Risk Implications of Dynamic Fire Propagation

A case study of the Ginninderry region

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Prepared for:
Ginninderra Falls Association

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Contents

Executive Summary ... 2
About the author: ... 3
1. Introduction ... 4
   1.1. Assessing bushfire risk ... 6
      1.1.1. Fire danger rating systems and indices ... 6
      1.1.2. Australian Standard (AS 3959) and Building Attack Levels ... 7
      1.1.3. Asset protection zones ... 8
2. Recent advances in bushfire risk analysis ... 9
   2.1. Effect of slope ... 9
   2.2. Dynamic fire propagation ... 10
      2.2.1. Eruptive fire behaviour ... 10
      2.2.2. Vorticity-driven lateral spread ... 11
      2.2.3. Mass spotting and spot fire coalescence ... 13
   2.3. Violent pyroconvection and pyrogenic winds ... 13
   2.4. Putting research into practice ... 14
3. Reflections on the Standard (AS 3959) ... 15
   3.1. Dynamic fire propagation ... 15
   3.2. Slope effects ... 17
   3.3. Distance from vegetation ... 17
   3.4. Direct flame contact ... 17
   3.5. Ember attack ... 18
   3.6. Pyrogenic winds ... 19
4. Ginninderry: a case study in bushfire risk ... 20
   4.1. Assessment of slope ... 20
   4.2. Likelihood of dynamic fire propagation ... 21
      4.2.1. VLS occurrence ... 21
      4.2.2. Eruptive fire behaviour ... 22
      4.2.3. Impacts of embers ... 24
5. Concluding remarks ... 25
References ... 26

Executive Summary

This report addresses the issue of bushfire risk assessment of the lands to the west of the district of Belconnen in the Australian Capital Territory. In particular, it considers the risk implications arising from some of the latest advances in the science of dynamic bushfire propagation and extreme fire development.

It provides a critical scientific review of the existing standards and methodologies that are employed in bushfire risk assessment. The review focuses specifically on the fire behavioural aspects of the current guidelines for construction in bushfire prone areas – building design and construction aspects are considered out of scope for this report.

The review highlights a number of areas where the standards and methodologies currently employed as best practice in bushfire risk assessment do not adequately acknowledge recent insights into dynamic fire propagation. The review only considers those fire behavioural insights that have been backed up by peer-reviewed scientific publications. Indeed, an overarching aim of this report is to emphasise the need for best practice in bushfire risk assessment to be underpinned by rigorous and well-established science.

The findings of the review indicate that what is currently considered best practice in the development of bushfire management strategies, may significantly under-estimate the risk of bushfire under extreme fire danger conditions. This is particularly true when applied to regions with steep slopes like that considered in this report. Moreover, the findings raise a number of questions about the adequacy of bushfire protection measures, such as building standards and asset protection zones advocated in existing statutory guidelines.

Jason Sharples, 1st June 2017.

About the author:

Dr Jason Sharples is a bushfire scientist and Associate Professor of Applied Mathematics in the School of Physical, Environmental and Mathematical Sciences (PEMS) at UNSW Canberra.

As part of the Applied and Industrial Mathematics Research Group, Dr Sharples has spent many years conducting intensive research into bushfires and combustion processes. His areas of interest include multistep combustion modelling, fire weather analysis, risk management methodologies, synergies between rural and urban (structural) firefighting, numerical simulation of wildfires, and analysis of processes driving extreme wildfire development.

He has collaborated extensively with researchers at the University of Manchester, the University of Coimbra, Portugal, the Russian Academy of Science and various Australian and New Zealand bushfire and structural firefighting researchers and organisations, including CSIRO, University of Melbourne, University of Wollongong, the Bureau of Meteorology, New South Wales Rural Fire Service and ACT Emergency Services Agency.

Throughout his career he has received numerous grants and awards including being chosen as a finalist for Australian Museum's Eureka Prize for Environmental Research for research into dynamic fire spread, which focused on the 2003 bushfires in Canberra and NSW.

Dr Sharples currently holds two Australian Research Council (ARC) Discovery Indigenous Grants that focus on dynamic wildfire propagation. He is also Project Leader for the Bushfire and Natural Hazards Cooperative Research Centre (BNHCRC) project 'Fire coalescence and mass spotfire dynamics', which forms part of the 'Next Generation Fire Modelling' theme within the BNHCRC research program. In addition, Dr Sharples was an expert witness at the 2014 Coronial Inquiry into the Wambelong Campground Fire,

Dr Sharples has also been a volunteer firefighter with the ACT Rural Fire Service since 2003.

1. Introduction

Bushfire is a well-established part of Australia's natural environment. Historically, bushfires have sporadically, but consistently, resulted in significant environmental and socio-cultural impacts. In particular, over the last few decades, major bushfires have impacted the ex-urban margins of Sydney, Canberra, and Melbourne, burning more than a million hectares of forests and woodlands and causing devastating loss of life and property. It total, there have been over 200 lives and 4000 homes lost. Other bushfire-related losses include cultural assets (e.g. historic sites), scientific facilities (e.g. astronomical observatories), important infrastructure (e.g. power lines and substations), and the often severe and long-lasting psychological stress suffered by firefighters and members of the public.

The losses caused by large bushfires over the last decade or so have prompted questions about the changing nature of bushfire events and how they impact densely populated areas. In particular, concern is centred on the occurrence or perception of a shift to a significantly more hazardous fire regime, characterised by increasing fire frequency and intensity associated with dynamic fire propagation, and the development of catastrophic 'firestorms' . Given the likely effects of climate change, the expectation is that large destructive fires will become more prevalent in the future (Sharples et al. 2016). This trend, combined with the increasing expansion of urban centres into wildland areas, will present an increasingly challenging problem to land managers and fire agencies.

In order to ameliorate the impacts caused by large bushfires, a number of protective measures have been developed and implemented. These include: enhanced hazard reduction programs (e.g. prescribed burning), revised public warning systems, and improved building design and construction guidelines combined with better informed urban planning. Bushfire science plays a key role in informing these measures and ensuring that they represent best practice. However, given the nature of the scientific process and the difficulties associated with altering statutory regulations, there is often a lag between what is accepted as best practice in bushfire risk management and the state of the science.

