radiant heat from a bushfire front if adjacent to an area of potentially hazardous vegetation with Very High Potential Bushfire Intensity.

Figure 3-11-Radiation sources and influences(Country Fire Authority 'CFA', 2012)

Ember attack occurs when twigs and leaves are carried by the wind and land on or around houses. Ember attack is the most common way houses catch fire during bushfires Embers can land on top of debris in your gutters and set fire the properties (Country Fire Authority 'CFA', 2012)

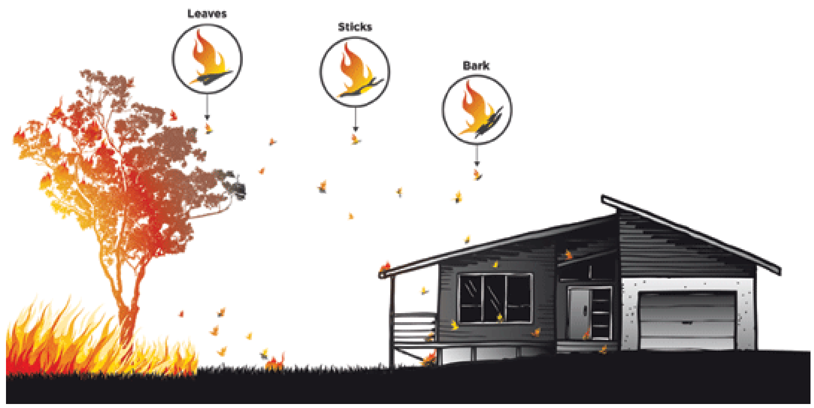


Figure 3-12-Ember Attack (Country Fire Authority 'CFA', 2012)

According to J Leonard *et al.* (2014), a Potential Impact Buffer adjacent to areas of Very High, High or Medium Potential Bushfire Intensity identifies land that may be subject to significant flame attack, radiant heat or ember attack.

J Leonard *et al.* (2014) states that the default width of 100m for the Potential Impact Buffer has been determined from analysis of heat radiation decay curves and national research indicating that in most fires over 80% of housing loss and 80% of human life loss has occurred within 100m of bushland (Chen *et al.* (2004); Blanchi *et al.* (2014)).

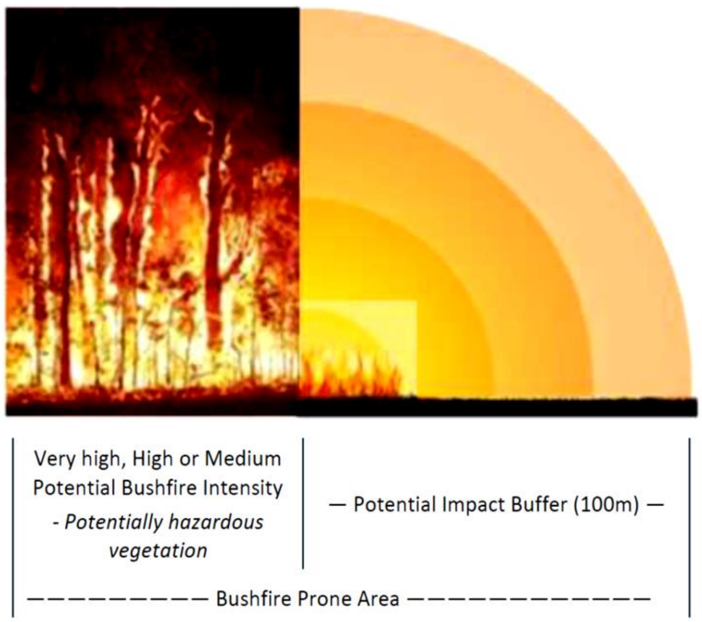


Figure 3-13-Potential Impact Buffer(J Leonard et al., 2014)

3.2.6 Proximity to power lines;

Power lines are infrastructures which carry high voltage electricity, when it comes to bushfire, power lines could always cause problem because electricity is the movement of negatively charged electrons, but a flame consists of both positive and negative ions. This could mean than fire could be a good conductor of electricity. The magnetic field caused by power lines are also a big cause of problem which will change the behaviour of fire and spread it more irregularly.

So power lines could cause the following problems during a controlled burn:

1- Caused fire spread more irregularly and therefore makes a controlled burn difficult to control
2- During fire, trees or branches can fall across the power lines and this may cause them break or pulling them off their insulators;
3- If some trees are broken during fire and fall across power lines, Live wires may fall to the ground; this may cause safety issues for fire fighters and prescribed burn operators
4- High voltage power lines falling onto other voltage power lines can cause flashovers and this may spread fire in unwanted

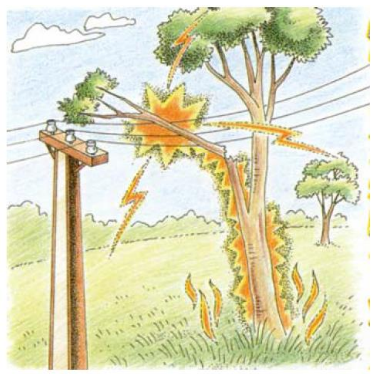


Figure 3-14- Impact of fire on powerlines- (D. o. E. I. Government of South Australia, 2008)

Usually a clearance and buffer zone of up to 3 meters vegetation free distance from medium power lines, and a distance of up to 5 meters clearance from high voltage power lines are considered by electricity provider companies (D. o. E. I. Government of South Australia, 2008).

3.2.7 Proximity to waterways;

Waterways usually act nicely as a firebreak, this causes the fire control become more efficient. Usually burn blocks that have some water courses or waterways inside could be very suitable for controlled burn because burn sectioning or patch burning is easily achieved in controlled way within that block and this makes fire control more easier and thus controlled burn more efficient. This means that fire will not spread from one burning patch to other burning patch without control. Furthermore accessibility to water is always a privilege in fire control activities. If fire fighter cars equipped with pumping system, water from watercourses could always be used as an eminent source of fire control. However, due to moisture content level in the bank of watercourses, a buffer distance of like 5 meters could best show unsuitability of areas closely adjacent to waterways or watercourses.

3.2.8 Fire history background;

Non-ecological rationales underlying the preference for burning areas with historical fire in background, suggests that practitioners exhibit “certainty bias” when making decisions about whether to implement prescribed burning (Maguire *et al.*, 2005).

Recently burned areas (either by controlled burning or by bushfire) may have some modified fuel load and may not be a suitable place to re-burn. Different types of vegetation have different behaviours of growth and the regrowth rate of the vegetation after a fire incident should be calculated to have a good impression of fuel load in the burnt area.
If an area is burnt recently it may not be suitable for re-burning, however it will be possible to calculate regrowth rate and actual fuel load. For this purpose information about the vegetation cover of area is needed and then with assumption that regrowth happens linearly, a rough estimation of current fuel load content could be calculated.

For overlapping historical burn patches, the latest burn date should be taken into consideration (refer to figure 4-8, where numbers represent burn years and the tick symbol shows the selected year, this example denotes 3 patches but number of burn patches could be even more than three, i.e. for more than three patches overlapped, same logic should be applied).

In calculating the current fuel load if a burn occurred in the past, the assumption is that the fuel load (vegetation regrowth) has a linear growth trend over time. Refer to section 4.2.1.18 for more details regarding calculating current fuel load

3.2.9 Located in ecologically significant areas

Ecologically significant areas are areas that should be protected and have environmental or ecological importance in the area of study. For fuel load reduction controlled burn activities, ecologically significant areas should be preserved and this means where some very important species, habitat, corridors, conservation area etc. exists in a place, that area should be preserved from burning.

Ecologically significant areas are very important criterion for finding suitable places for controlled burn yet it is not easy to find a proper map amalgamating all different criteria for considering an area as ecologically significant and quantify the significance itself. Fortunately Logan City Council department of Environment and Sustainability had done an extensive Multi Criteria Analysis to find out ecological significance values within Logan City Council Boundary. This map uses the following criteria and weighting to find out values for ecological significance in Logan:

Table 3-1- criteria and weighting to find out values for ecological significance in Logan (Adam, 2013)

Criterion	**Weighting out of 10**
Urban Land	1
Rural Land	3
Remnant Endangered	10
Remnant Of Concern	9
Remnant Least Concern	8
Tree Cover Endangered	7
Tree Cover Of Concern	6
Tree Cover Least Concern	5
Wetlands and Waterways	10
Locally significant vegetation	9
Ecological corridors	7
Koala habitat 1	8
Koala habitat 2	3
Conservation estate	3
Vegetation Complex	3
Species Complex as follows:	9, 7 or 4
• Very High score from Habitat for Endangered, Vulnerable and Rare (EVR) Species	9
• High Score from Habitat for Endangered, Vulnerable and Rare (EVR) Species	7
• Core Habitat for Wallum Froglets overlapping Very High or High Endangered, Vulnerable and Rare (EVR) Species	9

• Core Habitat for Wallum Froglets <u>not</u> overlapping Endangered, Vulnerable and Rare (EVR) Species buffers	7
• Core Habitat for Priority Species or Special Biodiversity Areas	4

All of the layers related to this criteria are then are overlayed and the weightings of each criteria summed for each portion of land in the City. A single resulting layer is produced which contains all of the information from each criterion layer, plus a total ecological value for every polygon of land in Logan City. (Figure 3-15). These ecological values range from a minimum of 1 to a maximum of 62 (Adam, 2013).

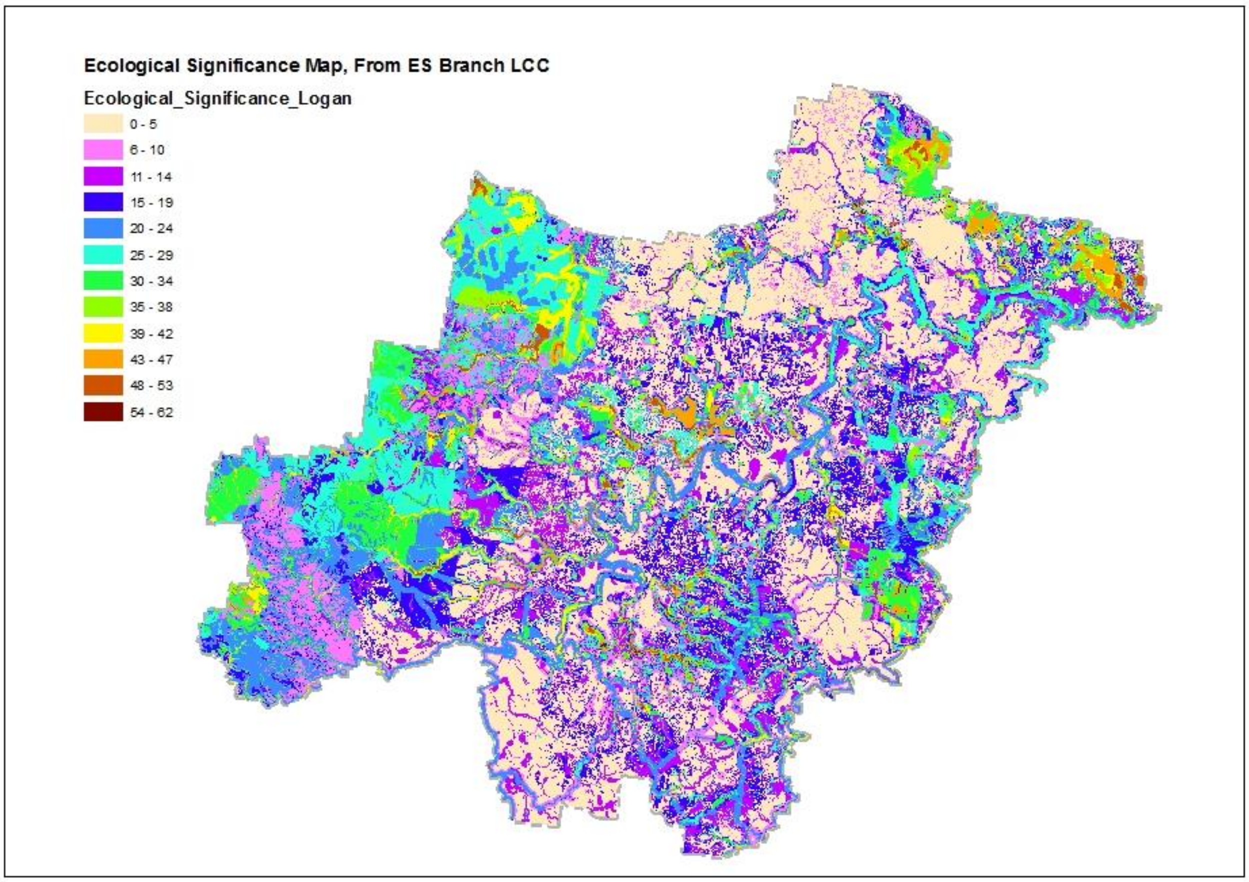


Figure 3-15-Ecological Significance values for Logan City Council (map reproduced with permission from Logan City Council)

Map created using weights in table 3-1-

3.2.10 Proximity to various infrastructure elements such as roads and rail

Consideration of a public safety threshold for drivers and railways passengers caused by associated smoke drift and flame heat radiation, this criterion has been considered. Roads adjacent to burn sites should be closed while controlled burning is in progress in case the burn site is in place closer than minimum safety threshold distance to road or rail. This may cause some issues and imposes some costs. Therefore the less close a burn site is to public infrastructures like road and rail, the more suitable the place is for burning purposes.

Major roads support higher volumes of traffic, therefore a greater buffer distance of the burn block to the road is required. For this purpose roads are categorised into main or arterial, secondary or collector road, and local roads.

3.2.11 Proximity to firebreaks and fire trails

Firebreak is a barrier, usually either a natural clearing or one created by removing vegetation (fuel break), that is designed to prevent or slow the spread of fire. It is also known as fire line (Park, 2007). Fire trail a track through forest or bush for use in fighting fires (Stevenson, 2010).
Fire break and fire trails are two features that help control of fire.

Fire brake and fire trails are simple and effective method of fire control, because, firebreaks and fire trails:

- Provide a control line to assist firefighters to perform a back burn or fire attack.
- Can be used for isolating fire hazards and e.g. firebreaks or fire tracks could be used around fuel dumps or hay stacks;
- Give good and safe access for burn control staff and fire control vehicles;
- Can help controlling the spread of fire because of providing no fuel area;

Considering above points, it is inevitable that if fire breaks or ire trails exist in a block of prescribed burn it would be very useful for a more convenience and well- composed implementation and this is why criteria is considered.

3.3 Multi Criteria Analysis

One of the most useful approaches to solve a problem related to decision support is Multicriteria or Multi Attribute decision making system (Keeney *et al.*, 1993). The basic principle is a decomposition of the decision problem into smaller, less complex sub problems (Arh *et al.*, 2007). For solving a Multicriteria Analysis problem it is necessary to build a suitability model based on values. According to Forman (1985), a multi-criteria analysis should have the following characteristics:

Could be represented by formulization

1- Considers most comprehensive criteria for the problem
2- Both qualitative and quantitative criteria is considered
3- Experts opinions are considered in building up the value model
4- Different judgments could be combined in it to find out a final value model
5- A good methodological and theoretical rationale is behind each criteria

Multicriteria analysis is a good method to evaluate the importance of various factors related to a subject to fulfil a given objective. This method models different factors by different quantitative figures and different figures could be represented in the model by a quantitavley representable importance outcomes. This is called a value model. Most of the criteria considered for blocks burn readiness are criteria which their importance could be represented qantitavely and therefore very easily consider as criteria in a MCA as a value model.

There are many assessment methods or approaches to find out weights and build up a MCA value model. One useful and credible method is AHP method. Analytical Hierarchical Process Developed by Thomas L. Saati (T. L. Saaty, 1980) is a good approach combining a very detailed criteria by criteria vision on a MCA problem and develops it into a unified value based solution to a MCA problem. In this thesis work the final aim is to develop the most suitable long term system or model to decide about suitability of blocks for performing prescribed burn. AHP method helps a lot regarding choosing weights for deciding about final value model. However, it has been tried to create a tool in that is independent of criteria weights. This means weights could be applied during each run of the model and different weights for criteria could be tested. But for demonstration of the best possible combination of the weights and according to research methodology principles AHP method is used to find out the best possible combination of weights for the selected criteria.

3.3.1 Analytical Hierarchical Process Method for Weighting Criteria

In using the AHP to model a problem one needs a hierarchic or a network structure to represent that problem and pairwise comparisons to establish relations within the structure. (R. W. Saaty, 1987). The final aim of the model is a formula and the variables are the main criteria. In this method the importance of each criteria is found out by a coefficient and these coefficients are found out by pairwise comparison of the criteria if they are related to the same level or common attribute.

Criteria consist of some other sub criteria in a hierarchical structure (figure 3-13). Therefore the first step would be identifying which criteria is dependent of other criteria and each criteria belongs to what level of dependency.

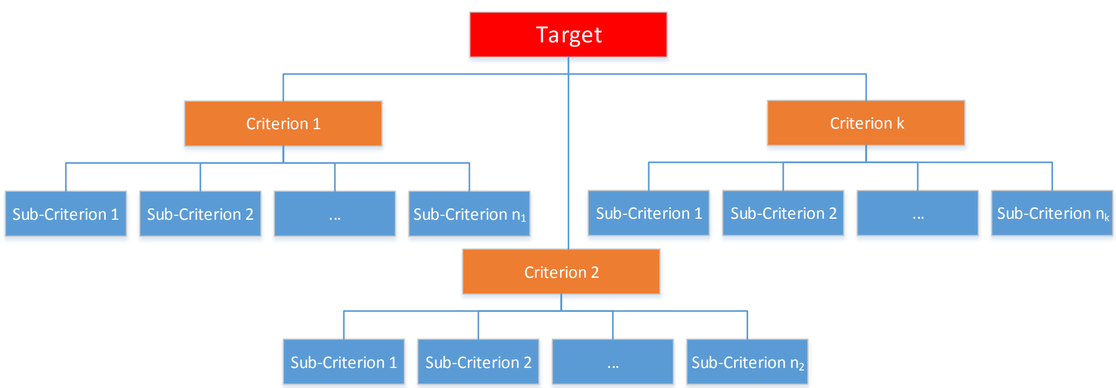


Figure 3-16- AHP Criterion hierarchical relationship (level one, orange; level 2, blue)

If we denote each criterion as “c” and sub-criterion as “sc” the target value model F is a linear combination of criteria weighted by the importance coefficient for each criteria and each criterion’s weight is from other sub criteria’s weighted combination. For the first two hierarchical levels we have:

$$F = \sum_{i=1}^{k} \alpha_i c_i$$

$$c_1 = \sum_{i=1}^{n_1} \beta_{1i} sc_{1i}$$ *Equation 1*

$$c_k = \sum_{i=1}^{n_k} \beta_{ki} sc_{ki}$$

The final target would be determining α values. (R. W. Saaty, 1987) recommends a pair wise comparison in each hierarchical level between each criterion's sub criteria. For the example above, for each c_i , different sc_{ki} are compared in pairs to find out β_{ki} for each level. The same applies for hierarchical level 2,3, etc. Then all c_i are compared in pairs with each other to determine their corresponding α_i.