This report provides a critical review of the guidelines that define current best practice in assessing the risk of bushfire. In particular, it considers the current Standards for construction of buildings in bushfire prone areas as they relate to the proposed rezoning of land to the west of Belconnen, a district in the Australian Capital Territory, and adjoining land in the Yass Valley of New South Wales (see Figure 1). We refer to this subject land as the Ginninderry region. The purpose of the rezoning is to allow development of the land in a joint venture between the ACT Government and private developers. The proposed development aims to ultimately house around 30,000 people, and so to ensure for their safety it is paramount that a comprehensive and accurate bushfire risk assessment is undertaken.

The review incorporates a number of relatively new scientific insights into the way bushfires propagate. Many of these insights were only established on solid scientific grounds after the current guidelines were developed. However, as mentioned above, what is considered best practice should evolve as the science progresses. As such, the critical review provided in this report offers a foundation for revision and improvement of bushfire risk management standards, which extends beyond the specific case study of the Ginninderry region.

The report begins by outlining the concepts underpinning the current guidelines, before providing a summary of the advances in bushfire science that are most relevant to bushfire risk assessment in the Ginninderry region. The report then highlights a number of shortcomings in the existing Standards that have been exposed by recent bushfire research. The report concludes with a re-examination of the bushfire risk to the Ginninderry region, which better incorporates the state of the science.

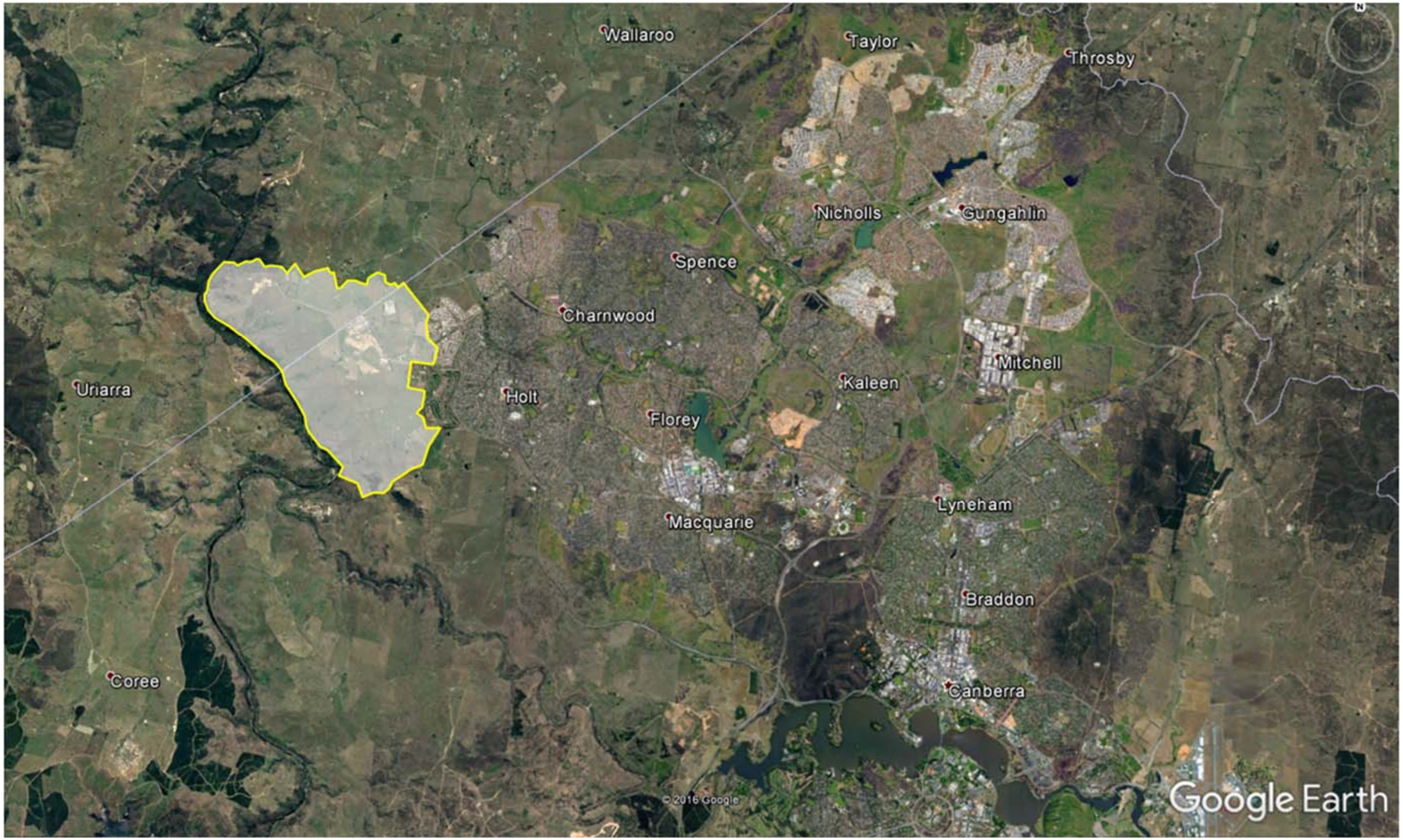

Figure 1: Map of the region around Canberra showing the Ginninderry region that is subject to rezoning.

1.1. Assessing bushfire risk

The overall level of risk posed by bushfire is generally assessed based on the concept of 'Fire Danger'. Fire Danger is the resultant of all factors which determine whether fires will start, spread and do damage, and whether and to what extent they can be controlled. These include tangible effects such as weather and topography, as well as random effects such as arson and lightning strikes. Unfortunately, it is not possible to encapsulate all of the varying aspects of fire danger in a single numerical measure. Instead, Fire Danger Rating Systems (FDRSs) incorporate a range of quantifiable factors to determine levels of preparedness, to issue public warnings and fire bans and to provide an appropriate scale for management, research and law in fire related matters. Typically, Fire Danger Rating Systems produce a numerical index, known as a Fire Danger Index, which relates to the level of fire danger.

1.1.1. Fire danger rating systems and indices

Many FDRSs have been developed around the world, mainly in North America and Australia. However, in the current context, the McArthur Mark 5 Forest Fire Danger Meter is the most relevant as it was developed for use in the forested landscapes of southeastern Australia (McArthur, 1967). The Mark 5 Forest Fire Danger Meter permits calculation of the Mark 5 Forest Fire Danger Index (FFDI), which reflects the expected severity of fire behaviour, quantified as rate of spread or intensity.

The FFDI can be expressed as the following mathematical formula, which incorporates air temperature T (°C), relative humidity H (%), mean wind speed at 10m U (km h^{-1}), and the drought factor D, which is a measure of fuel availability (Noble et al., 1980):

$$FFDI = 2\exp(-0.45 + 0.987\ln(D) - 0.0345H + 0.0338T + 0.0234U)\,. \quad (1)$$

The FFDI was developed based on observations of small experimental fires augmented by information from wildfires. In particular, the conditions associated with the 1939 'Black Friday' bushfires in Victoria were taken to correspond to an FFDI of 100. In its original inception, FFDI = 100 was defined as the upper limit, though FFDI has exceeded 100 a number of times in the last few decades.

The FFDI was specifically designed to provide a numerical value proportional to the expected rate of spread of a head fire. Given the FFDI, the expected rate of spread R (km h^{-1}) of a head fire burning in a fuel load of W (t ha^{-1}) on terrain with a topographic slope S (°), is given by

$$R = 0.0012\,W\,FFDI\,\exp(0.069S)\,. \quad (2)$$

It should be noted that McArthur only advocated the use of equation (2) for slopes below 20°; more will be said about this point in later sections. The FFDI can also be used to derive additional fire behaviour characteristics such as flame height and the distance at which spot fires can be expected to form ahead of the main fire front.

It is important to understand that equations (1) and (2) embody the specific modelling assumption that a fire burning under unchanging environmental conditions can be characterised by a quasi-equilibrium rate of spread. Specifically, it is assumed that for a particular set of input values (temperature, relative humidity, wind speed, etc.) a fire will exhibit a rate of spread that is approximately constant, or *quasi-steady*, with the approximate rate of spread provided by equations (1) and (2). We will refer to this assumption as the *quasi-steady assumption*. While there are many situations where the quasi-steady assumption is valid, research has identified a number of cases where fires can behave in ways that are manifestly at odds with the quasi-steady assumption. The inference is that for such cases, the guidance provided by equations (1) and (2) should be viewed with a much higher degree of uncertainty.

Indeed, the series of large fires experienced in southeastern Australia over the last few decades have shown time and again that the current suite of operational models (all of which are based on the quasi-steady assumption) perform relatively poorly under extreme conditions (e.g. Bushfire CRC, 2009; Cruz et al., 2012).

1.1.2. Australian Standard (AS 3959) and Building Attack Levels

The Australian Standard for construction of buildings in bushfire-prone areas (AS 3959) specifies requirements in order to improve the resilience of buildings against bushfire attack from burning embers, radiant heat, direct flame contact, or a combination of these three factors (Standards Australia, 2011). As such it provides a framework designed to ameliorate the risk of bushfire through better design and construction of buildings. For brevity we will refer to the Australian Standard as 'AS 3959' or simply as 'the Standard'.

AS 3959 informs the design and construction of buildings in bushfire-prone areas through the concept of Bushfire Attack Level (BAL). In principle, BAL can be determined through application of the Standard to any site in the landscape, thereby providing the appropriate design and construction measures required to reduce the risk of bushfire igniting a building situated at the site.

The calculation of BAL at a site relies on the following four main factors:

- Fire danger index (in the present context this is provided by FFDI);
- Vegetation type;
- Distance of the site from the classified vegetation;
- The topographic slope on which the vegetation is situated.

The fire danger index is used on a regional basis as a proxy for flame temperature, and for calculation of flame length and fire line intensity, all of which then determine the level of radiant heat impacting a structure. In the present context an FFDI of 80 (NSW) or 100 (ACT) is used. It should be noted that under the McArthur Mark 5 Forest Fire Danger Rating System a FFDI of 100 is categorised as 'Catastrophic' while a FFDI of 80 is categorised as 'Extreme'. More will be said on this point in later sections.

The vegetation type, in which a fire is burning, influences several fire behaviour characteristics including rate of spread and flame length. Implementation of the Standard requires that vegetation is categorised into one of six broad vegetation classes. The type of classified vegetation is then combined with information on fuel loads to determine expected rate of spread, fire line intensity and flame length. These fire behaviour characteristics are then used to estimate the radiant heat flux presented by the flames.

The distance between the site and the classified vegetation is used to calculate the radiation view factor as well as the atmospheric transmissivity of the radiant heat. These quantities are combined to calculate the level of radiant heat exposure of the site.

The topographic slope S of the terrain on which the classified vegetation is situated is used (via equation (2), for example) to determine the expected rate of spread of the fire, which as mentioned above is used to estimate the radiant heat flux. This effective slope is not to be confused with the slope of the terrain that lies between the vegetation and the site, which is used only in the calculation of the radiation view factor.

BAL categories are defined in Table 3.1 of AS 3959 in terms of radiative heat exposure thresholds. Table 3.1 also provides a brief description of the level of ember attack that could be expected in accordance with each of the BAL categories. In summary these are as follows:

- BAL-LOW: No mention of ember attack in Table 3.1;
- BAL-12.5: Table 3.1 simply states 'Ember attack' without any further quantification of ember intensity;

- BAL-19, BAL-29 and BAL-40: Table 3.1 states ‘Increasing levels of ember attack and burning debris ignited by windborne embers...’;
- BAL-FZ: Table 3.1 states that the structure will experience ‘Direct exposure to flames [...] and ember attack’. Again, no further specific information is provided on the ember intensities that might be expected.

Overall, Table 3.1 seems to imply that the threat to a structure from ember attack is related to the radiant heat exposure of the structure. However, the nature of this relationship is unclear; other than the loose implication that an increase in radiant heat exposure should result in an increase in the chance of ember attack, there is no specific information on how ember attack is related to radiant heat exposure. Indeed, there does not appear to be any peer-reviewed literature (or any literature of which the author is aware) that supports this implication, and it is easy to conceive of situations where ember intensity and radiant heat exposure are not strongly related. More will be said on this point in later sections.

1.1.3. Asset protection zones

In order to allow for more effective defence of properties from bushfire attack, development in bushfire-prone areas requires the provision of a set-back distance or buffer, known as an Asset Protection Zone (APZ), between vegetation and built assets. According to the NSW RFS guidelines for planning for bushfire protection (NSW RFS, 2006), an APZ is intended “to provide sufficient space and maintain reduced fuel loads, so as to ensure radiant heat levels at buildings are below critical limits and to prevent direct flame contact with a building”. An APZ ensures that built assets are separated from the bushfire hazard (i.e. the vegetation), thereby minimising the impact of radiant heat, and the likelihood of direct flame contact and ember attack. An APZ also provides a region from which firefighters can work more safely and effectively to suppress fire.