Saati proposes a consistency check for each c_i. If n sub-criterion exists for c_i to find out the importance coefficients of β_i, we need to do a_{ij} pairwise comparisons. This shown in matrix below

$$\begin{array}{c} \\ \beta_1 \\ \beta_2 \\ \vdots \\ \beta_n \end{array} \begin{array}{c} \begin{matrix} \beta_1 & \beta_2 & \cdots & \beta_n \end{matrix} \\ \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \ddots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix} \end{array}$$ *Equation 2*

If

$$a_{ik} \times a_{kj} = a_{ij}, \; i, j, k \in \{N\}$$ *Equation 3*

Then, the matrix is consistent, and we can say

$$a_{ij} = \frac{\beta_i}{\beta_j} \times 1$$ *Equation 4*

which is the value of importance of i to j. This means that matrix is consistence or inconsistency ratio is 1. If the matrix is not consistence, Saaty suggest a maximum ratio of 0.1 is acceptable and when the consistency ratio exceeds 0.10 appreciably the judgments often need re-examination (R. W. Saaty, 1987). In this thesis, for easy AHP analysis, no sub criteria has been considered. Only

11 criteria, which were elaborated on the previous chapter are taken into account. But for determining weights three themes of

1- Safety
2- Implementation
3- Equal

Has been considered and for the first two AHP process has been applied. For this end, a table was given to some staff at Logan City Council for pairwise comparison of the criteria for each theme. In each of these tables experts or staff needed to compare each criteria in pairs and give them the following comparisons:

Table 3-2- Values for the experts pair comparison of criteria

The choice	Preference Value
Extreme preference	9
Very Strong preference	7
Moderate Preference	5
Little preference	3
Equally preferred	1
Values in between preferences	2, 4, 6, 8

The number of experts who filled the questionnaires and their ranks are included in table 3-3-

Table 3-3- experts who filled the questionnaire and their functions

Branch/ Position	Number of Experts used for filling up questionnaires
Parks Branch / Fire fighting Manager	1
Parks Branch / Fire fighting supervisor	2
Parks Branch / Controlled burn management	2
Parks Branch / Controlled burn operator	3
Environment and Sustainability / Manager	1
Environment and Sustainability / Urban Planner	2
Environment and Sustainability / Biodiversity Expert	2
Environment and Sustainability / Natural hazards Expert	1

Total	14

Table 3-4- Questionnaire form produced for AHP pair comparison

Prescribed burn criteia questionair, **Please refer to instructions to fill the form** **Name:** **Organization:** **Title:** **Signature**	Slope	Aspect	Elevation	Fuel Type	Proximity to urban areas	Proximity to power lines	Proximity to waterways	Fire history background	Located in ecologically significant area	Proximity to infrastructures	Proximity to firebreaks and fire trails
Slope											
Aspect											
Elevation											
Fuel Type											
Proximity to urban areas											
Proximity to power lines											
Proximity to waterways											
Fire history background											
Located in ecologically significant areas											
Proximity to infrastructure											
Proximity to firebreaks and fire trails											

The consistency test is applied to choice matrixes if the matrix is consistent, then with normalisation of the choices the weight for each criterion is determined. If not consistent, the weight is determined by either some correction methods: least squares method, Logarithmic least squares method, Eigenvector method or approximation method. To test inconsistency and any correction method needed could be done by a software package supporting the AHP, called Expert Choice, This software was used to make these calculations as a guide to improve his inconsistency if needed (R. W. Saaty, 1987).

4 Modelling Methodology and design

4.1 Model design and methodology

4.1.1 Prescribed burn prioritization model aims

The purpose of GIS Multicriteria Analysis in this thesis is to create a tool that gives a decision aid support for prioritization of burn blocks. For this, raster analysis is the most suitable type of GIS analysis because it can give spatial scores for an area, many statistical spatial analyses could be applied to a raster and it can give a precise spatial scoring system to suitability. Therefore the proposed tool is using spatial analyst capabilities to generate a suitability surface (i.e., raster dataset) by overlaying location specific attributes (or static attributes, which are highly unlikely to change over time) which comprise: slope; aspect; elevation; proximity to various infrastructure elements such as roads and rail; proximity to urban areas; proximity to firebreaks and fire trails; proximity to power lines; proximity to waterways; having fire history background; being located in ecologically significant areas and fuel load content via scoring (normalisation) and weighting. Values of the output raster show how suitable a place is for undertaking a prescribed burn, with the suitability related to 'static factors' rather than dynamic factors such as weather and drought factor etc. 'Static criteria' means criteria which are not time-dependent but are in fact location-dependent as it conveys a clear understanding of the locational suitability. The outcome could be a good support for long term planning. The output of this model may be a good feed to another model which considers some dynamic factors which change by time and could be used for short term planning purposes. The scores resulting from this model could provide a good indication of how suitable the positioning of the block is. Prioritising prescribed burn blocks based on static factors is the other function that the model undertakes. The final model output also shows how much contribution each static factor has in the final suitability score of that block.

4.1.2 Prescribed burn prioritization model design

The process comprises several procedures aiming to prepare a raster giving spatial suitability for performing prescribed burning. The final raster then should be overlayed on top all blocks to investigate which blocks contain more suitability scores. Then sort the blocks according the total scores. The scoring method chosen is normalized scoring which means a numerical value, literally a positive and non-negative integer between 1 to 10. 1 means least suitable and 10 means most suitable. A schematic overview of general processes to do the job is shown in the diagram below (Figure 4-1).

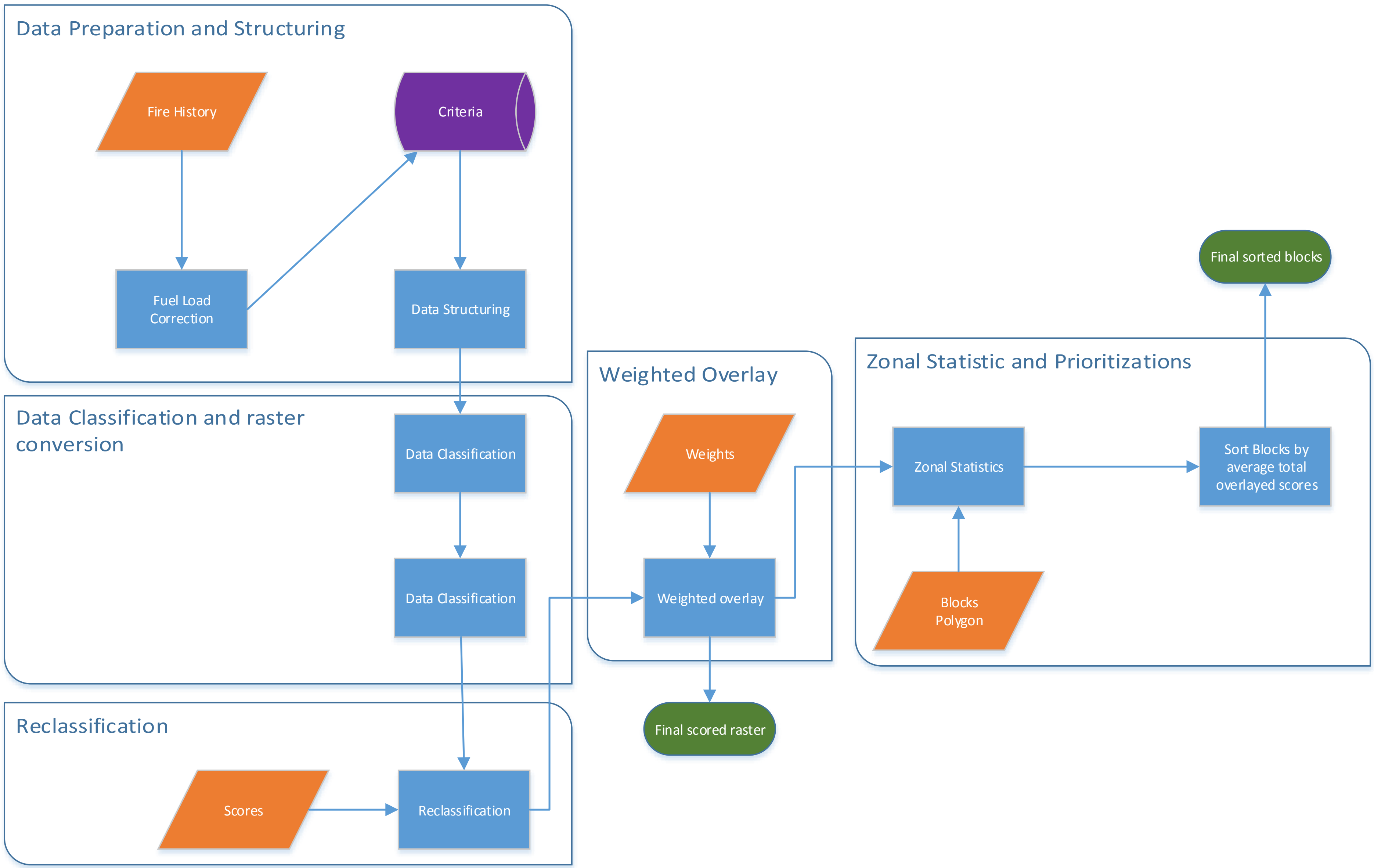


Figure 4-1-Overall GIS Geoprocesses for prioritization modelling

According to this diagram, the model developed tries to undertake the following tasks in order to reach the aim:

The following broad processes will be considered in the model:

1- ***Data Structuring:*** any types of process that is done to prepare the layers or feature classes related to each criteria ready for data classification

2- ***Data classification and raster creation:*** Any geoprocessing application in order to classify criteria based on suitability. For each criterion this may be different methods of classification, buffering, merging, dissolving and field calculation are some common geo-processing tools to classify data according to suitability.

3- ***Reclassification:*** It means applying normalized scores to the classified data. This process makes the suitability criteria standardised by applying scores 1 to 10.

4- ***Weighted overlay:*** each criterions weights determined by AHP process described before are applied to each normalized reclassified layer and then overlayed by spatial analysis tool this gives the final overall suitability raster

5- ***Zonal Statistics and prioritization:*** Then the final scores in each block are investigated by applying zonal statistics (blocks are zones and value rasters are the reclassified normalized values for each criterion). Prioritization is based on sorting average final score in each block. If the average final score is higher the block is more suitable.

4.2 Database design:

Data needed for modelling was requested from IT department of Logan City council. The preliminary database acquired were the database needed according to model design. Some of the data needed various data structuring preparation before using them for weighted overlay analysis including projection adjustments. In section 4-3-4- I will briefly cover data structuring tasks done for each criteria as well as the classification methodology.

Below is a list of raw data acquired form Logan City Council and what should be found in their metadata section:

Table 4-1- Selected Metadata of raw data acquired form Logan City Council

Dataset Description	Category	Resolution/ Original scale	Description	Source
Fire History Feature class	Spatial Input/vector	1:180,000	It is a layer with history of previously burn areas (both controlled burn or natural bushfire) during past 10 years with the burn dates for each burn polygon	Corporate data
Blocks polygon Feature class	Spatial Input/vector	1:180,000	Blocks which are mainly come from sectioning of natural parks and current areas intended to consider as for fuel reduction practices. It has been prepared by department of parks and natural areas for consideration of controlled burn practice and planning. These blocks are considered as the main polygons to perform prioritization on	Parks branch data
Urban Areas Feature class	Spatial Input/vector	1:180,000	Areas with urban landuse this comprises: Residential areas, streets, agricultural land and rural residential areas including factories, farms, and fields.	Corporate data
Fuel Load Raster	Spatial Input/Raster	25mx25m	It is a Queensland state data which is based on vegetation and shows the fuel load for each cell of the raster data. The methodology behind the preparation of this has been described in section 3.2.4-	State data: **Title:** Bushfire hazard area - Bushfire prone area - Queensland. **From:** ("Bushfire hazard area - Bushfire prone area - inputs - Queensland," 2014)

Dataset Description	Category	Resolution/ Original scale	Description	Source
Elevation Raster	Spatial Input/Raster	5mx5m	Raster data with elevation in meters	Corporate data
Aspect Raster	Spatial Input/Raster	5mx5m	Aspect in degrees	Corporate data
Slope Raster	Spatial Input/Raster	5mx5m	Slope in Radians	Corporate data
Fire-Breaks Feature class	Spatial Input/vector	1:180,000	The polyline feature class denoting fire Breaks within Logan	Parks Branch data
Fire Trails Feature class	Spatial Input/vector	1:180,000	The polyline feature class denoting fire Breaks within Logan	Parks Branch data
Waterway Corridors Feature class	Spatial Input/vector	1:150,000	Feature class denoting waterway corridors and water courses within Logan	Corporate data
Roads Feature class	Spatial Input/vector	1:200,000	Feature class showing all types of roads within Logan	Corporate data
Railway Feature class	Spatial Input/vector	1:180,000	Feature class showing all types of railway within Logan including commuter rail	Corporate data
Ecological Significance Feature class	Spatial Input/vector	1:150,000	Ecologically significant areas are areas that should be protected and have environmental or ecological importance The methodology behind creation of this layer has been discussed in section 3.2.9-	E&S data (Adam, 2013)
Electricity Feature class	Spatial Input/vector	1:180,000	Feature class all types of powerlines within Logan city council boundary	Corporate data

4.2.1 Data Structuring and classification for criteria

Here for each criteria, different data structuring activities and also methodologies for classifying criteria is explained. The classification is based on advices sought from fire fighters and Logan city council bushfire management experts in a discussion session the writer had with them. The data structuring and classification procedures have been modelled using model builder. In classification, it has been tried to define a spectrum or ramp of suitability for each condition of the criteria. This classification will be eventually reclassified into numerical figures from 0 to 10 for modelling purposes. This ramp has been shown in figure 4-2-.

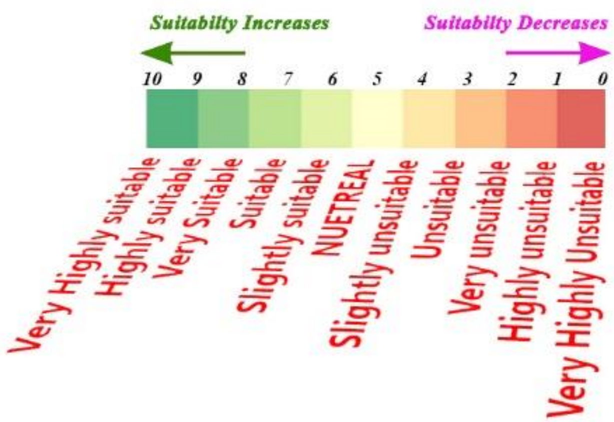


Figure 4-2- Suitability

4.2.1.1 Slope

Data Structuring

The slope received was in radian angle while slope classification is based on degrees.
This data has been converted to degrees (Refer to appendix 1).

Classification:

Table 4-2- classification of Slope

Slope (degrees)	Classification
0-8	Very Highly suitable
8--11	Highly suitable
11--15	Very Suitable
15--28	Slightly suitable
28--33	Slightly unsuitable
33-70	Highly unsuitable
<70	Very Highly Unsuitable

4.2.1.2 Aspect:

Data Structuring

The Aspect data received was in radian angle while slope classification is based on degrees. This data has been converted to degrees (Refer to appendix 1).

Classification

Suitability Classification of aspect is based on what was described in section 3.2.2- Regarding sun exposure and the rationale behind the suitability for burn and exposure with sun.
Below is the table showing the suitability classification for aspect

Table 4-3- classification of Aspect

Aspect	Direction	Sun Exposure
0-90	North to East	Slightly unsuitable
90-180	East to South	Very unsuitable
180-270	West to South	Neutral
270-315	North-West to West	Very Suitable
315-360	North to North-West	Very Highly suitable

4.2.1.3 Elevation

Data Structuring

This layer was ready to use for classification and not data structuring process done for it.

Classification:

Table 4-4- classification of Elevation

Elevation	Suitability
0--100	Very Highly suitable
100-255	Slightly unsuitable

4.2.1.4 Fuel Type

Data Structuring

The fuel load received was a state raster data the cell resolution used in the model was 5x5 meters but state fuel load raster was a little bit coarser than this 10m x 10m which for compatibility with other data the resolution was increased to 5x5m. The layer was clipped to the extent of Logan city council boundary and projection was changed to GDA_1994_MGA_Zone_56.

Classification

Suitability classification of the fuel load was based on the potential fuel load (Ton/ha) content of the vegetation class. After normalization a suitability class has been chosen for the fuel load class according to the table below:

Table 4-5- classification of fuel load

Fuel Type	Vegetation type	Fuel load	Normalization (/10)[1]	Suitability Classification
1	Melaleuca communities	33	10.0	Very Highly suitable
2	Open forests / woodlands - shrubby	30	9.1	Highly suitable
3	Tall open forests	28	8.5	Highly suitable
4	Heath communities	27	8.2	Very Suitable
5	Exotic and hardwood plantations	26	7.9	Very Suitable
6	Cypress and Casuarina communities	20	6.1	Slightly suitable
7	Open forests / woodlands - grassy	19	5.8	Slightly suitable
8	Acacia communities	10	3.0	Neutral
9	Coastal, fringing and dune communities	8	2.4	Neutral
10	Riparian and fringing communities	8	2.4	Neutral
11	Native grasslands, sedge lands and balds	5	1.5	Unsuitable
12	Mixture of rural classes - mainly grassland	5	1.5	Unsuitable
13	Cropping and horticulture	5	1.5	Unsuitable
14	Dry vine forest and vine thickets	5	1.5	Unsuitable
15	Hoop Plantations	5	1.5	Unsuitable
16	Mixture of urban classes	3	0.9	Highly unsuitable
17	Rainforest	1	0.3	Highly unsuitable
18	Mangroves and saltmarshes	1	0.3	Highly unsuitable
19	Sparse ground cover	1	0.3	Highly unsuitable
20	Water bodies	0	0.0	0

4.2.1.5 Proximity to Urban areas

Data Structuring

According to what was mentioned in criteria methodology a safety buffer distance of 100 meter from urban areas is necessary for considering possible fire risks to urban areas. However for suitability classification purposes some buffer proximity distances has been considered with 200 meters increments up to 500 meters for better protection against smoke and other safety issues.

Hence, a multiple ring buffer around urban areas with distances of 100 meter, 300 meter and 500 meter has been considered based on experts' advices. These distances where based on the experts ideas.