The definition of appropriate APZs relies heavily on the concept of BAL (NSW RFS, 2006). In particular, APZs are based on classification of the predominant vegetation within a 140m radius, effective slope under the classified vegetation, and 1 in 50 year fire weather (FFDI) scenarios. Basically, APZs roughly coincide with the distances associated with the BAL–29 category in AS 3959.

2. Recent advances in bushfire risk analysis

As mentioned above, the traditional approach to bushfire research focused on determining an expected rate of fire spread for a given set of environmental conditions. This approach to predicting bushfire spread amounts to finding a particular mathematical function that takes a set of appropriate environmental variables as inputs and delivers an expected rate of spread as the output. Equations (1) and (2) serve as examples in this context. Unfortunately, however, this approach is of limited validity, particularly when it comes to understanding the local drivers of bushfire risk and the broader development of large, destructive bushfires.

Recent research into bushfire risk has gone beyond the traditional (quasi-steady) research paradigm. Indeed, a new paradigm that acknowledges the dynamic nature of fire spread in the landscape has emerged over the last decade or so. This new approach has already provided a number of important insights into the local drivers of bushfire risk, and has highlighted the role of environmental factors that are significant for large fire development. These factors include aspects of the vertical structure of the atmosphere (Mills and McCaw, 2010), meso-scale fire weather processes (Peace et al., 2012), modifications of fire weather conditions by the local topography (Sharples, 2009; Sharples et al., 2012) and interactions between the fire and the atmosphere (Simpson et al., 2013; 2016).

In particular, a number of processes that can contribute significantly to the level of risk posed by a bushfire have been identified. These include:

- Extreme fire weather processes;
- Dynamic fire propagation;
- Violent pyroconvection and pyrogenic winds.

In addition, research has shown that some of the long-held concepts that underpin the way we assess bushfire risk are in error.

2.1. Effect of slope

While it is well known that topographic slope affects the rate at which a fire spreads, the way that slope is often accounted for in rate of spread calculations is over-simplistic. For example, in the Standard (Standards Australia, 2009; p85) it is stated that the forward rate of spread of a fire (R) must be corrected for the effective slope (S) using the equations:

$$R_{\text{slope}} = R\exp(0.069S) \quad \text{for 'downslope'}, \tag{3}$$

$$R_{\text{slope}} = R\exp(-0.069S) \quad \text{for 'upslope'}. \tag{4}$$

Note that, somewhat confusingly, the Standard uses the term ‘downslope’ to describe the situation where a fire is propagating upslope towards an asset, and uses the term ‘upslope’ to describe the situation where a fire is propagating downslope towards an asset; see Figure 2.2 in AS 3959. In what follows we will describe a fire propagating up a slope as experiencing a positive slope, while a fire propagating down a slope will be described as experiencing a negative slope.

Essentially, equations (3) and (4) embody the *rule of thumb* that a fire’s rate of spread will double for every 10° of additional positive slope it encounters (McArthur, 1967), and will halve for every 10° of negative slope it encounters. McArthur (1967) only advocated the use of equation (3) for slopes between 0° and 20° - this is likely the reason that the Standard only considers slopes up to 18°. McArthur does not appear to have advocated the use of equation (4). Instead, equation (4) appears to have been adopted out of a combination of loose reasoning and convenience.

Sullivan et al. (2014) considered fire spread on negative slopes and demonstrated that equation (4) can significantly under-predict the rate of spread of a fire burning on a negative slope. For example, on a slope of -20°, equation (4) under-predicts rate of spread by about a factor of three; on a slope of

-30° equation (4) under-predicts by a factor of six. In fact, Sullivan et al. (2014) advocate that for negative slopes, rates of spread should never be taken as less than 60% of the zero-slope rate of spread. By contrast, equation (4) implies that rate of spread should approach zero on steep negative slopes.

For fires burning on positive slopes above 20° the notion of a quasi-equilibrium rate of spread becomes problematic. On such slopes, the interaction of the wind and topographic aspect can cause the fire's plume to behave in ways that can have significant implications for how heat is transferred from the burning zone into unburnt fuels. In such circumstances, the fire may not achieve a quasi-equilibrium rate of spread; rather the fire spread becomes distinctly dynamic in nature. More will be said about this in the next section.

2.2. Dynamic fire propagation

Dynamic fire propagation arises from complex interactions between the terrain, the atmosphere and the fire. It can produce effects that cannot be predicted by current operational fire spread models. Moreover, dynamic fire propagation is often subject to threshold behaviour, which means that slight changes in environmental conditions can result in substantial changes in fire behaviour.

2.2.1. Eruptive fire behaviour

Fires burning in steep and confined terrain have been shown to exhibit exponential increases in rate of spread, despite burning under unchanging environmental conditions (Viegas, 2005; Dold and Zinoviev, 2009). This phenomenon has been termed *eruptive fire spread* or *fire eruption.*

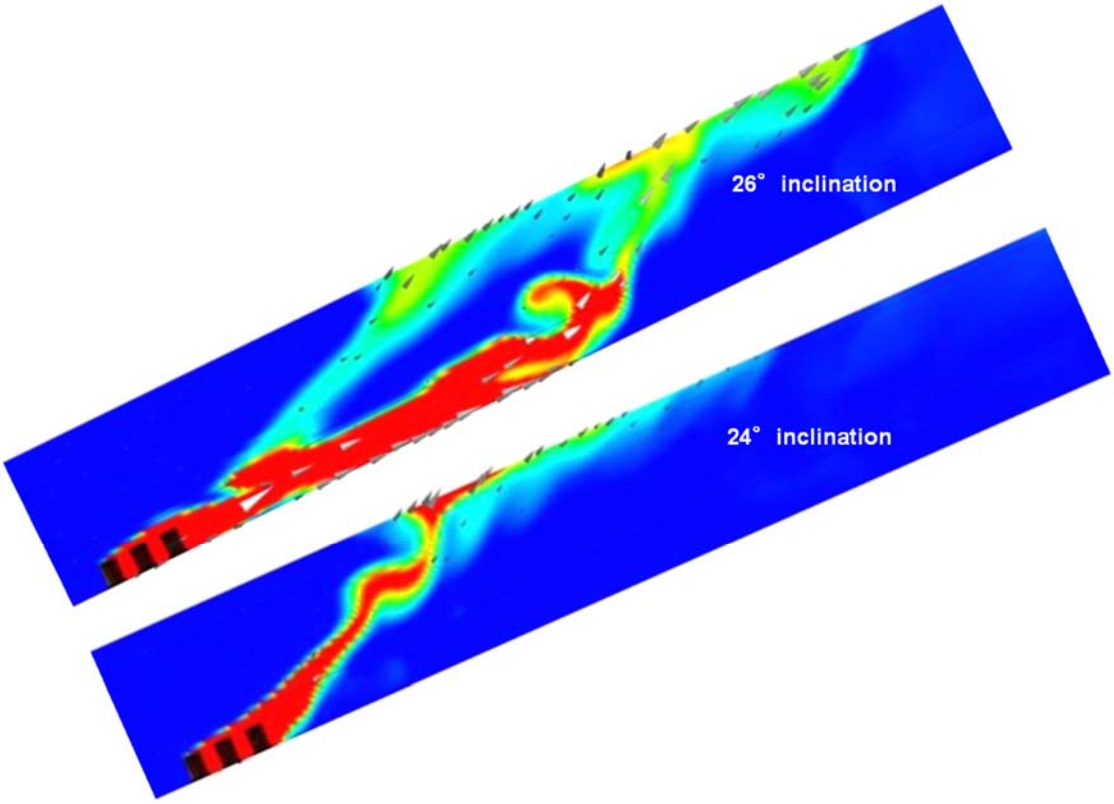

Figure 2: Computational Fluid Dynamics simulation of plume behaviour over inclined surfaces. The plume is indicated by the colour shading, which represents air temperature (red = hot, blue = cold). Convective plumes emanating from surfaces inclined at 24° (bottom) and 26° (top) are shown.

Eruptive fire spread arises due to an interaction between the slope of the terrain and the fire's plume. For shallow slopes a fire's plume will rise into the air, but when slopes become sufficiently steep, a localised pressure deficit can form immediately upslope, ahead of the fire. This pressure deficit can cause the flames and plume to attach to the terrain surface. Flame or plume attachment leads to enhanced preheating of fuels upslope, ahead of the fire and resultant acceleration of the fire spread. Numerical and laboratory experimentation has shown that in the absence of wind, plume attachment can be expected on terrain that is inclined at roughly 24° or more. The particular geometry of the terrain will cause some variation about this threshold value, and the effects of wind could cause plume attachment on slopes inclined at angles of 24° or lower.

Figure 2 shows the results of Computational Fluid Dynamics (CFD) simulations of the behaviour of a hot, buoyant plume above surfaces inclined at different angles. The figure shows that for the surface inclined at 24° the plume separates from the surface and rises to the top of the domain. However, for the surface inclined at 26° the plume attaches to the surfaces for a considerable distance above the source of the plume.

Although the heat source present in the CFD analysis depicted in Figure 2 does not faithfully represent a fire, a similar effect should be expected in the case of a real fire. As mentioned, this effect has important implications for the way heat is transferred into unburnt fuels ahead of a fire front. If a plume attaches to a surface then fire spread will be dominated by convective heat transfer rather than radiant heat transfer.

Moreover, the acceleration of the head fire in eruptive fire occurrences results in a deepening of the flaming zone; that is, it produces a larger area of active flame, from which heat is released into the atmosphere. This mode of fire propagation is completely contrary to that expected under the quasi-steady fire spread paradigm, and has been associated with several firefighter fatalities (Viegas, 2009). Even in cases where lives are not lost, it is clear that eruptive fire behaviour poses a serious threat to the successful containment of a bushfire and provides a mechanism that can substantially elevate the risk posed by a bushfire in areas that are prone to its occurrence.

Eruptive fire spread also has implications for prescribing appropriate APZs. Flame attachment can pose a significant safety risk to fire crews and the fact that flames bathe the surface during eruptive fire events means that firefighters could be exposed to intense convective heat fluxes, which are not accounted for in the BAL calculations that underpin APZ requirements.

2.2.2. Vorticity-driven lateral spread

Analyses of fire propagation during the 2003 Canberra fires revealed the existence of an atypical mode of fire spread (Sharples et al., 2012). This mode of fire spread is characterised by:

- Rapid lateral spread of a fire across a lee-facing slope in a direction that is nearly perpendicular to the prevailing winds – see Figure 3;
- Fire spread constrained on the upwind edge by a significant break in topographic slope;
- Dense spotting and downwind extension of the flaming zone (for up to several kilometres);
- Dark, turbulent smoke (with cumuliform appearance) on the advancing flank – see Figure 4.

Simpson et al. (2013) found that the key driver of this phenomenon was the generation of *pyrogenic vorticity*; that is, the interaction of the winds, the terrain and the fire causes the generation of significant fire whirls on lee-facing slopes, which carry the fire laterally. Hence the terminology: vorticity-driven lateral spread (VLS). The existence of the VLS phenomenon has also been confirmed in a series of laboratory experiments conducted in Portugal (Sharples et al., 2010; Raposo et al. 2015) and the USA, and in numerous post-2003 wildfire observations (e.g. Quill and Sharples, 2015).