[1] Normalization means: (Fuel_load*10)/[Max(fuel_load)]

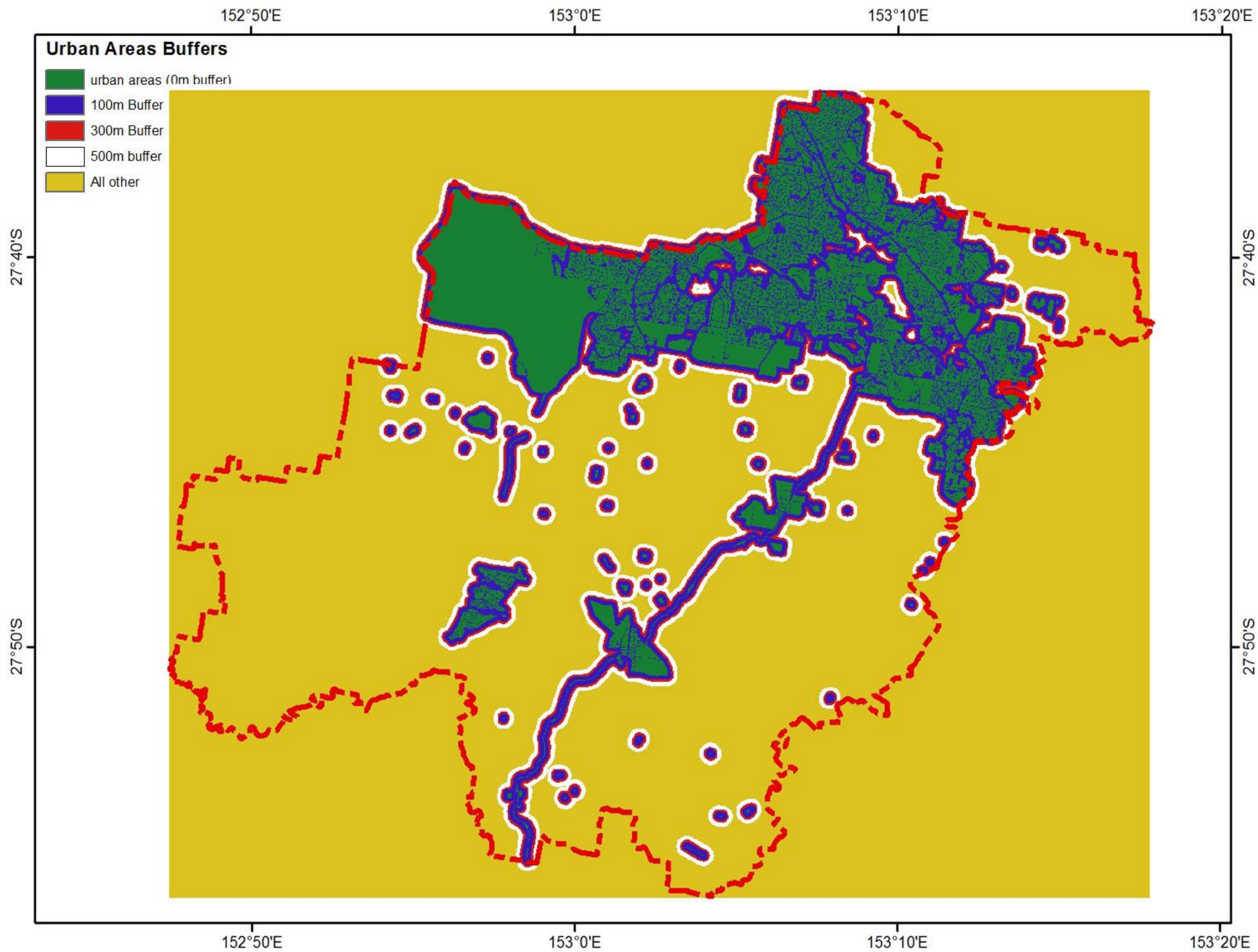


Figure 4-3-Urban areas buffers

Classification:

Table 4-6- Classification of Urban areas

Distance	Suitability
In Urban areas	Very Highly Unsuitable
Within 100m distance from urban areas	Very Unsuitable
Within 300m distance from urban areas	Neutral
Within 500m distance from urban areas	Suitable
All other areas	Very Highly suitable

4.2.1.6 Proximity to Powerlines

Data Structuring

The polyline layer received comprised of different kinds of powerlines at service in Logan. The categorisation was based on voltage and type of transmission which is upper head or underground. Among all different voltages the high voltage and medium voltage lines as well as ordinary street lines were of interest. A select layer by attribute was used to select only overhead lines. Another selection was made to choose only voltages more than 11 KV (ordinary street lines) and disregard the other types of powerlines which were mainly pilot cables and "other" types of lines.
Buffer distances of 10m, 20m and 50m have been applied for low voltage, medium voltage and High voltage Powerlines. The definition of Low, medium and high voltages could be seen in table 4-7. Figure 4-3- shows different buffers around different kinds of powerlines.

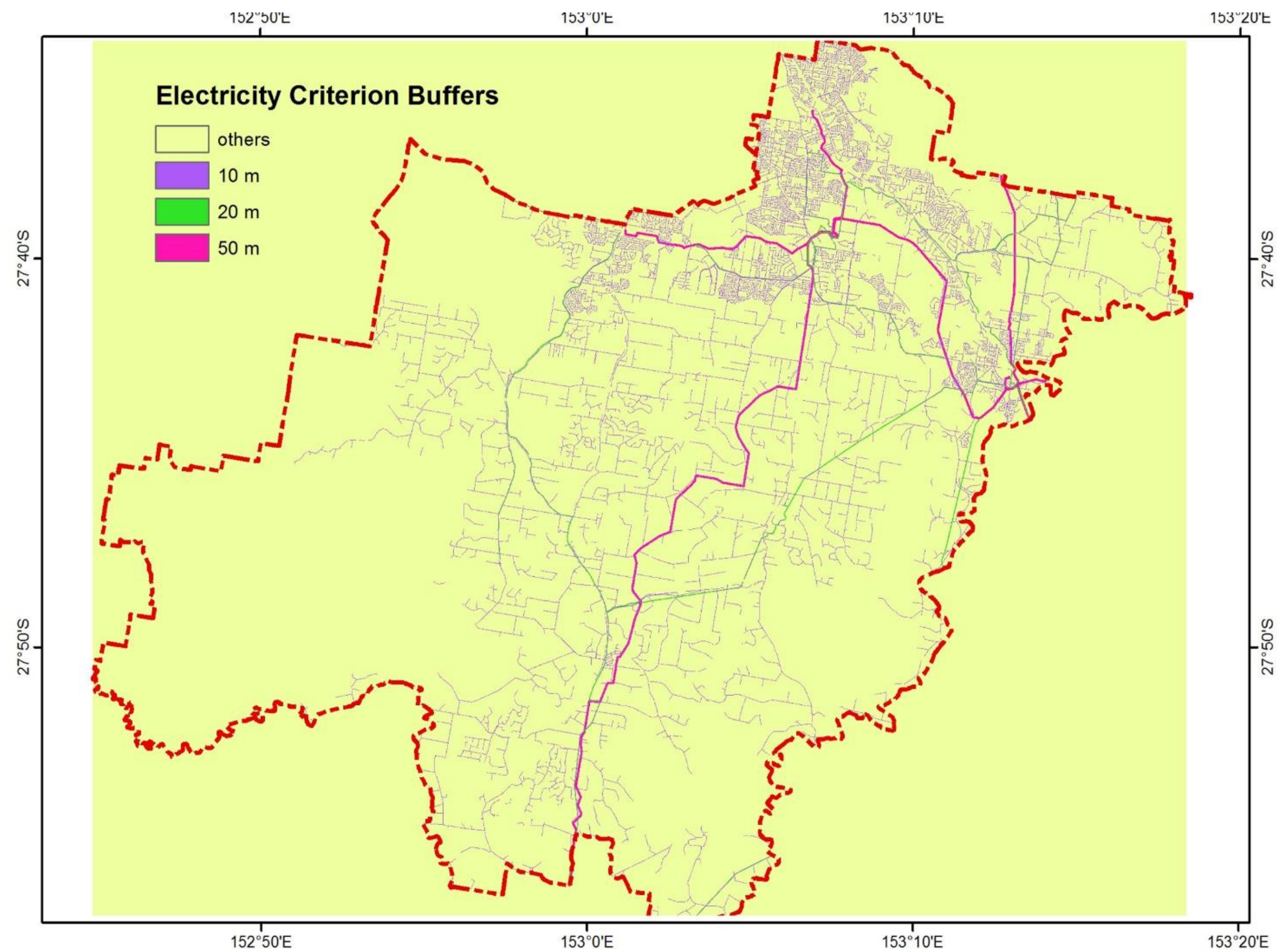


Figure 4-4-Electricity Criterion Buffers

Classification

The suitability classification is based on the importance of the powerlines by the risk they may create during burning practice and their corresponding buffer distance. The power lines has been categorized in three groups of *high*, *low* and *medium*. The basis of this categorization is the voltage inside the cables; high voltage lines has bigger towers and that is why a more buffer needs to avoid them. But for small cables the buffer size has been decreased due to this logic. Based on experts' ideas, by decreasing the buffer the scores have been decreased as well. The reason is that for small cables the fire is not as important as big cables.

Table 4-7- Electricity criterion classification

Importance	Voltage	Buffer	Suitability classification
Low voltage	11kv≤x<33kv	10m	Slightly Unsuitable
Medium voltage	33kv≤x<90kv	20m	Unsuitable
High Voltage	90kv≤x	50m	Highly Unsuitable

4.2.1.7 Proximity to Waterways

The layer received for waterways comprised of different kinds steam orders. The stream order was up to six level. As the lowest rank streams –smallest ones– where not of interest; only stream order 5 to 2 was considered. So stream orders 0 and 1 was excluded. As mentioned in section 3.2.7- because waterways could act as a natural good firebreak, having water streams within a burning block would be very useful in regards with fire spread and fire control. But the water banks, because they are very wet are unsuitable for burning should be considered as highly unsuitable. The data structuring methodology used for the preparation of waterways as a suitability classification criteria has shown in the diagram of figure 4-4- :

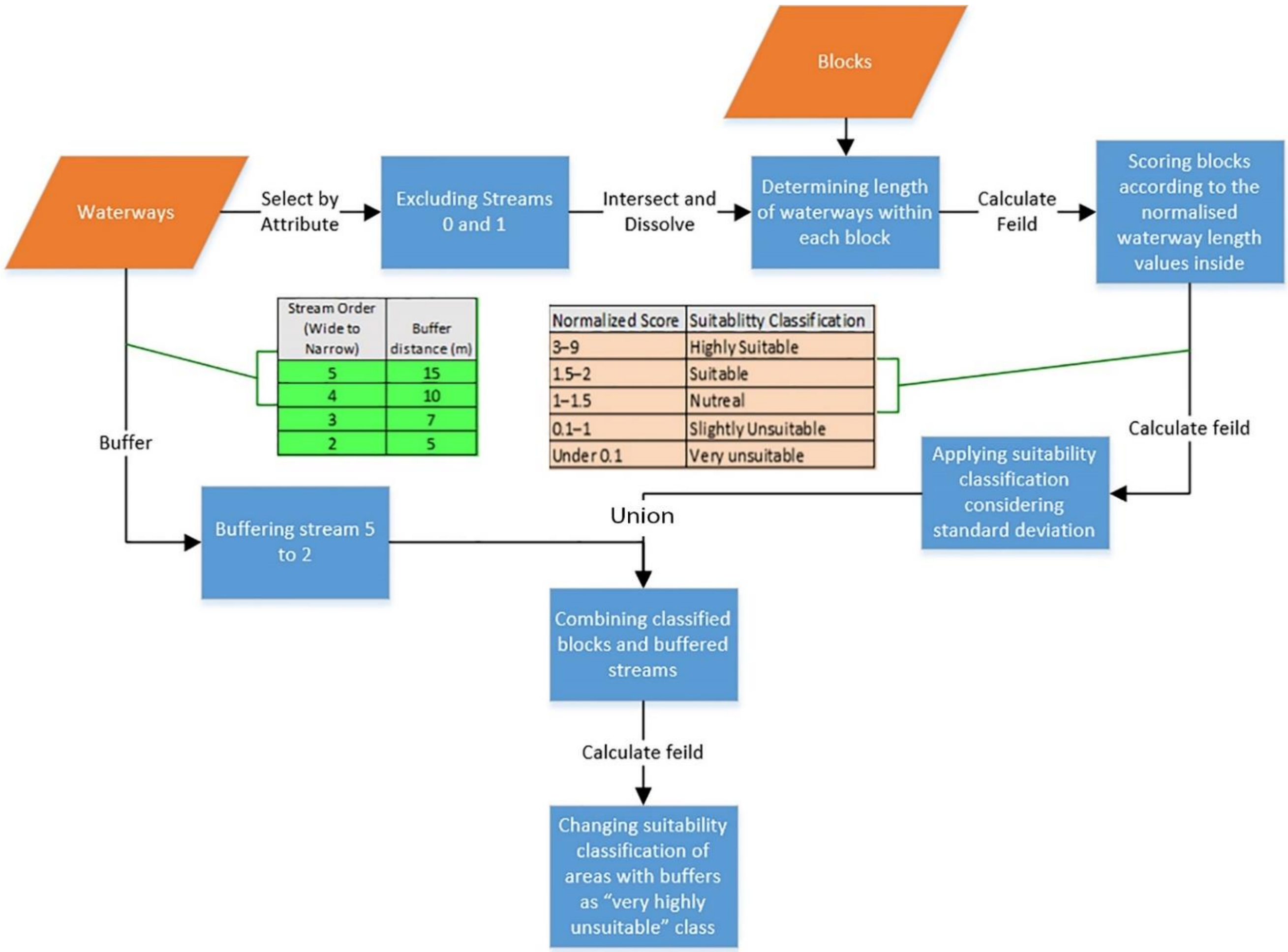


Figure 4-5-Proximity to waterway criterion data structuring work

The idea was to score each block according to the extent of waterways existing inside each block. This means the longer waterway stream inside a block the higher the score is. But at the same time the waterway banks should be considered as very highly unsuitable because of water content. The suitability criteria has been decided for each block according to the normalized score 0 to 10. This means a block for which the score is 10, it contains maximum length of waterways amongst other blocks and a block scoring zero contains no waterways inside. The final suitability for each block is decided by considering these normalised values and the data distribution (standard deviation).

Table 4-8- Classification of blocks suitability for waterway criterion

Normalized Score	Suitability Classification
3–9	Highly Suitable
1.5–2	Suitable
1–1.5	Neutral
0.1–1	Slightly Unsuitable
Under 0.1	Very unsuitable

The other factor which is nearness to the river should be considered and combined with this suitability. As higher streams have always higher bank wetness in terms of distance, the buffers chosen for different kinds of streams are different:

Table 4-9- Buffer distances for waterway criterion

Stream Order (Wide to Narrow)	Buffer distance (m)
5	15
4	10
3	7
2	5

The final data structuring task done was combining the Length of water ways in the block in previous step and the buffers. The areas with buffers will be considered as very highly unsuitable. The rest of the areas suitability class will remain the same.

Classification:

The suitability classification is based on the combination of length of waterways inside blocks and exclusion of areas within certain distance from different kinds of streams. Below is a summary of the classification used:

Table 4-10- Final Classification for waterway criteria

Within * (meter) from	Stream order	Suitability classification
15	5	Very Highly unsuitable
10	4	
7	3	
5	2	
Block Contains * of length of all streams		
30%-90%		Highly Suitable
15%-20%		Suitable
10%-15%		Neutral
1%-10%		Slightly Unsuitable
Under 1%		Very unsuitable

The following map shows a section with the above mentioned classification:

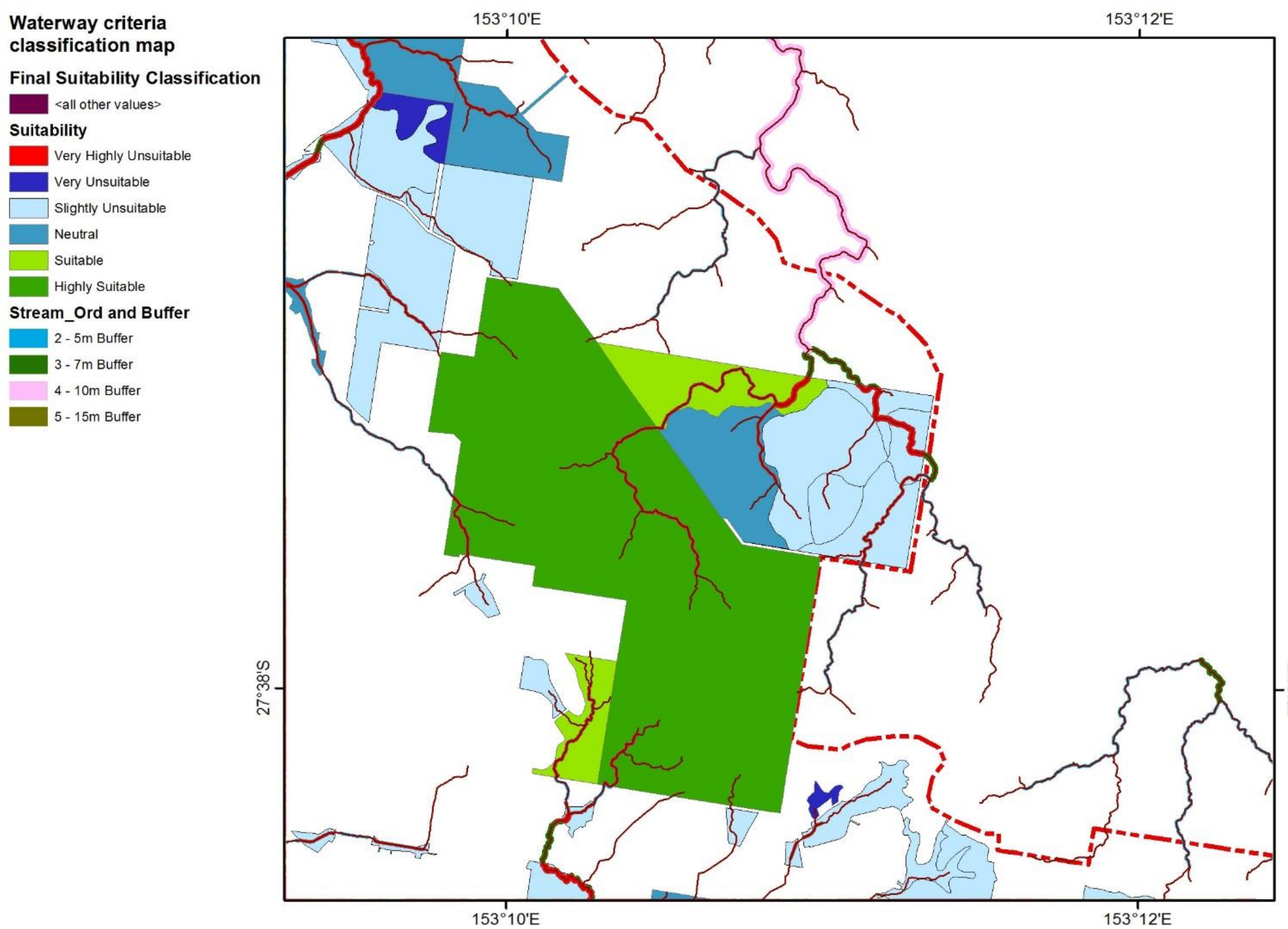


Figure 4-6-Final Classification map for Waterway criterion

4.2.1.8 Fire History Background

According to what was mentioned in section 3.2.8-, recently burned areas (either by controlled burning or by bushfire) may have some modified fuel load and may not be a suitable place to re burn. Different types of vegetation have different behaviours of growth and the regrowth rate of the vegetation after a fire incident should be calculated to have a good impression of fuel load in the burnt area.