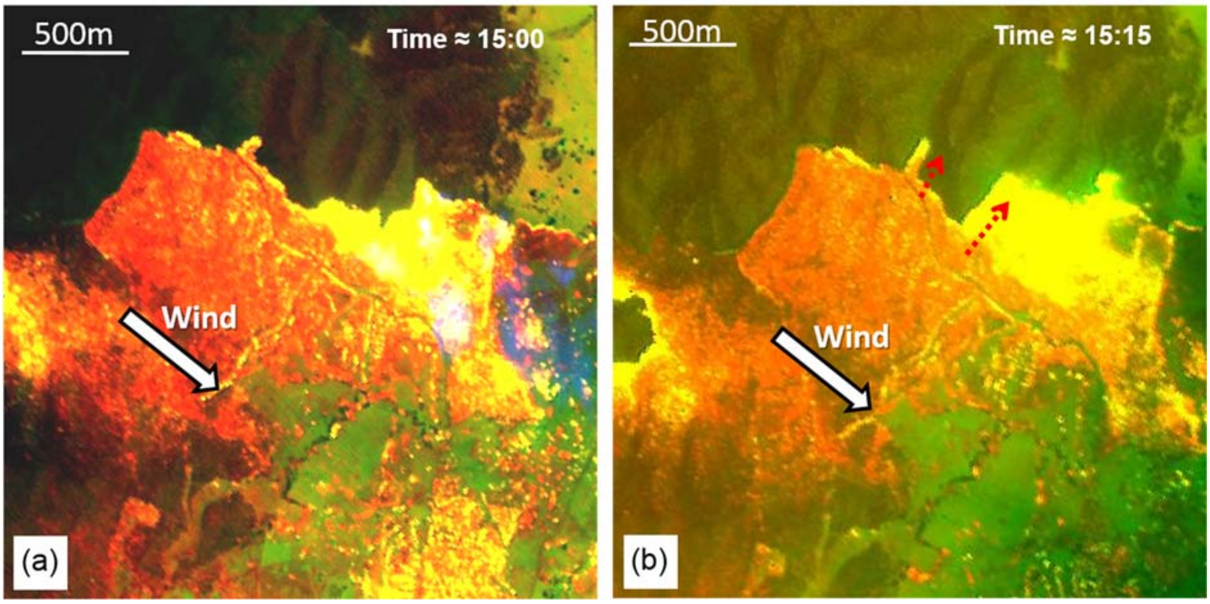

Figure 3: Multispectral linescan imagery of VLS during the McIntyres Hut Fire (Pig Hill), west of Canberra, 18 Jan 2003: (a) Fire at 15:00 approximately; (b) Fire at 15:15 approximately. The red arrows in (b) show the regions of lateral spread. Note the region of deep flaming (bright yellow) downwind of the lateral spread. Some lateral spotting is also evident.

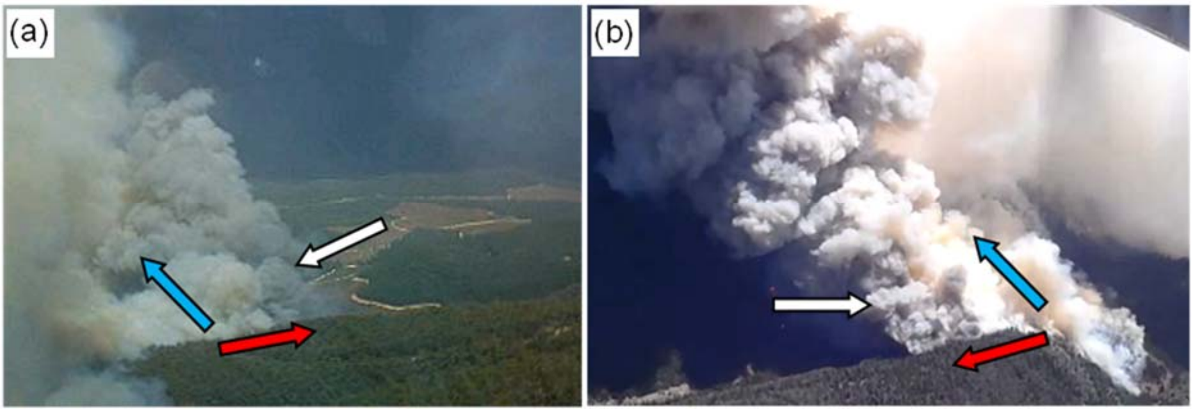

Figure 4: Photographs of VLS events in the landscape: (a) McIntyre's Hut Fire (Blue Range), NSW, Jan 2003 (Photo: Stephen Wilkes); (b) Fontenelle Fire, Wyoming, Jun 2012 (Youtube, 2012). In each photograph the blue arrow shows the prevailing wind direction (as indicated by the main orientation of the smoke plume), the red arrow shows the direction of fire spread across the lee-facing slope, and the white arrow highlights the darker smoke on the advancing flank, which is characteristic of VLS.

Recent research has confirmed that the VLS phenomenon is subject to a number of environmental thresholds (Simpson et al., 2016). That is to say that VLS can only be expected to occur on parts of the landscape, and under fire weather conditions, that meet certain necessary conditions. In particular, VLS occurrence depends critically on the following:

1. Steepness of the leeward slope – slopes greater than 20-25° are required;
2. Aspect of the leeward slope in relation to the wind direction – wind direction must be within 30-40° of the topographic aspect;
3. Wind speed – winds in excess of about 20 km h^{-1} are required;
4. Fuel type and load – generally VLS is only observed in heavy forest fuel types with load in excess of 15-20 t ha^{-1};

5. Fuel moisture content – dense spotting and downwind extension of the flaming zone are far more likely when fuel moisture contents are around 5% or less.

The above environmental thresholds relate either to the likelihood of the ambient wind flow separating over the leeward slope and forming a lee eddy, or to the likelihood of an intense fire on the leeward slope. VLS occurrence requires ambient vorticity in the form of a lee eddy and a fire plume of sufficient intensity in comparison to the prevailing winds.

In relation to the likelihood of flow separation and lee eddy formation, the following wind-terrain filter identifies the necessary wind and terrain conditions for VLS occurrence:

$$\chi(S,\alpha,\theta) = \begin{cases} 1 & \text{if } S \geq 20^\circ \text{ and } |\theta - \alpha| \leq 40^\circ \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

Here S is the topographic slope, α is the topographic aspect and θ is the direction the wind is blowing (e.g. for a westerly wind, $\theta = 90°$). In simple terms, the wind-terrain filter identifies parts of the terrain that are both sufficiently steep and sufficiently lee facing

Terrain data are typically derived from an underlying Digital Elevation Model (DEM), which is represented over a grid of a particular spatial resolution. Hence, when assessing the likelihood of VLS occurrence using equation (5), it is important to account for the resolution of the underlying DEM.

For example, when using a 90m resolution DEM as the source of topographic data, the slope threshold of 20° in equation (5) is modified to 16°. This is done to account for the fact that as the resolution of the DEM decreases, the associated topographic slopes will also decrease across the landscape.

2.2.3. Mass spotting and spot fire coalescence

Fire behaviour in dry eucalypt forests in Australia (and in many other vegetation types to a lesser extent) is characterised by the occurrence of spot fires; that is, new fires ignited by the transport of burning debris such as leaves and bark ahead of an existing fire. Under most burning conditions, spot fires play little role in the overall propagation of a fire, except where spread is impeded by breaks in fuel or topography and spot fires allow these impediments to be overcome. However, under extreme conditions, spot fire occurrence can be so prevalent that spotting becomes the dominant propagation mechanism and the fire spreads as a cascade of spot fires forming a ‘pseudo’ front.