If an area is burnt recently it may not be suitable for re-burning, however it will be possible to calculate regrowth rate and actual fuel load. This criteria is similar to fuel load. The difference is the areas of interest are areas with fire history background, and inside them, the areas which are not in their full fuel load due to fire history background, should be found out and scored according to their current situation. The percentage of current fuel load compared to the full fuel load conforms the score assigned to this criteria. This means if the fuel load is in full, score is 10 which mean most suitable for burning and if it is not, the percentage of fuel load determines the score. For example, if it is 30% of actual full fuel load the score should be 3.

Data received as fire history comprises a number of polygons with some overlapping fire history patches. The attribute table of this layer shows the burn dates of each patch and the reason for the burn i.e. wildfire, prescribed burn or arson.

Some information regarding the vegetation cover of area with the regrowth interval is needed and then with assumption that regrowth happens linearly, an estimation of current fuel load content could be calculated.

The aim is to find out from the areas with fire history, which place have full fuel load and otherwise, how much is the regrown fuel load now. Then the areas are classified as very highly suitable for full fuel load, and the suitability decreases with less fuel loads.

For this, the following data structuring was done:

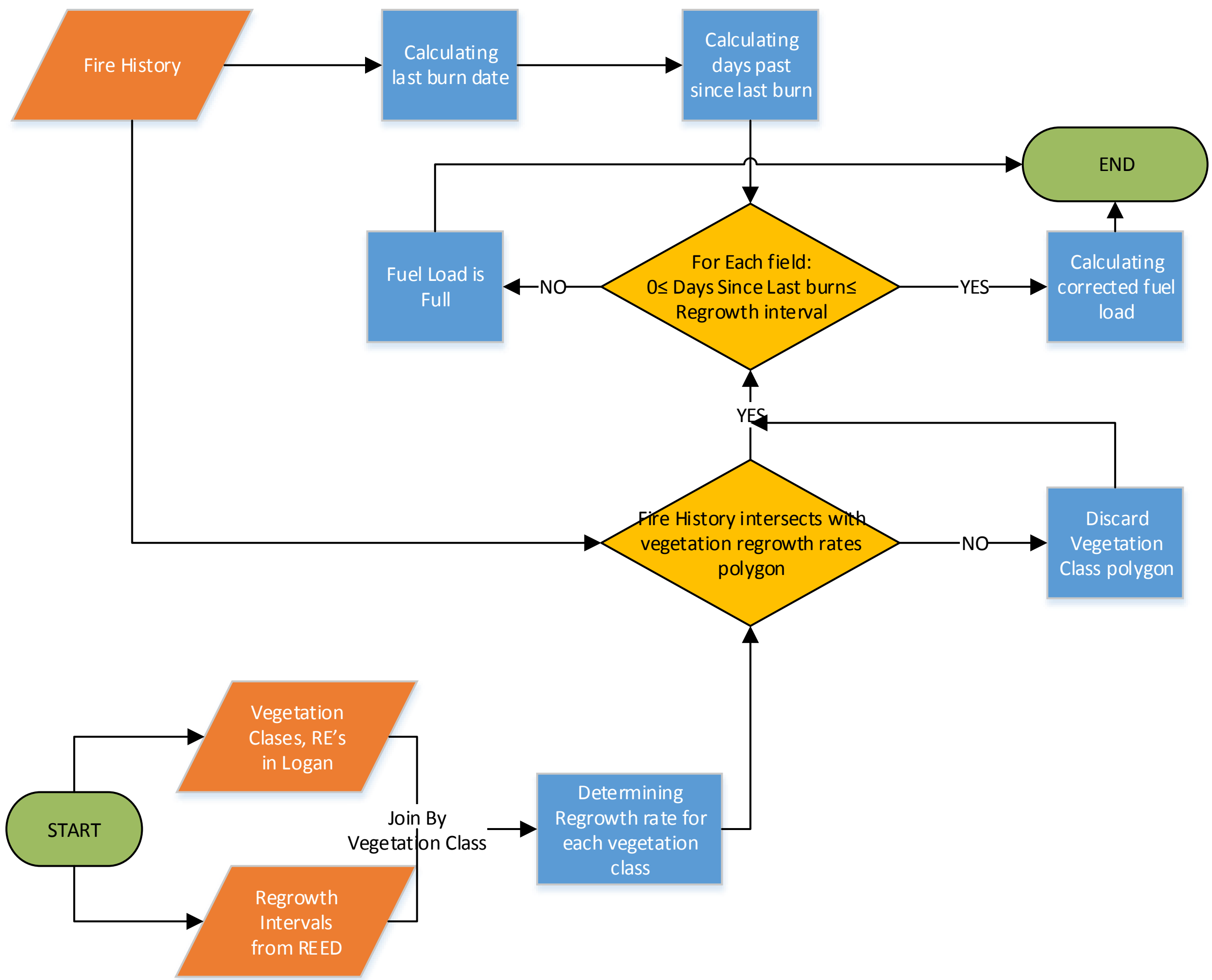


Figure 4-7- Data Structuring processes done for fire history criterion

Below is an explanation how the data structuring process is done according to the above sub-model:

Finding Last Burn date for overlapping fire history

For overlapping historical burn patches, the latest burn date has should be taken into consideration This is shown in figure 4-7-, where numbers represent burn years and the tick symbol shows the selected year, this example denotes 3 patches but number of burn patches could be even more than three, i.e. for more than three patches overlapped, same logic should be applied.

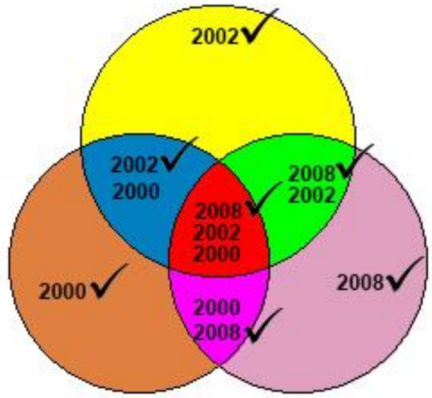


Figure 4-8-logic how last burn date is selected in overlapped burn patches

The following process where done:

- Overlapping burn history polygons are broken into polygons with similar areas and shapes
  Unironed burn history with itself will do this (for example in figure 4-7-, this creates 15 separate polygons)
- historical burn dates for each patch is converted into days intervals and historical last burn interval of each burn block per different burn history patches within each block are calculated;
- Finds minimal 'days since last burn' values for each patch and selects polygons according to this query: (*days_scince_last_burn is Minimised for each ovelapping polygon)*

Fuel load calculations and RE, fire guidelines assignments

Fire guidelines is a document based on Regional Ecosystem (RE). Regional ecosystems were originally defined by (Sattler *et al.*, 1999) as vegetation communities in a bioregion that are consistently associated with a particular combination of geology, landform and soil. (Queensland Government, 29 September 2014). For each RE there is a fire guideline which includes the regrowth interval. This information is stored in a database published by Queensland State Herbarium and consist of many information about different RE's. This database is a MS Access database called Regional Ecosystem Description Database (REDD) (Queensland Herbarium, 2008). Information Regarding Vegetation Classes covering Logan City Council Boundary was received from Logan City Council Environment and Sustainability Branch. (Fig 4.10). The fire history layer could be seen in figure 4.-9-

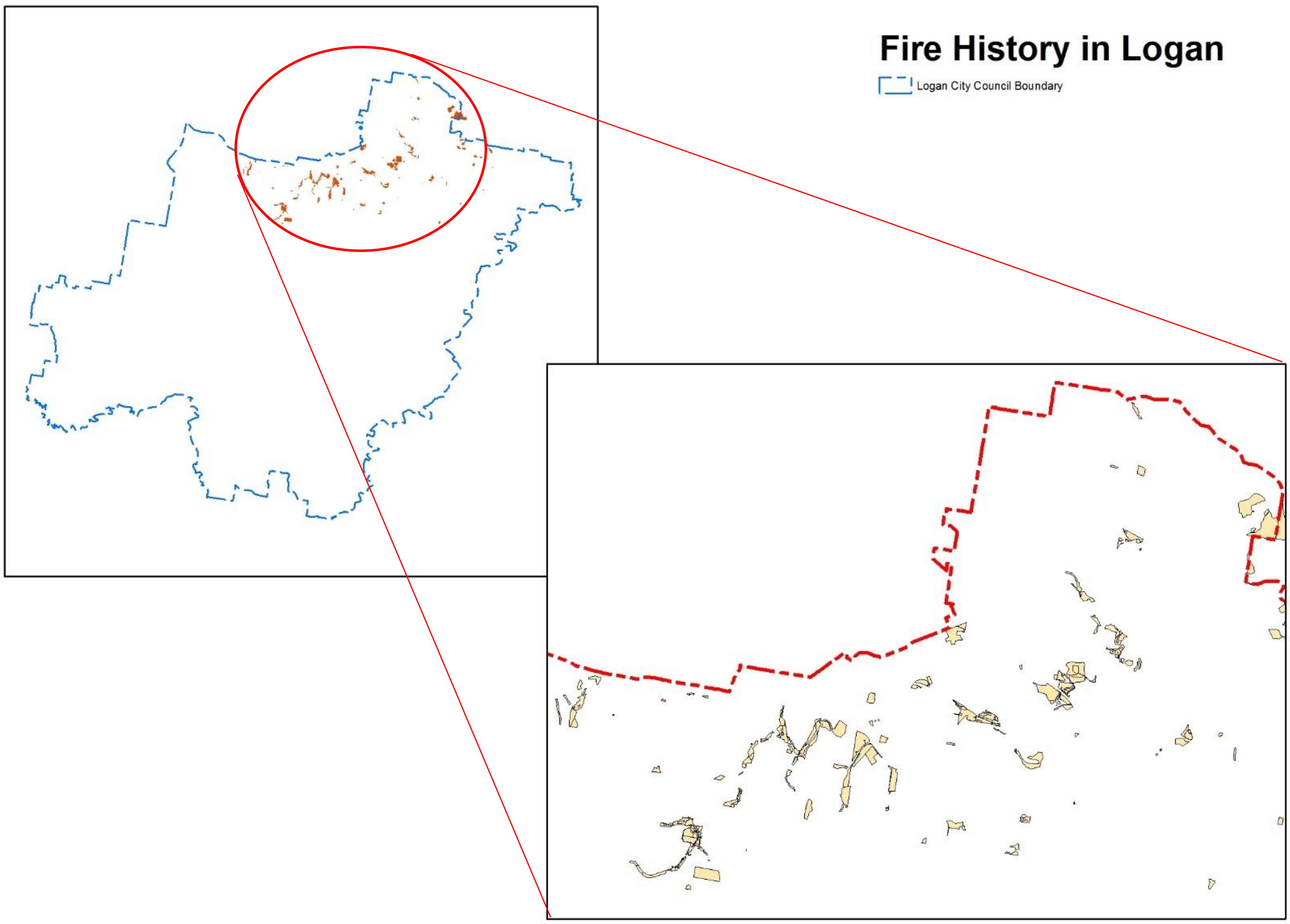


Figure 4-9-Fire History Feature class

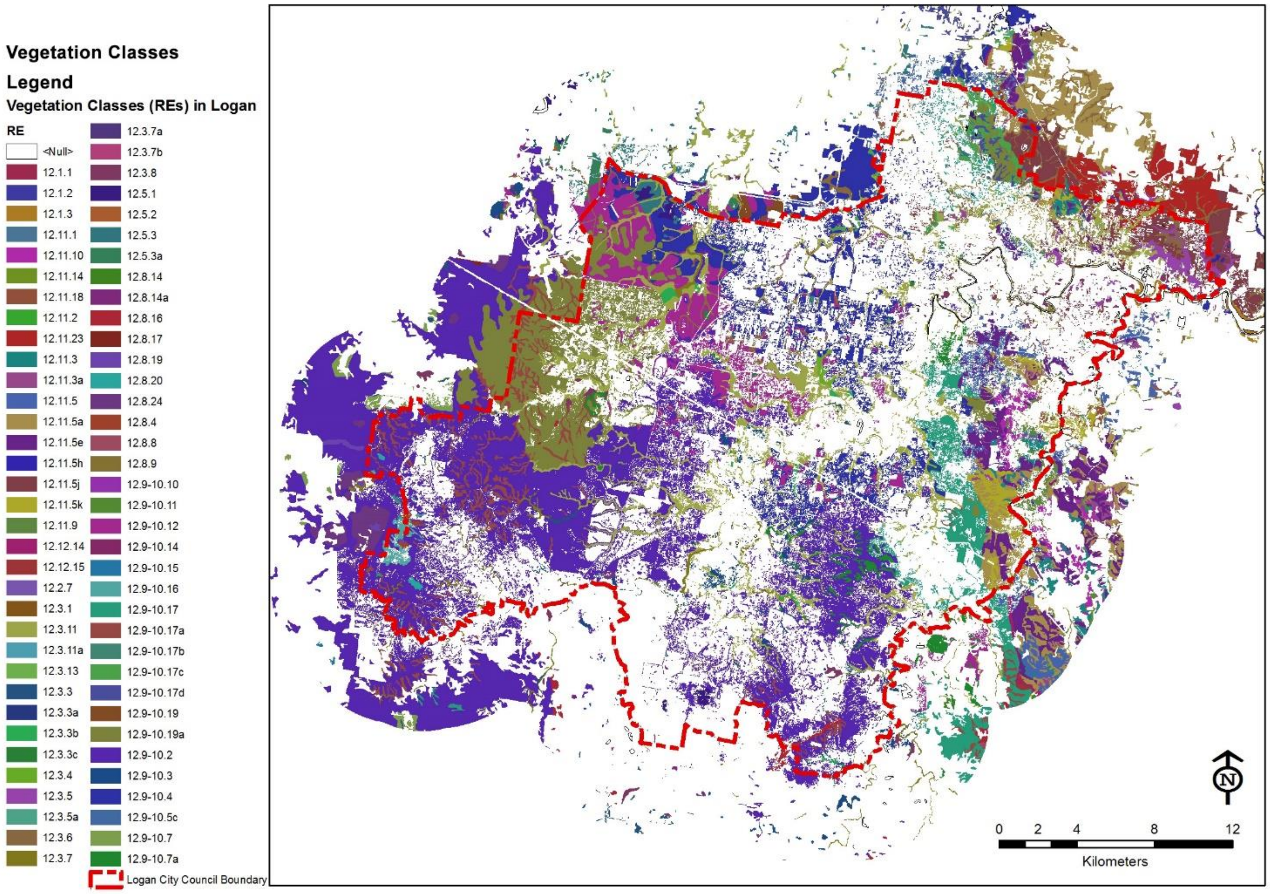


Figure 4-10-Vegetation Classes in Logan. Source: (Queensland Herbarium, 2008)

The following process where done:

- Combines RE definitions with fire guidelines;
  - Fire guidelines and regrowth intervals for each RE found in REED database is joined with Logan RE's layer. (Join field REs)
  - The result from above is intersected with fire history layer to find overlapping. The areas without intersection is of no interest so they are excluded.
- Matches patches of different RE with patches of different burn history
  - Union burn history polygons for each of which last burn interval and date is calculated, are overlayed (union) with Logan RE with REED regrowth intervals
- Checks if regrowth period after last burn, in the current date has already reached full fuel load (i.e. Fuel load reached its full condition) or no regrowth interval exists, this implies that the fuel load is actual otherwise, the corrected current fuel load is calculated (percentage) (see figure 4-10)

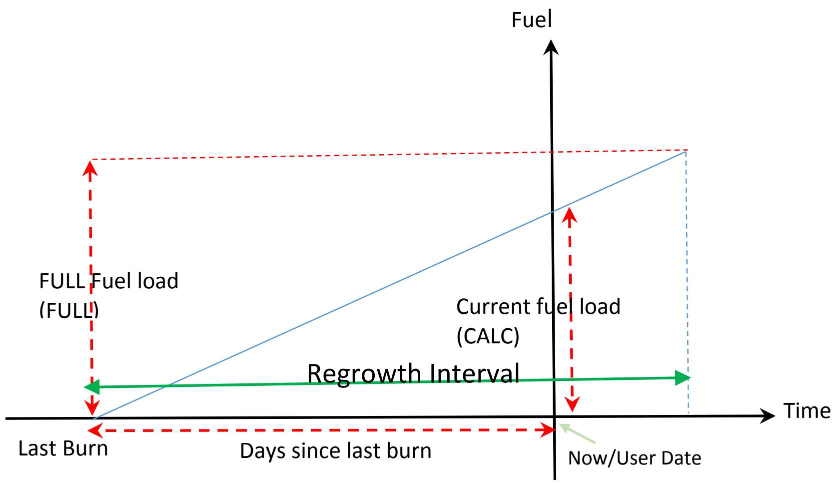


Figure 4-11- Fuel load (vegetation Regrowth) linear change over time

  - Assuming that the regrowth happens linearly as shown in the diagram in figure 4-10, actual fuel load has been calculated (Refer to Appendix 1).

Classification:

The final classification for this criteria is as follows:

Table 4-11- Final Classification of Fuel Load criterion

Fuel load condition	Suitability classification
Full (100%)	Very Highly Suitable
Partial: (percentage of full fuel load)	
90-99	Very Highly suitable
80-90	Highly suitable
70-80	Very Suitable
60-70	Suitable
50-60	Slightly suitable
40-50	Neutral
30-40	Slightly unsuitable
20-30	Unsuitable
10--20	Very unsuitable
0-10	Highly unsuitable

4.2.1.9 Located in ecologically significant areas

The main layer received for ecological significant areas in Logan city council is the layer produced in Environment and Sustainability branch as described in section 3.2.9- Ecological significance values range from a minimum of 1 to a maximum of 62 in that map which means an area with ecological significance value of 62 is of highest importance and value 1 is of lowest importance. Areas with higher ecological significance should be protected and could not be considered in fuel reduction controlled burn activities.

Classification

Classification of these areas are done in regards with ecological significance value. The areas with higher ecological significance value are more suitable for controlled burn.

Table 4-12- Classification of Ecological significance criterion

Ecological Significance Values	Suitability
0-5	Very Highly suitable
5-12	Highly suitable
12-19	Very Suitable
25-30	Suitable
30-36	Neutral
36-41	Unsuitable
41-47	Very unsuitable
47-62	Very Highly unsuitable

4.2.1.10 Proximity to various infrastructure elements

The roads data received is a polyline shape file denotes the various hierarchies of arterial, industrial access, industrial collector, main roads, rural access, rural arterial, rural collector, urban access, urban collector.

The rail data received is a polyline shapefile with the main rail roads within Logan which consists of: Beaudesert branch railway, Brisbane Sydney railway, Beenleigh railway.

These two layers were merged together to make a unique infrastructure layer. Then the various types of road and rain has been classified into three major categories: 1, the high importance infrastructure, 2 for medium importance infrastructure and 3 for lower importance infrastructure, as shown in table 4-13.