The presence of multiple individual fires affects the behaviour and spread of all fires present. The convergence of separate individual fires into larger fires is called coalescence and can lead to rapid increases in fire intensity and spread rate. Fire behaviour in and around convergence zones can be dominated by dynamic feedback processes between the energy released by each fire and the coupling of that energy with the atmosphere. As such, they invalidate the quasi-steady assumption and so their behaviour cannot be described using models like those in equations (1) and (2).

In fact, fire intensities associated with spot fire coalescence can be raised considerably. Dynamic interactions between different parts of the fire and the atmosphere cause the individual fire fronts to accelerate, with a consequent increase in fire line intensity. The increases in intensity caused by spot fire coalescence are not accounted for in AS 3959. In this context it is also of interest to note that dynamic modes of fire propagation such as VLS are highly effective at producing mass spotting events.

2.3. Violent pyroconvection and pyrogenic winds

Under conditions of extreme and dynamic fire behaviour, the large amounts of heat and moisture released from the fire can cause its plume to rise high into the atmosphere – up to several kilometres. If the plume reaches a height above which water vapour condenses into liquid water, the moisture originating from the fire releases its latent heat of condensation. This additional release of heat causes the plume to develop to even higher levels of the atmosphere. At this stage the plume incorporates a large cumulus cloud, and the whole system is referred to as a *pyrocumulus* (pyroCu).

In unstable atmospheric environments, if a fire releases a significant amount of heat and moisture over a relatively short time, the fire's plume can develop beyond the pyroCu stage and transition into a towering pyrocumulus or a *pyrocumulonimbus* (pyroCb) (Fromm et al., 2010). McRae et al. (2015) demonstrated a link between deep flaming events caused by VLS and the formation of pyroCb.

Once a fire develops into a towering pyroCu or pyroCb, it has evolved beyond a purely surface-based phenomenon. It is now a violent pyroconvective system, which takes on many of the characteristics of typical atmospheric storms (Fromm et al. 2006). Moreover, as a fire's plume reaches higher into the atmosphere, larger scale mixing can cause drier and higher-momentum upper air to be transferred back to the surface, thereby further exacerbating the potential for more intense fire behaviour.

It is important to note the similarities between an ember storm originating from a pyroCb and the effects of a typical thunderstorm. Violent pyroconvection can generate strong and unpredictable winds, which can exacerbate fire intensity and enhance ember formation. Pyrogenic winds can also cause considerable damage to structures on their own. It is also important to note the differences: ordinary thunderstorms produce rain and hail, whereas pyroCb's carry dense swarms of embers, fire and other burning debris, with very little rain or hail (although reports of black hail have occurred). McRae et al. (2012) reported that the pyroCb which formed during the 2003 Canberra fires actually spawned an F2 tornado.

2.4. Putting research into practice

Many of the new insights into extreme and dynamic bushfire propagation and extreme fire development described above have yet to be incorporated into standardised bushfire risk assessment. The scientific process takes time to establish findings with enough rigour to allow them to be considered as facts. This process requires establishment of research programs, collection of the appropriate data sets, doing the actual research, writing papers and communicating the research in various ways, and engaging in the peer-review process, which can be lengthy in itself. Each of these steps is necessary to ensure the quality and dependability of scientific findings.

Once the science has been appropriately established, the next step is to transfer the research findings to the practitioners that will benefit from using them. This is also a challenging and time consuming undertaking. New findings are often couched in very technical terms, which may not be easily understood by fire practitioners, risk analysts and other operational personnel with various levels of technical literacy. Moreover, many of the new findings on extreme fire development are counter-intuitive, which can make practitioners reluctant to adopt them in favour of the traditional tools they have greater familiarity with. Ultimately, before new findings are formally incorporated into standardised frameworks (e.g. AS 3959) they must be subject to appropriate advisory oversight. Unfortunately this means that best practice will often lag behind the state of the science.

3. Reflections on the Standard (AS 3959)

In this section we reflect upon the methodology of AS 3959 from a perspective that incorporates the current state of the science on dynamic fire propagation and extreme bushfire development, which was discussed in the previous section.

3.1. Dynamic fire propagation

As described above, the guidelines formalised in AS 3959 are entirely predicated on the assumption that fires propagate at a quasi-steady rate of spread. For example, for situations involving vegetation classified as 'forest', the radiant heat flux thresholds that define the BAL classification are based on equations (1) and (2), which posit that a given set of environmental conditions uniquely determines a quasi-equilibrium rate of spread. Research has shown that this is not always the case.

Moreover, research has indicated that escalation of fires to their most catastrophic state is associated with dynamic modes of fire propagation, which act in direct violation of the quasi-steady assumption. As such it could be argued that the Standard does not consider the factors that produce the types of fire behaviour with the greatest potential of causing damage.

The Standard considers FFDI thresholds of 80 or 100, depending on the region under consideration, which are indicative of 1 in 50 year fire weather events. As noted by the Standard, FFDI values of such magnitudes require winds speeds of approximately 45 km h^{-1} or greater. However, dynamic modes of fire propagation such as VLS or eruptive fire spread can be expected to occur under much more benign conditions. For example, the environmental thresholds for VLS occurrence discussed in Section 2.2.2. can be breached with fire weather conditions corresponding to FFDI values of around 35-40, which are less than half the values espoused in AS 3959, and only require winds of about 25 km h^{-1}. Similarly, eruptive fire behaviour can occur under conditions of very slight or no wind.

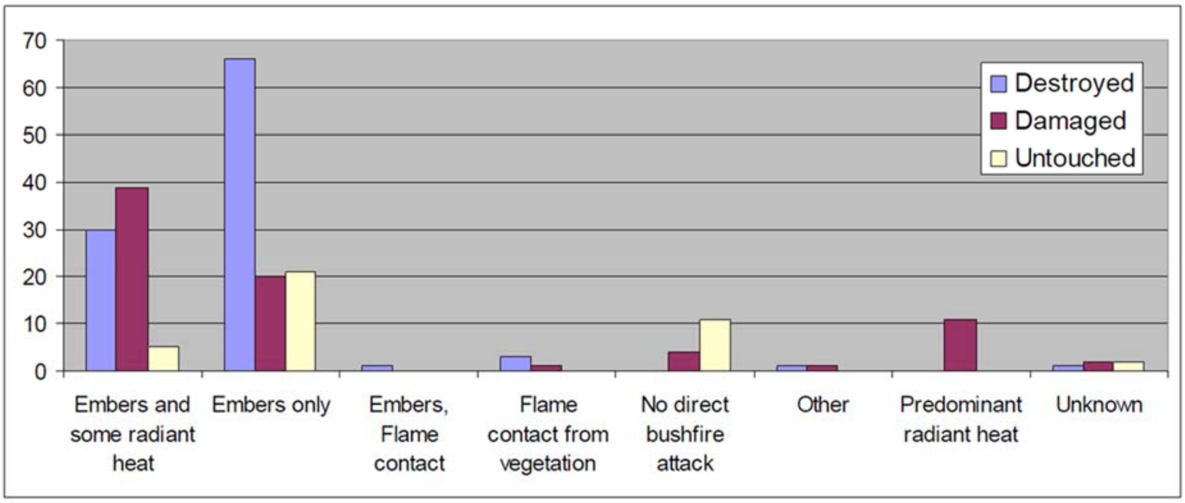

Figure 5: Causes of house loss/damage in Duffy during the 2003 Canberra fires. Figure taken from Leonard and Blanchi (2005).