Table 4-13- Importance classification of infrastructures Hierarchy at Logan

Hierarchy	category
ARTERIAL	1
INDUSTRIAL ACCESS	2
INDUSTRIAL COLLECTOR	3
MAIN ROADS DEPT	1
RURAL ACCESS	2
RURAL ARTERIAL	1
RURAL COLLECTOR	3
URBAN ACCESS	2
URBAN COLLECTOR	3
BEAUDESERT BRANCH RAILWAY	1
BRISBANE SYDNEY RAILWAY	1
BEENLEIGH RAILWAY	1

The buffer distance for each of these three categories was determined as shown in table 4-14:

Table 4-14- Buffer distances per each importance category of infrastructure

Importance	Buffer distance (m)
1	50
2	30
3	10

Classification

Classification of these areas are done in regards with the importance of infrastructure. The areas with higher importance value are more suitable for controlled burn.

Table 4-15- Final classification of infrastructure criterion

Within applied buffer distance of the category	Suitability
1	Highly Unsuitable
2	Very Unsuitable
3	Unsuitable
NoData	Very Highly Suitable

The following map shows the classification outcome for infrastructure:

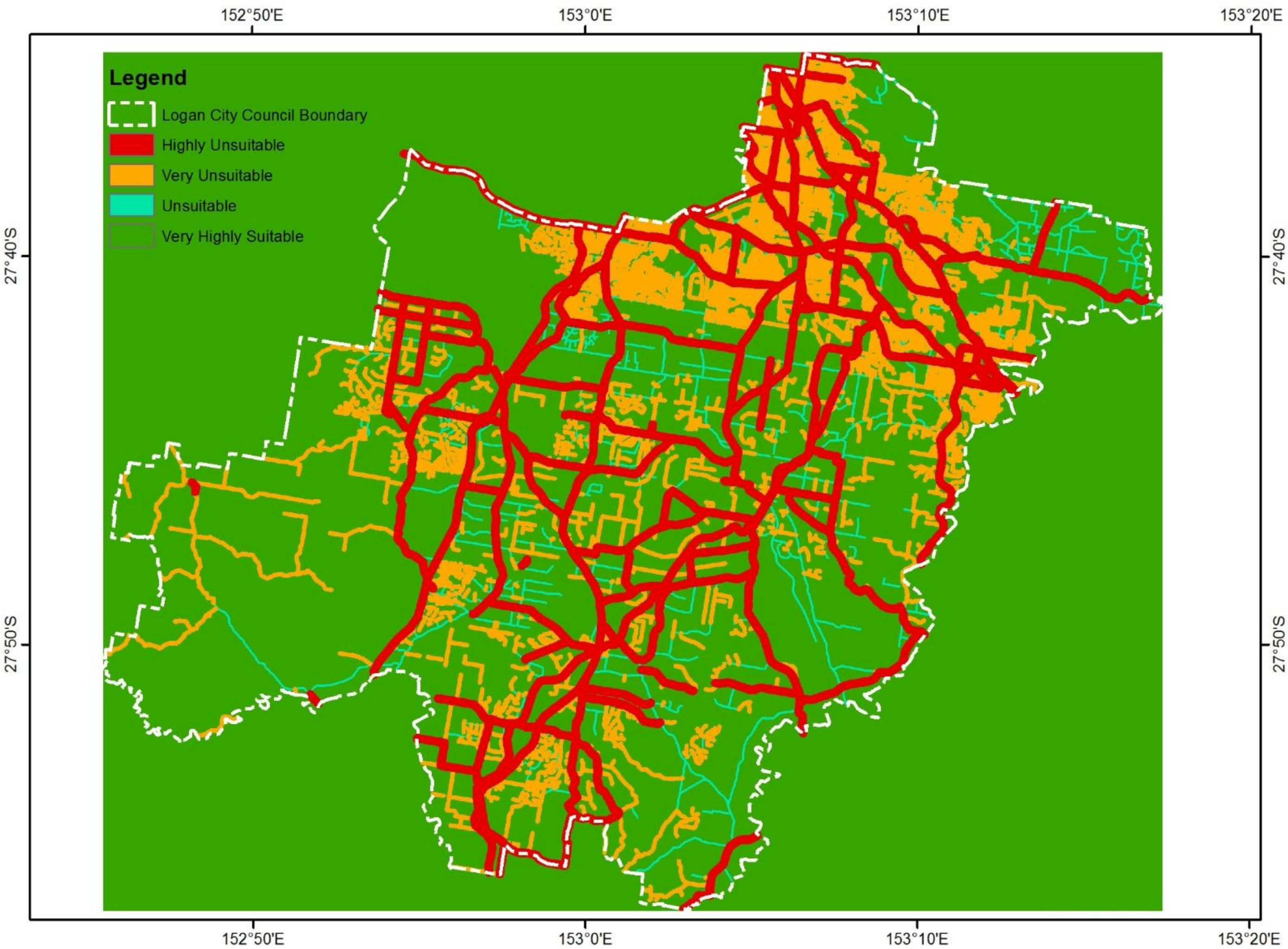


Figure 4-12-Classification map of infrastructure criterion

4.2.1.11 Firebreaks and firetrails:

Two separate layers for fire breaks and fir trails where received. This two layers have been merged and a buffer distance of 200 meters where applied to the layer this area shows the highest suitability according to this criterion.

Classification:

However the areas that are not falling inside buffer distance of fire breaks and may be still suitable. Because of this reason, for no data available, the suitability has been set to Neutral.

Table 4-16- Final classification of Firebreaks and firetrails criterion

Within applied buffer distance	Suitability
Yes	Very Highly Unsuitable
No	Neutral

4.3 GIS Modelling:

The aim was to create an outcome raster of the multicriteria analysis and then score each proposed burning block for prioritization based on this raster. It is also intended to find out each criterion's influence of the final score for each block. As shown in figure 4-12-, after data structuring and reclassification, the following broad processes was modelled as the main body of model process:

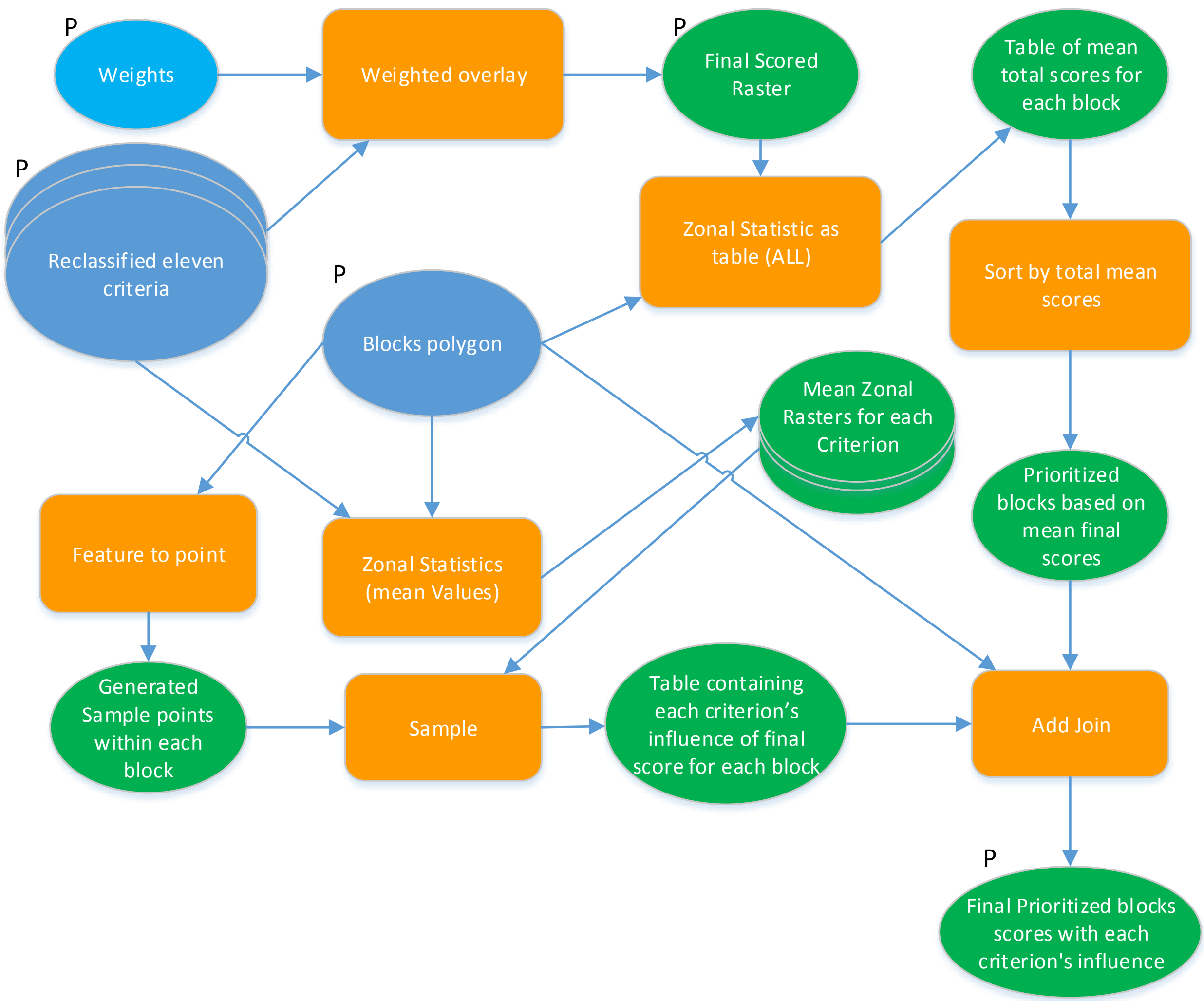


Figure 4-13-Geoprocessing structure of the model

4.3.1 Reclassification

The reclassification process is done for all criteria in order to quantitate all criteria in a value based format and make them ready for weighted overlay. The criteria which are vector based are converted into raster before reclassification. Based on the classification qualitative values applied on classification process the following reclassification:

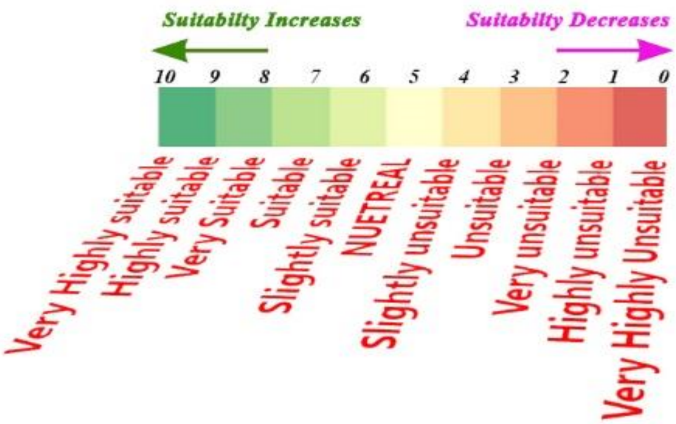


Figure 4-14- Re-Classification Ramp

Table 4-17- Reclassification conversion

Old values	New Values
Very Highly suitable	10
Highly suitable	9
Very Suitable	8
Suitable	7
Slightly suitable	6
Neutral	5
Slightly unsuitable	4
Unsuitable	3
Very unsuitable	2
Highly unsuitable	1
Very Highly Unsuitable	0

4.3.2 Overlaying different criteria and weighting

The overlaying process is based on eleven main criteria and their corresponding weights determined after performing AHP analysis. The GIS tool used for this process in weighted overlay analysis.

Inputs

- Reclassified raster datasets of eleven different criteria;
- Weights for different criteria, weights are user defined, based on AHP analysis for different themes and are out of 100. The sum of the weights should add up to 100.

Processes

- Collects weights of each criterion for overlaying;
- Converts null values in each criterion's layer (if any) to .001;
- Overlays the criteria raster based on user weights;
- Normalises the final score of the weighted overlay outcome into 0-10 interval (0 least suitable, 10 most suitable).

Methodology:

- Final scored raster denoting the final suitability scores of each cell. Cells scores are between "0" to "10". Value "0" means least suitable and value "10" means most suitable. The values in between, if they are closer to "10", they are more suitable and closer to "0", less suitable. (refer to Appendix 1 for the code block)

4.3.3 4-4-3- Calculating each criterion's contribution of overall score for each block

Inputs

- Reclassified raster datasets of eleven different criteria;
- Blocks polygon;

- Generated sample points for each block in order to sample each block's value.

Processes

- Performs zonal statistics to find the mean value of each criterion's score for each block;
- Uses 'Sample point' method to tabulate collected mean scores for each block in a single table.

Methodology

- Zonal statistics creates block polygons in raster format denoting mean suitability scores out of 10 for each block; (refer to Appendix 1 for the code block)
- Generated random sample points within each block that collect the constant raster values for each block for each criterion and tabulate them into a single geodatabase; (refer to Appendix 1 for the code block)
- Generated table in which each criterion's mean score is collected for each block; (refer to Appendix 1 for the code block)

4-4-4- Calculating zonal statistics of mean total final score for each block and prioritization

Inputs

- Final scored raster denoting the final suitability scores of each cell;
- Blocks polygon;

Processes

- Performs zonal statistics on the overlayed outcome raster to find out mean statistical values of the overall suitability score of each block;
- Sorts the blocks by their mean values and ranks them by the sorted value;
- Joins the final sorted blocks attribute table and each criterion's contribution scores table and creates a final feature class into the target output geodatabase.

Methodology:

- Generated Final zonal statistics table denoting mean of overall suitability for each block is created by zonal statistics as a table geoprocessing tool (refer to Appendix 1 for the code block)
- Generated blocks polygon with all the above mentioned info attached to it. This consists of zonal statistics of each blocks statistics of overall suitability score, including mean value of overall suitability score based upon which the blocks are prioritized and the mean value contribution of each criterions on overall score for each block. This is done by joining (refer to Appendix 1 for the code block)

The final shapefile created consist of the following fields in the attribute table:

Table 4-18- Final fields in the model result attribute table

Field Name	Description
OBJECTID	Priority rank
Park Name	Blocks park name
FID	Original Block ID
count	Count number of cells within block
Area	Blocks Area
MIN	Minimum Final Score of the block
MAX	Maximum Final Score of the block
RANGE	Range of Final Score of the block
MEAN	Mean of Final Score of the block
STD	Standard Deviation of Final Score of the block
SUM	Sum of Final Score of the block
Zones	Block Park Zone Category
Sample_Point_X	Sampling point X coordinate
Sample_Point_Y	Sampling point Y Coordinate
Zonal_Urban	Proximity to urban areas score of the block
Zonal_FireHistory	Fire History score of the block
Zonal_Fuel_Type	Fuel type score of the block
Zonal_Elevation	Elevation score of the block
Zonal_Aspect	Aspect score of the block
Zonal_Slope	Slope score of the block
Zonal_Fire_Break	Fire break score of the block
Zonal_waterway	Waterway score of the block

Zonal_infrastructure	Proximity to Infrastructure score of the block
Zonal_eclg_significance	Locating in Ecological significance score of the block
Zonal_powerlines	Proximity to power lines score of the block
Shape_Leng	Block's shape Length
Shape_Area	Blocks shape area

4.4 GIS model in model builder environment

In order to facilitate the model multiple tests for different weights determined for different themes and also to create a good decision aid-support system for decision makers, I was tried to create a model in ArcGIS model builder environment. In this model the following points have been taken into account:

1- Data structuring and classification process has been modelled
2- Weights and reclassification values has been considered as model parameters
3- A unique scratch and output geodatabase is created for each run of the model in order to avoid overwriting different run’s outcomes.
4- Model has been designed with interactive run mode criteria dialog box

In Appendix 3, the overall scheme of the model could be seen.

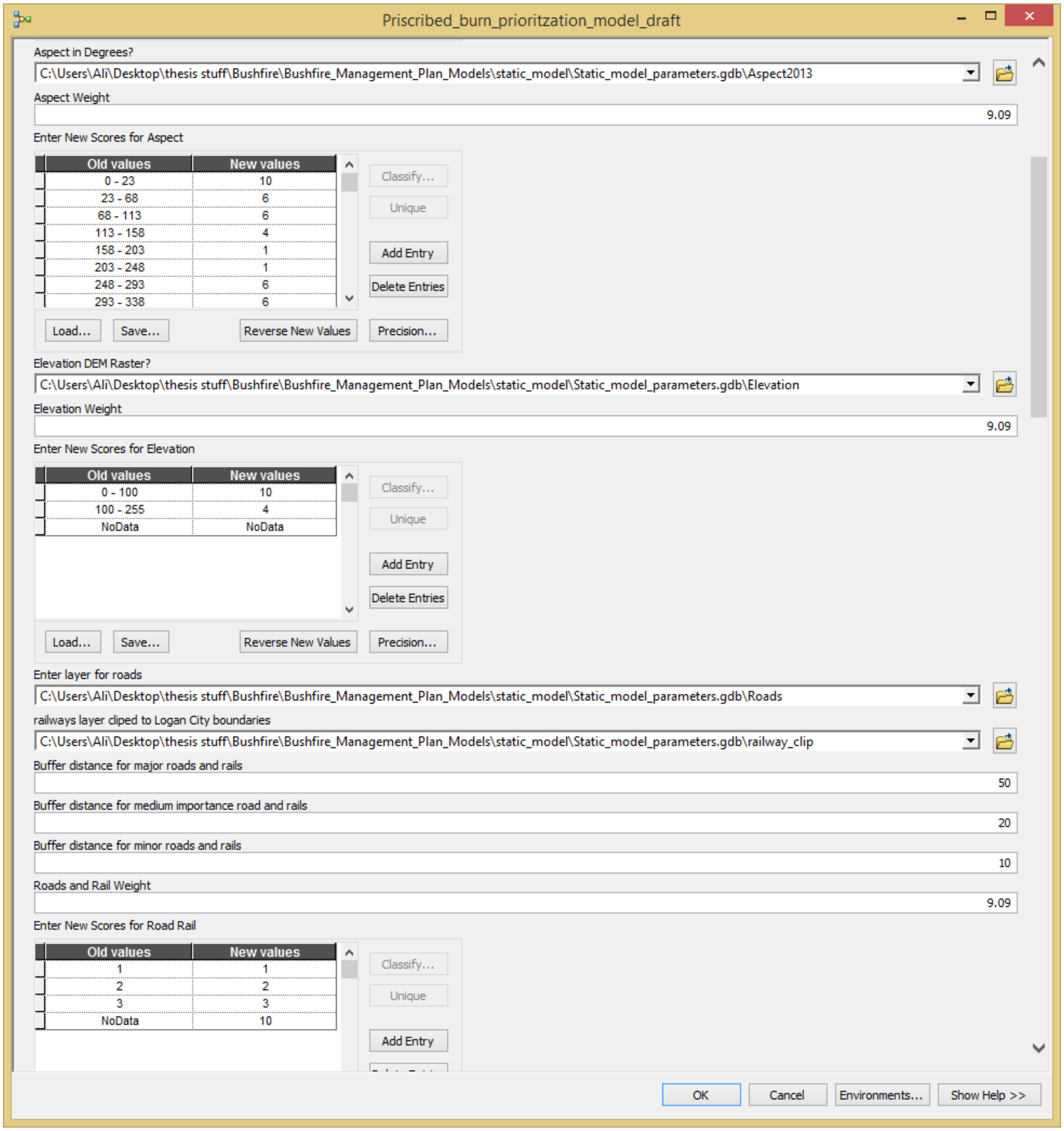


Figure 4-15- Model Run Mode dialogue

5 Model Application (Case Study)

Once the model is ready, decision should be made regarding weights for different themes. As mentioned in section 3.3.1, the final aim of the model is a formula applied for weighted overlay raster analysis. In this overlay analysis, variables are the main criteria rasters as well as the weights for representing the importance of each criteria considering different themes as it is represented in equation 5.

$$TotalScore = \sum_{i=1}^{n}(k_i C_i) \qquad \text{Equation 5}$$

Where k_i is weight for criterion i and C_i is the score values of criterion i (in raster format) for each criteria.

In Analytical Hierarchical Process Method, the importance of each criteria is found out by a coefficient that could be applied in weighted overlay analysis as weights. In the methodology used for AHP analysis, coefficients are found out by pairwise comparison of the criteria if they are related to the same level or common attribute. (R. W. Saaty, 1987)

Criteria could be of different levels and can consist of some other sub criteria in a hierarchical structure. In Logan City Case study, criteria are all considered in the same level therefore the first step of identifying which criteria is dependent of other criteria and each criteria belongs to what level of dependency is not taken into account. All the eleven criteria has been considered as the first level and for determining weights three themes of

1. Safety
2. Implementation
3. Equal

have been considered. For the first two themes, AHP process has been applied. For this purpose, two questionnaires were given to some staff at Logan City Council for pairwise comparison of the criteria for each theme. A sample of this questionnaire could be seen in table 3-3-. In pairwise comparison the staff were instructed to use comparison codes for each pair analysis. A table of these complete codes could be seen in table 3-2-. After analysing the responses regarding pairwise comparison, the inconsistency of the responses were investigated based on (R. W. Saaty, 1987) theorem. This means if the matrix of responses is not consistence, i.e. the consistency ratio is higher than the maximum ratio of 0.1, that questionnaire should be handed over the related person for re-consideration and applying new judgments.

5.1 Safety Theme:

In this theme the staff have been asked to compare the criteria with considering safety of conducting prescribed burn activity. Safety is an important aspect that should be considered in whole burn process. Safety could be translated as considering the safety of the staff conducting the prescribed burn activity and also the safety of residents.

The following AHP derived weights has been considered for Safety theme:

Table 5-1- Criteria wighting for Safety theme

Criteria	Weights (%)
Infrastructure (C_1)	16.1
Slope (C_2)	4.2
Aspect (C_3)	3.1
Elevation (C_4)	2.1
Fuel Type (C_5)	9.2
Fire history (C_6)	6.8
Power lines (C_7)	13.3
Waterways (C_8)	9.3
Ecological Significance (C_9)	7.2
Fire Break, Fire trails (C_{10})	11.3
Urban (C_{11})	17.4

Hence the formula used for weighted overlay in Safety theme is as follows:

$$T_{Safety} = (0.161C_1 + 0.042C_2 + 0.031C_3 + 0.021C_4 + 0.092C_5 + 0.068C_6 + 0.133C_7 + 0.093C_8 + 0.072C_9 + 0.113C_{10} + 0.174C_{11})$$

Equation 6

After applying it to the model the following map was the result for this theme:

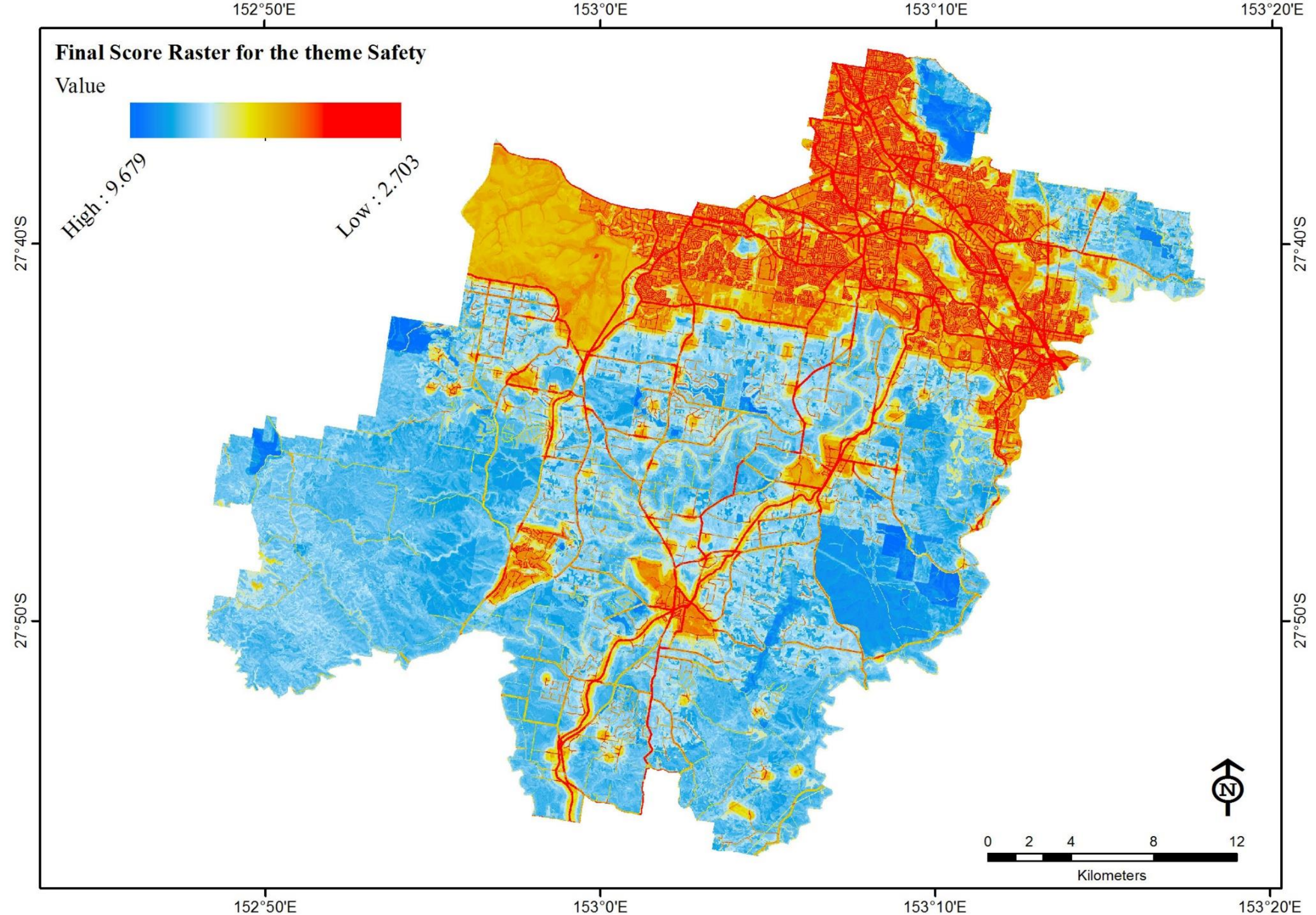


Figure 5-1- Final Score raster for theme safety

5.2 Implementation Theme:

In this theme the staff have been asked to compare the criteria with considering ease of implementation in conducting prescribed burn activity. Easy implementation is an important aspect that should be considered for burn process. Implementation could be translated as considering the easiness of access to burn blocks and applying fire to the prescribed burn patches with least possible and recommended human resource and cost imposed for best controlling and management of fire engagement.

The following AHP derived weights has been considered for Safety theme:

Table 5-2- Criteria wighting for implemntation theme

Criteria	Weights (%)
Infrastructure (C_1)	11.9
Slope (C_2)	12.4
Aspect (C_3)	8.2
Elevation (C_4)	10.9
Fuel Type (C_5)	13.3
Fire history (C_6)	9.8
Power lines (C_7)	5.4
Waterways (C_8)	3.9
Ecological Significance (C_9)	3.8
Fire Break, Fire trails (C_{10})	12.2
Urban (C_{11})	8.1

Hence the formula used for weighted overlay in Safety theme is as follows:

$$T_{Safety} = (0.119C_1 + 0.124C_2 + 0.082C_3 + 0.109C_4 + 0.133C_5 + 0.098C_6 + 0.054C_7 + 0.039C_8 + 0.038C_9 + 0.122C_{10} + 0.081C_{11})$$

Equation 7

After applying it to the model the following map was the result for this theme:

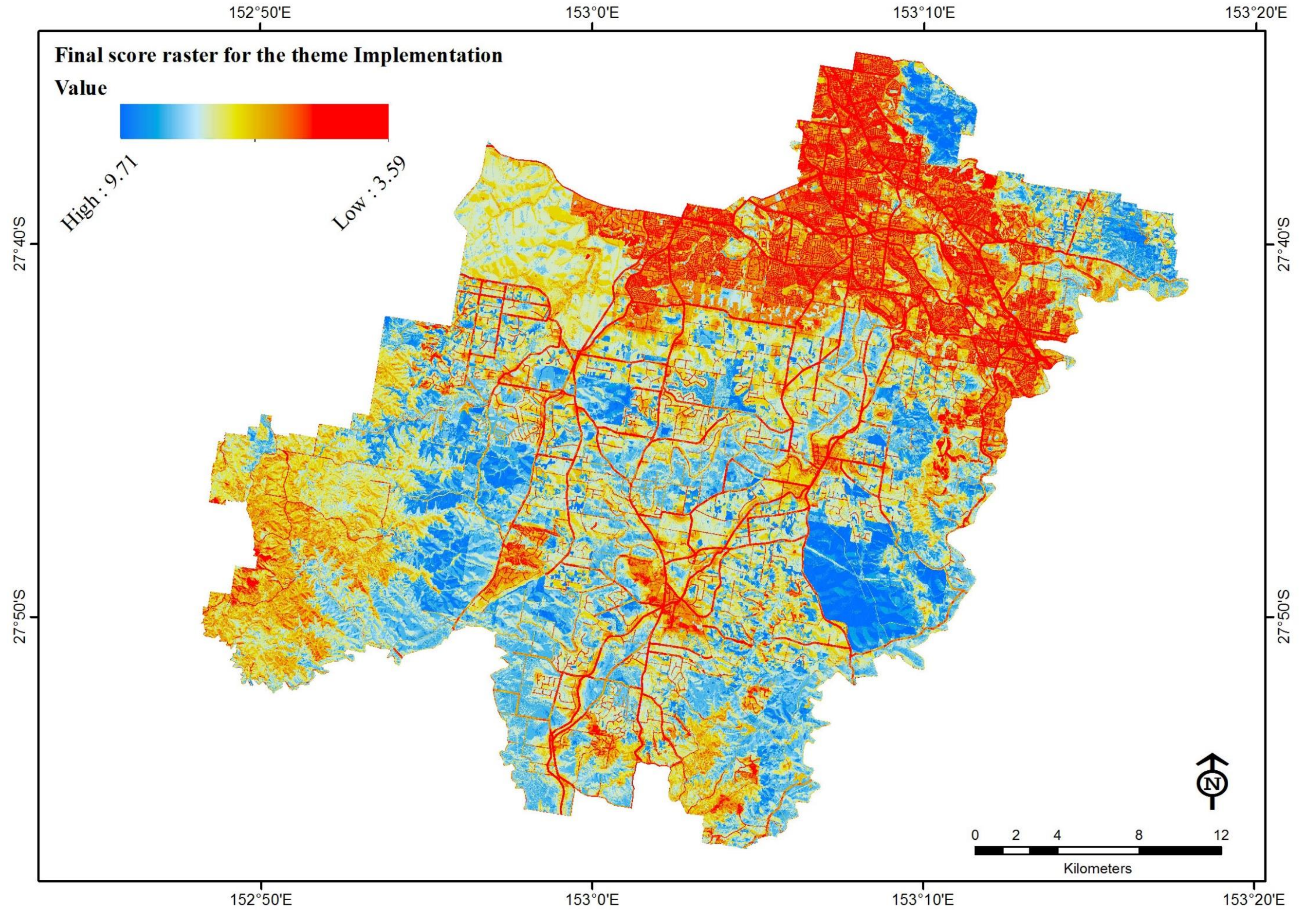


Figure 5-2- Final Score raster for theme Implementation

5.3 Equal theme

In this theme all the weight have been considered as equal. This is just an equal situation in which all the criteria are considered as the same level of importance. Although this theme is applied to model. The main usage of this model may be comparing it with other main themes of safety and implementation to see how different themes change by changing different weights on the main themes.

The following AHP derived weights has been considered for Safety theme:

Table 5-3- Criteria wighting for Equal theme

Criteria	Weights (%)
Infrastructure (C_1)	9.09
Slope (C_2)	9.09
Aspect (C_3)	9.09
Elevation (C_4)	9.09
Fuel Type (C_5)	9.09
Fire history (C_6)	9.09
Power lines (C_7)	9.09
Waterways (C_8)	9.09
Ecological Significance (C_9)	9.09
Fire Break, Fire trails (C_{10})	9.09
Urban (C_{11})	9.09

Hence the formula used for weighted overlay in Safety theme is as follows:

$$T_{Safety} = (0.0909C_1 + 0.0909C_2 + 0.0909C_3 + 0.0909C_4 + 0.0909C_5 + 0.0909C_6 + 0.0909C_7 + 0.0909C_8 + 0.0909C_9 + 0.0909C_{10} + 0.0909C_{11})$$

Equation 8

After applying it to the model the following map was the result for this theme:

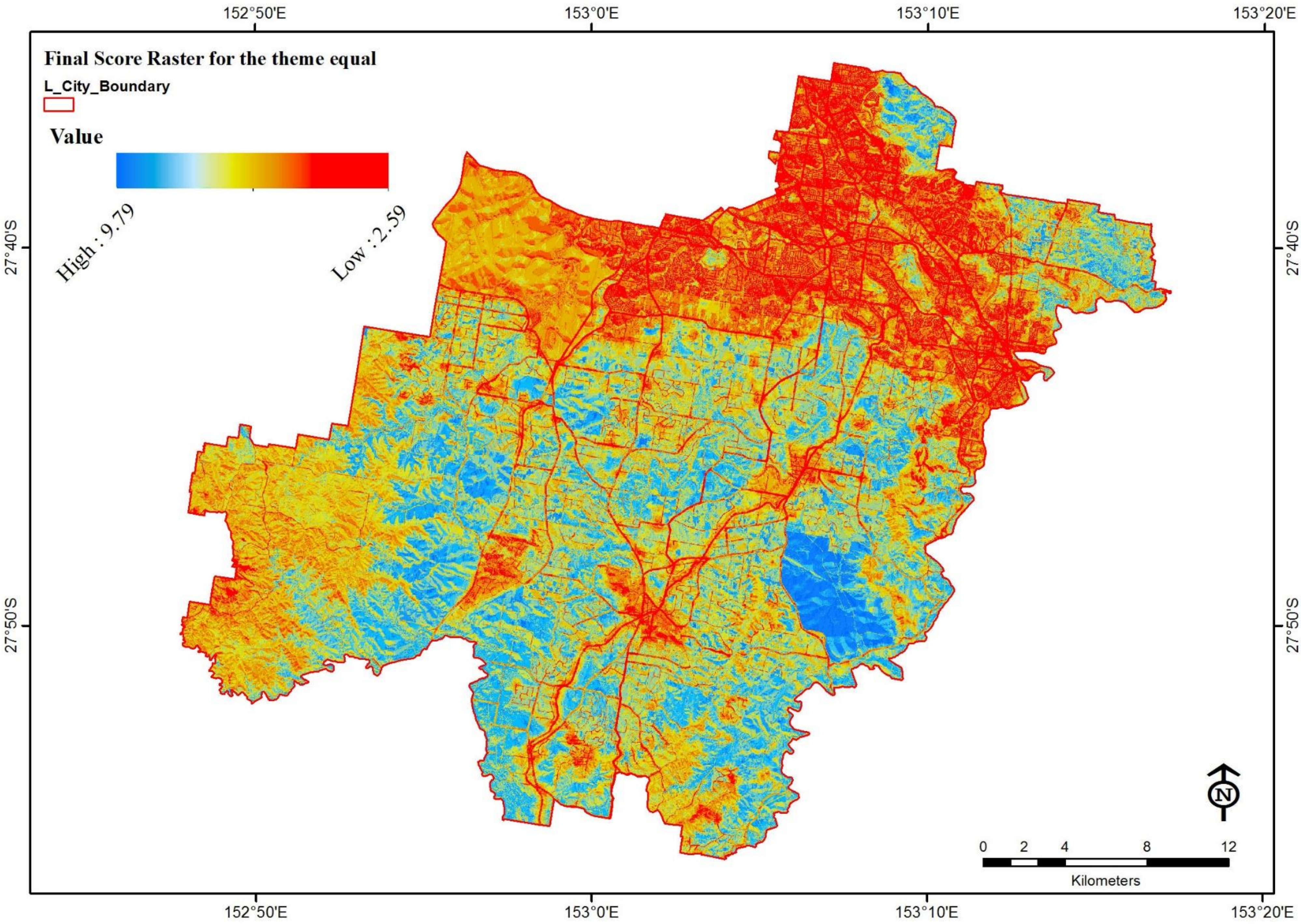


Figure 5-3-- Final Score raster for theme Implementation

6 Results and Conclusion:

6.1 Results optimization methodology and discussion:

For generating the final prioritized blocks a combination of safety and implementation is used to prioritize blocks. But for generating a more precise and a balanced selection of blocks between two themes for planning and decision making a correction methodology was used.

Prioritization of burn blocks is generally based on the blocks mean zonal values of the final scores scoured from different themes modelling. Based on the two main themes of safety and implementation, two blocks prioritization was generated. Each block is ranked according to the mean zonal score of the block. This means if a block has higher mean score, the rank is higher.

In the final prioritization these two themes must be considered properly so that the final prioritization shows a realistic view of safety and implementation. Combining the final results by overlaying can cause some bias as some blocks show a good match for safety theme but not a good match for implementation and vice versa. The aim of the correction methodology was to select a rank difference interval within which the ranking of both themes can be considered as equal importance and outside which block shows more sensitivity towards one of the themes, i.e. safety or implementation. Figure 6-1- below is a scatter diagram shows rank distribution between two themes of all 580 blocks analysed. Each dot shows the rank of the block per each theme. The horizontal axis is the safety theme rank of the block and the vertical axis shows the implementation theme rank of the block.

$(x, y) = (Rank_{Safety}, Rank_{implem.})$

As seen there is a good spatial correlation between safety and implementation themes. This means that the rank increase and decrease of many blocks are not very dependent on the weights applied for each theme. These blocks could be subject to equal weight themes overlay in final prioritization. However, some blocks rank difference are very high in favour of a theme.

The green lines in the Figure 6-1- shows the distinction selected based on the methodology. The blocks in orange are safety dependent blocks and the blocks in light blue are implementation dependant blocks. The other blocks in red are blocks that considered independent of themes.

The methodology for generalizing and selecting equally important blocks in terms of themes is finding a normal probability distribution for blocks dependence on one theme.

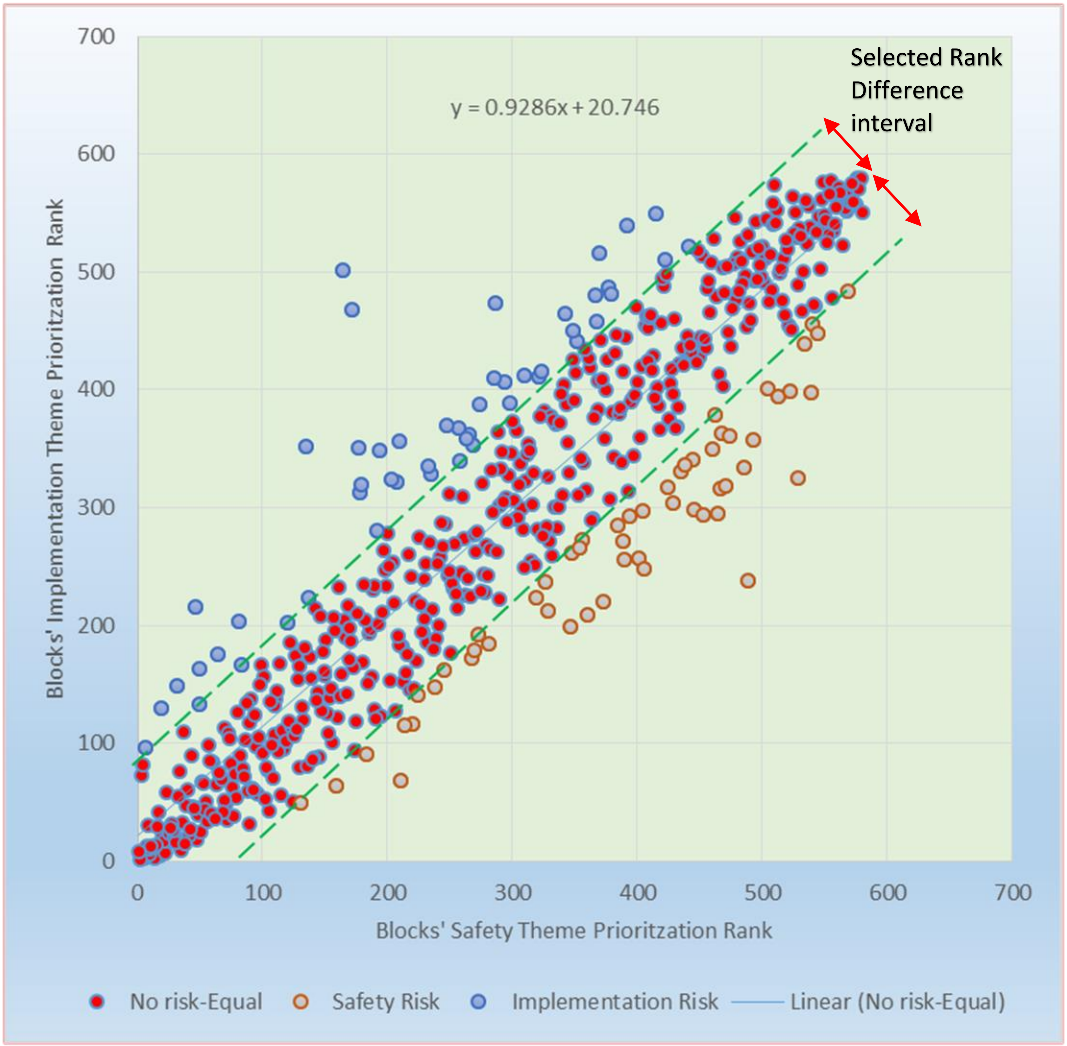


Figure 6-1-rank distribution between two themes of all 580 block

For selecting the best dependence interval a test was carried out, the number of blocks with different rank difference intervals were plotted in a diagram to see if they follow any regular pattern. This Plot has been shown in figure 6-2. In this plot horizontal axis shows the difference between safety and implementation rank of the blocks i.e.

$$\alpha = Rank_{Safety} - Rank_{implem.} \qquad \textit{Equation 9}$$

and the vertical axis shows $\sum R_{\alpha}$ the total number of blocks with rank difference of α with the following condition:

R_{α} = each block's rank difference

$\sum R_{\alpha}$ =

$\forall \alpha \in (-n,n): R_{\alpha} \geq 0, n \in \mathbb{N}$,

if $\alpha < 0 : R_{\alpha} < \alpha$

if $\alpha > 0 : R_{\alpha} > \alpha$ *Equation 10*

The negative values of α means the sensitiveness to implementation theme and the positive values of α mean the sensitiveness to safety theme. The plot in figure 6-2 has a sample population of α with increment increase of *10*.

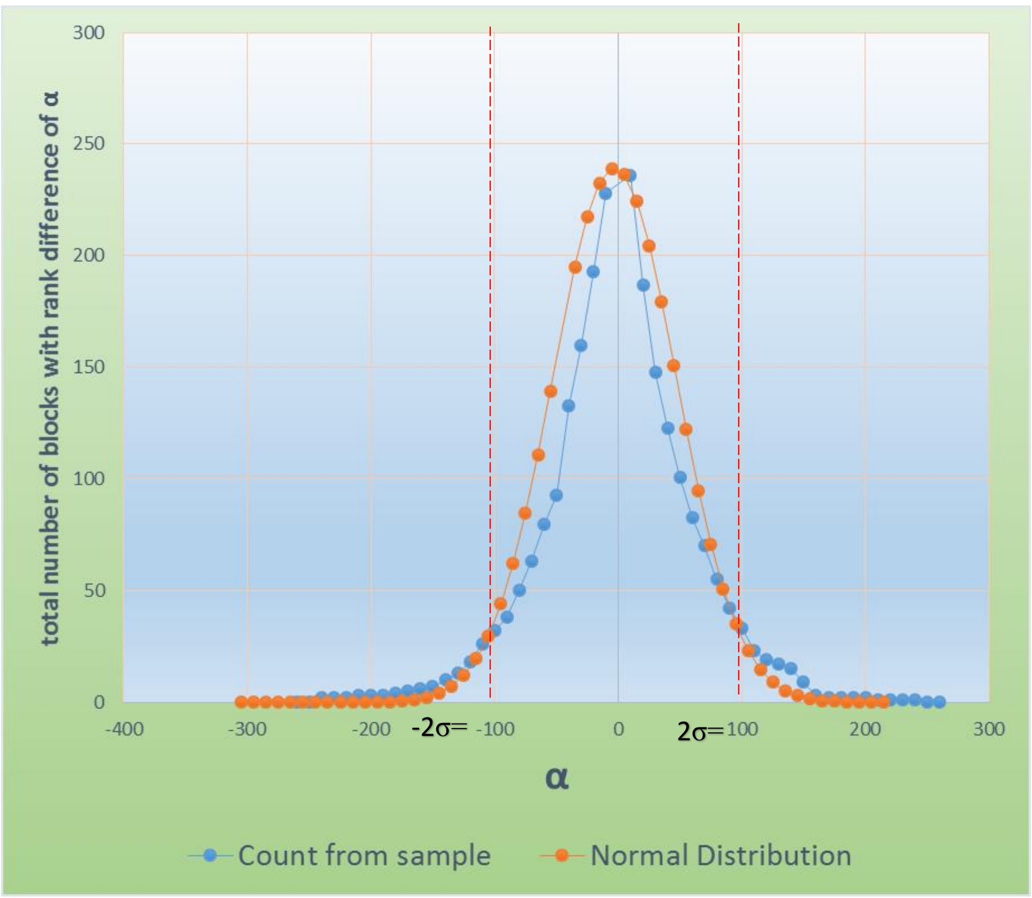


Figure 6-2- distribution blocks by rank difference

As seen in plot a normal distribution with $\mu = 0$ and $\sigma = 50$ has a good fit with our sample distribution. Hence, accruing to tolerance interval rule in normal distribution, we can say with 95% of the distribution is within $2\sigma = 100$. Therefore the rank difference interval of 100 would be an interval that we could trust that blocks within this interval are with 95% of confidence with no more than ± 100 fluctuation in interval. In other words these blocks are with ± 100 tolerance in rank are independent of the themes weights and could be considered as equal weighted themes overlay in final prioritization result. For other blocks if the rank interval difference is less than -100 then we can say these blocks are influenced by implementation theme, therefore a weight of "0.8 Implementation + 0.2 Safety" is applied to them. The other way round, if the rank interval difference of the blocks are more than +100 then we can say these blocks are influenced by safety theme and therefore a weight of "0.2 Implementation + 0.8 Safety" could be applied in final theme overlaying. The idea behind choosing this combination of weights is based on Pareto Principle which states for many events, 80% of effects come from 20% of the causes (Newman, 2005). This could translate as 20% of all biases are good representation of 80% trueness.

In brief, the blocks combination scoring of the themes are as follows:

For each block, $S_{total} =$

$$\begin{cases} 0.5S_{safety} + 0.5S_{implem.} & \text{if} \quad -100 \le R_\alpha \le 100 \\ 0.8S_{safety} + 0.2S_{implem.} & \text{if} \quad 100 < R_\alpha \\ 0.2S_{safety} + 0.8S_{implem.} & \text{if} \quad R_\alpha < -100 \end{cases}$$

Equation 11

The final blocks prioritization is based on this overlaying scheme which could represent a realistic score for planning purposes. This scheme shows a statistically corrected prioritization based on two main themes of safety and implementation.

The final blocks prioritization map are shown in figure 6-3- The label numbers show the rank of the blocks

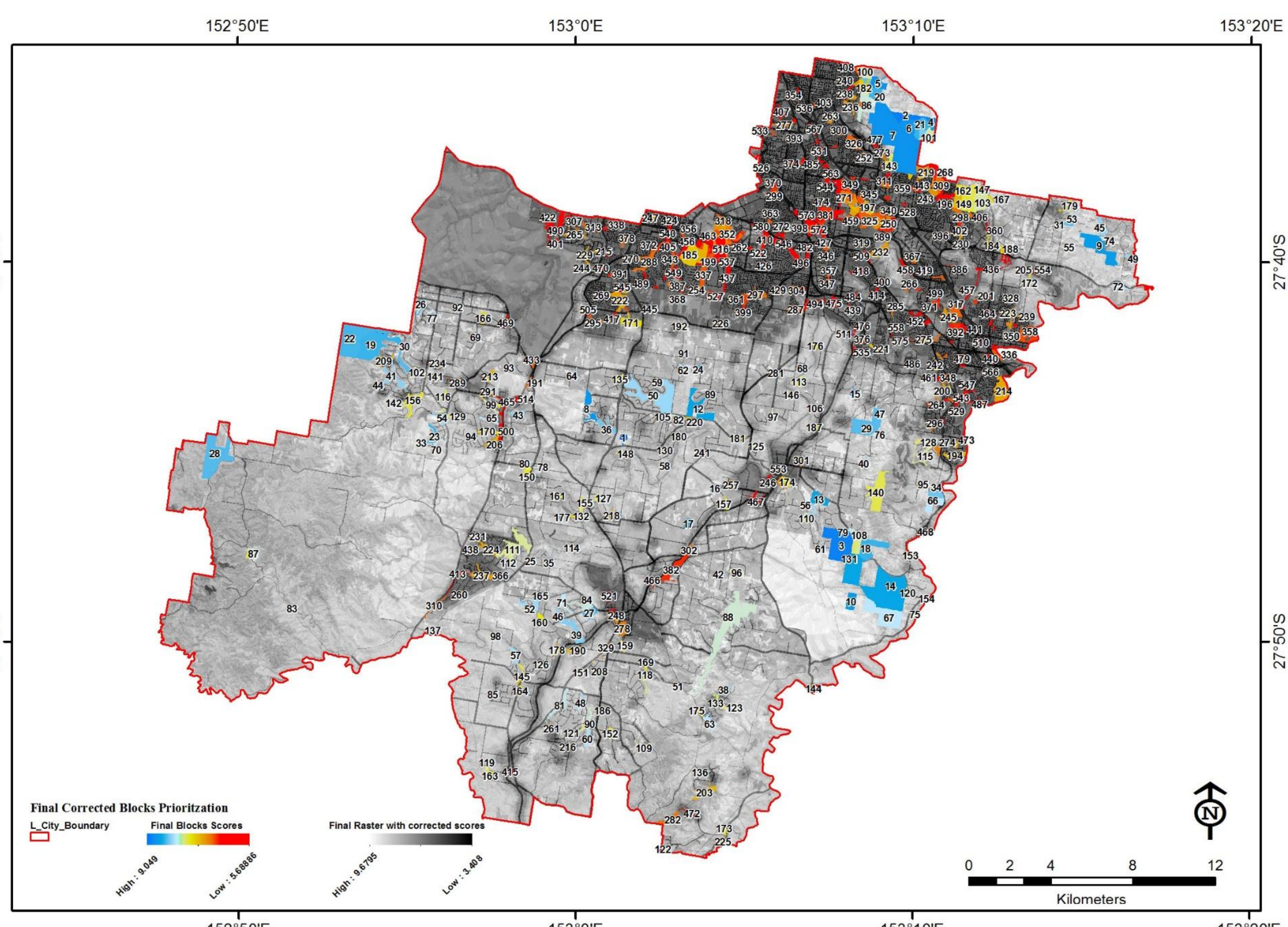


Figure 6-3- Final Score raster and blocks prioritization

The final attribute table of the prioritized blocks shows different information regarding blocks and now it also show some safety and implementation triggering found out in correction step to help decision makers have a good perception of the blocks with both safety and implementation issues. The attribute table for 3 sample blocks no. 21, 75 and 483 for which priorities have become 2, 195 and 472 respectively have been shown in 6-1- (The attribute table has been transposed)

Table 6-1- The attribute table for 3 sample blocks selected for demonstration

Field name	Block Sample 1	Block Sample 2	Block Sample 3
Priority rank	2	195	472
Sub_block	Block 1	Block 6	NA
Park Name	Lawrie	Boronia	TREMAYNE LANEWAY
Original Block ID	21	75	483
Count number of cells within block	16395	661	746
Area	409875	16525	18650
Minimum Final Score of the block	6.74	5.29	5.190000057
Maximum Final Score of the block	9.67	8.83	8.029999733
Range of Final Score of the block	2.93	3.54	2.839999676
Mean of Final Score of the block	8.951223	8.181982	6.818445054
Standard Deviation of Final Score of the block	0.335574	0.650889	0.341287201
Sum of Final Score of the block	146755.3	5408.29	5086.56001
Block Park Zone Category	Block 1	Bushland Zone	
Sampling point X coordinate	516589.8	503119.8	506092.2694
Sampling point Y Coordinate	6945626	6935964	6911770.876
Proximity to urban areas score of the block	10	2.918306	0.056300268
Fire History score of the block	10	9.854766	10
Fuel type score of the block	9.741507	9.60817	9.302948952
Elevation score of the block	10	10	4.016085625
Aspect score of the block	5.317902	6.069592	3.603217125
Slope score of the block	8.54541	8.980332	6.962466717
Fire break score of the block	9.92699	9.006051	7
Waterway score of the block	6.280329	3.877458	3.569705009
Proximity to Infrastructure score of the block	10	8.88351	9.746648788
Locating in Ecological significance score of the block	6.925461	4.170953	5.05212
Proximity to power lines score of the block	10	9.845689	9.895442009
Implementation High Risk	NO	YES	NO
Safety High Risk	NO	NO	YES
Block's shape Length	3624.68	718.8308	1955.576689
Blocks shape area	409863.2	16553.38	18709.57394

6.2 Conclusion and future work

The objective of this thesis was to design a Decision Support System tool for deciding about best blocks for conducting controlled fuel reduction burns in long term planning. The model developed for this purpose considers the most important criteria for physically selecting the potential burn blocks according to their priorities. The prototype model was developed using ArcGIS 10.2 model builder with a user interface that allows the user to have a good control on the weights and data input.

The usability test of the result generated by this model was done by Logan City Council managers and Parks Department bushfire experts. The suitability of the blocks was very close to what experts had in their minds and this model results were validated completely satisfactory by them. The most difficult blocks to decide about were the blocks near or among residential areas which although showing lower priority rank compared to blocks located in urban areas, have a rational ranking order. The testing method was based on experience of experts on local blocks and comparing them to each other. All of the blocks ranked by the model were according to what they had a practical perception from the field visit and field knowledge.

This systematic and scientific method of prioritizing blocks considers two main themes of safety and implementation which are the key prospects of managing a controlled burn could be a good basis for justification of long term investments and plans. This could reduce significantly the time and resources allocated to select the most qualified and best ranked blocks among blocks that a decision needs to be made for. The introduced method for optimization of selecting a combination of Safety and Implementation themes is a very handy method to come to a prioritization that both themes have been considered. The methodology used could be a good basis for future optimizations.

In this thesis some limitations was faced and this may result in some weaknesses that shall be addressed and improved in future work:

1- This should be noted again that this thesis result could not be a main source of final design making because the other aspects of proposing a prescribed burn plan which are not long term or directly spatially non-model-friendly should be considered for that purpose. A good future work could be developing a model for analysing short term factors and Fire Danger Rating (FDR) factors which is based on CSIRO's McArthur Forest Fire Danger Index (FFDI).(A. G. McArthur, 1967; Noble *et al.*, 1980). These factors include wind speed, humidity, smoke drift, drought factor, soil moisture and temperature for setting up fire in burn blocks. This short term that model shall assist decision makers if the blocks proposed by the model introduced in this thesis is practically possible to set fire to at the current situation. Another model that could help decision makers. Another model that could be developed to use as a basis for prescribed burn blocks decision making is a tool that could forecast short term parameters. This way it is possible to simulate short term suitability for long term. The proposed tool is then able to prioritise prescribed burn blocks in long term based on short term factors context and specifically based on the burn suitability interpretation of Fire Danger Rating (FDR) which is based on CSIRO's McArthur Forest Fire Danger Index (FFDI).(A. G. McArthur, 1967; Noble *et al.*, 1980), and historical Meteorological data acquired from Australian Bureau of Meteorology (Australian Government Bureau of Meteorology)

2- Multicriteria analysis is based on 11 main factors which mainly were based on experts' ideas and knowledge and data availability. This means that data limitations may have caused some main factors not to be considered in the model. In future works, literature search could be expanded and some other important factors could be added to the model in case the data is available for them.

3- Data accuracy is in an acceptable level now but it could be upgraded with some more accurate and higher resolution data. Using such kind of high quality data would improve model results and therefore more accurate outcome could be achieved. Some data needs to be enhanced for example some districts have no fire history data in the current database and this is because the database is not completed by Logan City Council. A more comprehensive input data will always result in more accurate outcomes

4- Validation of the model is now is based on a qualitative method and expert's ideas. Validation could be quantitative and more scientific. It is suggested that some random blocks are selected and examined quantitatively to see how different criteria are satisfying the block burn readiness in some separate analyses and compared against the model results. The more agreement is between the model result and quantitative analysis of the individual blocks, the more results could be considered as satisfactory. This quantitative model validation was not considered in this study due to time and resources restrictions but as a suggestion it would be a good idea that in future works and researches a good scientific-based validation method is considered for the model.

It is noteworthy to mention research questions again and briefly include answers that this study has revealed for each questions:

- Why using a multi-criteria analysis is a good methodology for analysing blocks readiness for burn?

Multicriteria analysis is a good method to evaluate the importance of various factors related to a subject to fulfil a given objective. This method models different factors by different quantitative means and this could be represented in the model by quantitatively representable importance outcomes. This is called a value model. Most of the criteria considered for blocks burn readiness are criteria which their importance could be represented quantitatively and therefore very easily considered as criteria in a MCA as a value model.

- Which characteristics makes a block suitable for burning? Are these characteristics spatial?

The purpose of this study is to generate a suitability surface (i.e., raster dataset) by overlaying location specific attributes (or static attributes, which are highly unlikely to change over time) After a literature search and discussion with experts, eleven main criteria of slope; aspect; elevation; proximity to various infrastructure elements such as roads and rail; proximity to urban areas; proximity to firebreaks and fire trails; proximity to power lines; proximity to waterways; having fire history background; being located in ecologically significant areas and fuel load content were considered. The criteria were analysed for spatial modelling and the data related to each criteria were manipulated in order to make them suitable for modelling purposes.

- How could the characteristics be modelled in Decision Support System GIS model?

The best approach chosen and used in this model was AHP method. Analytical Hierarchical Process Developed by Thomas L. Saati (T. L. Saaty, 1980) is a good approach combining a very detailed criteria by criteria vision on a MCA problem and develops it into a unified value based solution to a MCA problem. AHP method helps a lot regarding choosing weights for deciding about final value model. This method could be used as a basis for GIS modelling. The final GIS model is chosen based on weighted overlay raster analysis which uses the AHP analysis approach to generate a spatial value model for each criterion in MCA analysis.

- How could short term and long term GIS models be developed?

Short term and long term approaches were discussed and it was decided to disregard short term model in our study. It was discussed that it is inevitable that in short term, some deterministic factors like wind speed, wind direction, humidity, temperature and soil moisture is very important to start burning an area. The reason why the short term factors are not considered, is because they are not relevant for long term strategies. Some of these factors, although very important in prescribed burn principles, are not easy to model for long term planning or they could not give us a good spatial perception in long term or they are considered for a unique burn. For example for wind speed or wind direction we should have a yearly estimation of average wind speed or wind direction which is practically too difficult to prepare and to put it into long term modelling. In long term planning on the other hand, estimation of where is the best areas to burn blocks based on static long term criteria, could help decision makers plan to put their priorities to those areas

- What data is necessary to be integrated and structured in the system to assist planners to have most suitable database for producing burn plans?

It was discussed how a burning plan may look like and for producing a burning plan many spatial and non-spatial data is needed. Some of spatial data could be sourced from the model introduced in this study. Data like block size, block vegetation and fuel types, burning instructions based on fuel types, elevation, slope, aspect, etc. could be easily produced by model. Some other data which is mostly related to short term characteristics of the block should be integrated into the burn plan. This data is humidity, wind speed, moisture etc. which may be entered by user into the burn plan.

In overall and in general, the tool created by this study, will help decision makers has a good basis for deciding about long term priorities to plan for controlled burn activities. Decision makers could use this model to have a long term outlook for the budget and resources needed to be allocated to fuel reduction controlled burn practices. This will facilitate short term planning as well.

Appendix 1: Scripts used in Modelling

Conversion of slope and Aspect from Radian to Degrees

```
>>> import math
>>> rad2deg = 180.0 / math.pi
>>> from arcpy.sa import *
>>> OutRas = ACos (InRas) * rad2deg
```

From (ESRI, 2014)

Calculation of Days since Last Burn date of fire history for each patch:

```
days_scince_last_burn = DateDiff ("d",[Fire_Date],Now (  )  )
```

Calculation of minimal 'days since last burn' values for each patch (*days_scince_last_burn is Minimised for each overlapping polygon)*

```
>>> arcpy.Dissolve_management(fire_history_unioned, output, "SHAPE_Lenght", "
days_scince_last_burn MIN", "SINGLE_PART", "DISSOLVE_LINES")
```

Script applied for calculating actual fuel load:

```
>>> def calculate_fule (!days_past_till_user_date!, !RE_fire_guidelines_Intervals! ,
!actual_load! , !intersect_status!):
>>>  if (!intersect_status!=='yes'):
>>>   interval = !RE_fire_guidelines_Intervals! * 365
>>>   if (!days_past_till_user_date! < 0):
>>>    return !actual_load!
>>>   elif (!days_past_till_user_date! < interval):
>>>    return ((!days_past_till_user_date!*!actual_load!)/ interval)
>>>   else:
>>>     return !actual_load!
>>>  else:
>>>    return !actual_load!
```

Script produced for: Proximity to various infrastructure elements

```
>>> type ( !Road_Hierarchy! , !Name!  )
>>>def type (a,b):
>>>    try:
>>>        if (a is None and b is not None) or'ARTERIAL' in a or 'MAIN' in a:
>>>            return 1
>>>        elif  'ACCESS' in a:
>>>            return 2
>>>        elif 'COLLECTOR' in a:
>>>            return 3
>>>        else:
>>>            return 999
    except:

>>>buffer_dis ( !type! , %Buffer distance for major roads and rails% ,%Buffer distance for medium importance road and rails% ,%Buffer distance for minor roads and rails% )
>>>def buffer_dis (a,x,y,z):
>>>    try:
>>>        if a==1:
>>>            return x
>>>        elif  a==2:
>>>            return y
>>>        elif a==3:
>>>            return z
>>>    except:
>>>        return None
```

Script for overlaying and producing Final scored raster denoting the final suitability scores of each cell. Cells scores are between “0” to “10”. Value “0” means least suitable and value “10” means most suitable.

```
>>> arcpy.gp.RasterCalculator_sa("(Con(IsNull(\"%Reclass_Urb%\"),1,\"%Reclass_Urb%\") *
float(%Urban Areas Weight%) + Con(IsNull(\"%rcls_fireH%\"),1,\"%rcls_fireH%\") * %Fire
History Weight% + Con(IsNull(\"%rcls_ful_typ%\"),1,\"%rcls_ful_typ%\") * %Fule Type
Weight% + Con(IsNull(\"%reclss_elev%\"),1,\"%reclss_elev%\") * %Elevation Weight% +
Con(IsNull(\"%reclass_asp%\"),1,\"%reclass_asp%\") * %Aspect Weight% +
Con(IsNull(\"%recl_slope_T%\"),1,\"%recl_slope_T%\") * %Slope Weight% +
Con(IsNull(\"%rclss_FireB%\"),1,\"%rclss_FireB%\") * %Fire Breaks Weight% +
Con(IsNull(\"%rclss_Wtrwy%\"),1,\"%rclss_Wtrwy%\") * %Waterway Weight% +
Con(IsNull(\"%reclss_rd_rl2%\"),1,\"%reclss_rd_rl2%\") * %Roads and Rail Weight% +
Con(IsNull(\"%rclss_elcgSig%\"),1,\"%rclss_elcgSig%\") * %Ecological Significance Weight%
+ Con(IsNull(\"%rclss_powerline%\"),1,\"%rclss_powerline%\") * %Powerline Weight%)/100",
Final_Raster)
```

Script sing Zonal statistics to for creating mean raster datasets for each of the eleven criterion:

```
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", Reclass_Urb, ZonalSt_Urban,
"MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rcls_fireH,
ZonalSt_FireHistory, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rcls_ful_typ,
ZonalSt_FuelType, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", reclss_elev,
ZonalSt_elevation, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", reclass_asp3,
ZonalSt_Aspect, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", recl_slope_T,
ZonalSt_Slope, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rclss_FireB,
ZonalSt_FireBreak_trail, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rclss_Wtrwy,
Zonal_watertway, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", reclss_rd_rl2,
ZonalSt_infrastructure, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rclss_elcgSig,
Zona_elcgSignificance, "MEAN", "DATA")
>>> arcpy.gp.ZonalStatistics_sa(all_blocks_union, "OBJECTID", rclss_powerline,
ZonalSt_power, "MEAN", "DATA")
```

Script for creating Sample points within each block

```
>>> arcpy.FeatureToPoint_management(all_blocks_union, all_blocks_union_Point, "INSIDE")
```

Script for generating a table in which each criterion's mean score is collected for each block

```
>>> arcpy.gp.Sample_sa("'%Scratch WS%\\ZonalSt_Urban';'%Scratch
WS%\\ZonalSt_FireHistory';'%Scratch WS%\\ZonalSt_FuelType';'%Scratch
WS%\\ZonalSt_elevation';'%Scratch WS%\\ZonalSt_Aspect';'%Scratch
WS%\\ZonalSt_Slope';'%Scratch WS%\\ZonalSt_FireBreak_trail';'%Scratch
WS%\\Zonal_watertway';'%Scratch WS%\\ZonalSt_infrastructure;'%Scratch
WS%\\Zona_elcgSignificance';'%Scratch WS%\\ZonalSt_powerlines'", all_blocks_union_Point,
Sample_ZonalSt, "NEAREST")
```

Script for generating Final zonal statistics table denoting mean of overall suitability for each block is created by zonal statistics as a table geoprocessing tool ;

```
>>> arcpy.gp.ZonalStatisticsAsTable_sa(all_blocks_union, "OBJECTID", Final_Raster,
final_Zonal_Statistics_of_blocks_, "DATA", "ALL")
```

Script for attaching mean value of overall suitability score based upon which the blocks are prioritized into blocks polygon attribute table

```
>>> arcpy.AddJoin_management(all_blocks_union_2_Layer, "all_blocks_union_2.FID",
all_blocks_union_Point_Layer, "all_blocks_union_Point.FID", "KEEP_ALL")
```

Appendix 2, Summary Criteria classification and weights

SLOPE		
Slope (degrees)	**Classification**	**Scores**
0-8	Very Highly suitable	10
8--11	Highly suitable	9
11--15	Very Suitable	8
15--28	Slightly suitable	6
28--33	Slightly unsuitable	4
33-70	Highly unsuitable	1
<70	Very Highly Unsuitable	0
ASPECT		
Aspect	**Sun Exposure**	**Scores**
0-90	Slightly unsuitable	4
90-180	Very unsuitable	2
180-270	Neutral	5
270-315	Very Suitable	2
315-360	Very Highly suitable	0
ELEVATION		
Elevation	**Suitability**	**Scores**
0--100	Very Highly suitable	10
100-255	Slightly unsuitable	4
FUEL LOAD		
Fuel load	**Suitability Classification**	**Scores**
33	Very Highly suitable	10
30	Highly suitable	9
28	Highly suitable	9
27	Very Suitable	8
26	Very Suitable	8
20	Slightly suitable	6
19	Slightly suitable	6
10	Neutral	5
8	Neutral	5
8	Neutral	5
5	Unsuitable	3
5	Unsuitable	3
5	Unsuitable	3
5	Unsuitable	3

5	Unsuitable	3
3	Highly unsuitable	1
1	Highly unsuitable	1
1	Highly unsuitable	1
1	Highly unsuitable	1
0	0	0
PROXIMITY TO URBAN AREAS		
Distance	**Suitability**	**Scores**
In Urban areas	Very Highly Unsuitable	0
Within 100m distance from urban areas	Very Unsuitable	2
Within 300m distance from urban areas	Neutral	5
Within 500m distance from urban areas	Suitable	7
All other areas	Very Highly suitable	10
PROXIMITY TO POWERLINES		
Importance	**Suitability classification**	**Scores**
Low voltage& 10m bufer	Slightly Unsuitable	4
Medium voltage& 20m buffer	Unsuitable	3
High Voltage& 50m buffer	Highly Unsuitable	1
PROXIMITY TO WATERBODIES		
If: Within * (meter) from	**Suitability classification**	**Scores**
15 meter from stream order 5	Very Highly unsuitable	0
10 meter from stream order 4		
7 meter from stream order 3		
5 meter stream order 2		
Or, if: Block Contains *% of length of all streams	**Suitability classification**	**Scores**
30%-90%	Highly Suitable	1
15%-20%	Suitable	7
10%-15%	Neutral	5
1%-10%	Slightly Unsuitable	4
Under 1%	Very unsuitable	2
Fuel LOAD CONTENT		
Fuel load condition	**Suitability classification**	**Scores**
Full (100%)	Very Highly Suitable	10
Partial (percentage of full fuel load):		
90-99	Very Highly suitable	10
80-90	Highly suitable	9
70-80	Very Suitable	8
60-70	Suitable	7
50-60	Slightly suitable	6
40-50	Neutral	5

30-40	Slightly unsuitable	4
20-30	Unsuitable	3
10--20	Very unsuitable	2
0-10	Highly unsuitable	1
ECOLOGICAL VALUE		
Ecological Significance Values	**Suitability**	**Scores**
0-5	Very Highly suitable	10
5--12	Highly suitable	9
12--19	Very Suitable	8
25-30	Suitable	7
30-36	Neutral	5
36-41	Unsuitable	3
41-47	Very unsuitable	2
47-62	Very Highly unsuitable	0
PROXIMITY TO INFRASTRUCTURE		
Within applied buffer distance of the category	**Suitability**	**Scores**
1	Highly Unsuitable	1
2	Very Unsuitable	2
3	Unsuitable	3
NoData	Very Highly Suitable	10
PROXIMITY TO FIRE BREAKS AND FIRE TRAILS		
Within applied buffer distance	**Suitability**	**Scores**
Yes	Very Highly Unsuitable	0
No	Neutral	5

Appendix 3, Scientific Summary

Alireza Mollasalehi

GIS Based Modelling for Fuel Reduction Using Controlled Burn in Australia

Bushfire problem is a long-lasting problem which is a big threat and environmental problem in Australia. Planning to control bushfire is very important for Australian Environment. One of the most effective methods to fight bushfire disasters is planning for controlled burns in order to reduce the risk of unwanted bushfire events. Controlled burns management and planning has been always considered as important by town planners. In this study the aim is to produce a tool for prioritizing burn blocks based on diffract criteria in order to help planners have a sound scientific basis for choosing the most important blocks to have controlled burn on.

In this study the following research tasks have been considered

1. Investigate criteria related to prescribed burn management and their usability to design a model for analysing long term geospatial suitability of bushfire prescribed burns.
2. Finding out suitable model for scoring blocks designated as fuel reduction bushfire prescribed burns blocks in long term
3. Testing model in a pilot area

Several criteria for building up a multi-criteria analysis with GIS model were studied and the corresponding importance weight for them were debated. Research methodology used in this section was investigating literature and methods for determining weights and possibly, using experts' ideas by interviews or small surveys or running focus groups in a stakeholder organization to find out the most relevant and the most important criteria. Finally eleven most important criteria were chosen and compared to each other by interviewees to find out their importance weight.

The model developed considers all the criteria which is usable to plan and prioritize burn blocks selected in the criteria analysis phase. This model works as a basis for having a sound and robust decision on which blocks are most suitable to be burnt in long term point of view. GIS database used in this model were acquired from the pilot area's relevant authorities. Model was developed based on the ESRI's ArcGIS analysis tools as well as ArcGIS Spatial Analyst extension. In this model Analytical Hierarchical Process Methodology was used for combining criteria importance and develop a unified value-based solution to the study's Multi Criteria Analysis problem based on two main themes of 'Implementation' and 'Safety'.

Model was tested on Logan City Area in south of Queensland, Australia. The case study is an administration area within Australia that all the criteria data has been prepared and acquired from.

Results:

As combining the final results by overlaying can cause some bias as some blocks show a good match for safety theme but not a good match for implementation and vice versa, two main themes results were combined using an optimization methodology based on probabilistic principles for generating final prioritized blocks.

The usability test of the result generated by this model was done by Logan City Council managers and Parks Department bushfire experts. The suitability of the blocks was very close to what experts had in their minds and this model results were validated completely satisfactory by them. All of the blocks ranked by the model were according to what they had a practical perception from the field visit and field knowledge.

In overall and in general, the tool created by this study, will help decision makers has a good basis for deciding about long term priorities to plan for controlled burn activities. Decision makers could use this model to have a long term outlook for the budget and resources needed to be allocated to fuel reduction controlled burn practices. This will facilitate short term planning as well.

Keywords: *GIS, Controlled Burn, Multi-Criteria Analysis, Blocks Prioritization*
Advisor: *Ulrik Mårtensson*
Master degree project 30 credits in Geographical Information Sciences, 2015
Department of Physical Geography and Ecosystem Sciences, Lund University. LUMA-GIS thesis nr 38

Appendix 4, Popularized Summary

Alireza Mollasalehi

Controlled Burn in Australia: A GIS based approach for better planning

Bushfire problem is a long-lasting problem which is a big threat and environmental problem in Australia. Planning to control bushfire is very important for Australian Environment. One of the most effective methods to fight bushfire disasters is planning for controlled burns in order to reduce the risk of unwanted bushfire events. In controlled burn, some patches or blocks which are risky to cause threat to environment and humans are selected and burned deliberately under a very safe and controlled condition. This way it is ensured that in real situations the ready-to-burn barks and tree canopy or simply ‘fuel load’ are eliminated from the area.

This research aims to investigate different approaches to build up spatial model to aid decision makers have a rational justifications for planning controlled burns in long term. This includes finding out suitable model for scoring blocks designated as bushfire prescribed burns blocks. The target of this research is to investigate suitability criteria related to prescribed burn management and use them to design a model for analysing spatial suitability for bushfire prescribed burns. In the process of this research, first it is tried to find out how prescribed burn programs work, what characteristics a burn plan has and how different criteria may contribute in forming suitability for performing a prescribed burn. Then a model has been developed for this purpose. The model output is the prioritized blocks based on two main themes of ‘Safety’ and ‘Implementation’. A combination of these two themes has been used in order to generate prioritized blocks. In this output the higher is the rank of a block it means that it has higher priority to be burn first in long term planning.

The model was tested in Logan City area in South East Queensland Australia. Finally the outcome showed a good agreement between planners suitability choice which was based on field visits and the prioritized blocks generated by model. This agreement was investigated gathering different decision makers’ opinions regarding different blocks and comparing it with the actual model outcome.

In overall and in general, the tool created by this study, will help decision makers has a good basis for deciding about long term priorities to plan for controlled burn activities. Decision makers could use this model to have a long term outlook for the budget and resources needed to be allocated to fuel reduction controlled burn practices. This will facilitate short term planning as well.

Keywords: *GIS, Controlled Burn, Multi-Criteria Analysis, Blocks Prioritization*
Advisor: *Ulrik Mårtensson*
Master degree project 30 credits in Geographical Information Sciences, 2015
Original title: GIS Based Modelling for Fuel Reduction Using Controlled Burn in Australia
Department of Physical Geography and Ecosystem Sciences, Lund University. LUMA-GIS thesis nr 38

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