It is also of interest to note the recommendations associated with FFDI values of 100 ('Catastrophic') and 80 ('Extreme'). According to the post-2009 Forest Fire Danger Rating System, under 'Catastrophic' conditions 'thousands of embers will be blown around' and 'spot fires will move quickly and come from many directions up to 20km ahead of the fire'. The same can be expected under 'Extreme' conditions, except that spot fires are only expected to form up to 6 km ahead of the fire. The indication here is that fire behaviour associated with such high levels of FFDI would be highly dynamic in nature.

Also as mentioned above, the Standard is predicated on the notion that radiant heat exposure is the main determinant of house loss. This notion is contradicted by the findings of a study into bushfire attack mechanisms resulting in house loss in the suburb of Duffy during the 2003 Canberra fires (Leonard and Blanchi, 2005). Indeed, Leonard and Blanchi (2005; Figure 8), reproduced here as Figure 5, indicates that radiant heat accounted for only a small proportion of house damage. In fact, Leonard and Blanchi (2005) state emphatically that there was no evidence of direct radiation attack from the flame front resulting in house loss in Duffy. The house damage that could be attributed to radiant heat flux was found to be caused by radiant heat originating from neighbouring houses, which had already been set alight by other bushfire attack mechanisms.

The fire that impacted the suburb of Duffy did not fit the typical pattern of fire spread. While fires typically spread as a well-defined, contiguous front that distinguishes burnt from unburnt ground, the fire that impacted Duffy was of quite a different nature. Indeed, the fire that impacted the western suburbs of Canberra in 2003 propagated as a full blown ember storm associated with a large pyroCb event. The Standard in its current form does not account for fires of such a nature. In this respect, it is of interest to note that the Ginninderry area is only about 15km from Duffy, and also on the western fringe of suburbia.

The plume or flame attachment associated with eruptive fire spread also raises some questions about the general suitability of using radiant heat exposure thresholds to determine bushfire attack levels. In AS 3959 radiant heat exposure is based on the assumption that flames will be configured in a way similar to the black outlined flames in Figure 6; that is, separated from the surface. This assumption is justified since flame attachment would not be expected on slopes below 20°, which are what is considered in the Standard.

However, as mentioned in the previous section, research has shown that flames can attach to steep slopes in a way similar to that depicted by the orange and yellow flames in Figure 6. In such a circumstance, convective heat flux would dominate radiant heat flux. This is of significance because with exposure to a radiant heat flux only, it is still possible for the building components to cool convectively. On the other hand, convective heat flux immerses the building components in super-heated air, so that convective cooling cannot occur. So while AS 3959 does assess the potential for flames to contact a built asset by assuming that the flames follow the slope of the site (consistent with flame attachment) it is not clear if the differences in convective and radiative heat fluxes are accounted for. The indication is that the dynamic increase in fire intensity associated with flame attachment is not adequately accounted for in the methodology espoused in AS 3959.

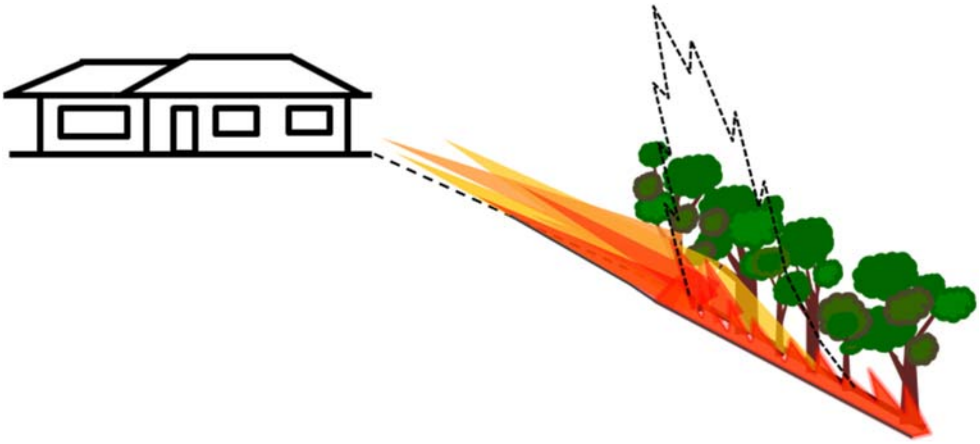

Figure 6: Schematic diagram of a fire burning up a positive slope towards a house. The orange and yellow flames represent the case of eruptive fire spread, in which the flames have attached to the surface. The black outlined flames represent the case of a separated plume, which is the situation depicted in AS 3959.

3.2. Slope effects

We have just discussed the fact that AS 3959 only considers positive slopes below 20°, and how this excludes consideration of phenomena such as eruptive fire spread. In addition, the restricted consideration of slope in AS 3959 results in a number of other shortcomings.

The Standard considers fires as burning either ‘upslope’ or ‘downslope’. We note again that the terms ‘upslope’ and ‘downslope’ in AS 3959 differ from the way they are usually used with respect to fire spread. For example, the situation depicted in Figure 7 is referred to as ‘upslope’ in AS 3959. From the perspective of the Standard, ‘downslope’ fires pose a greater threat than ‘upslope’ fires. However, Figure 7 shows a situation where an ‘upslope’ fire spread scenario could pose a significantly greater threat than a corresponding ‘downslope’ scenario. In this figure, the winds have separated from the surface on the leeward side of a ridge. As discussed in Section 2.2.2. this is a precursor condition for VLS occurrence, which if it were to occur would result in a high intensity fire and an increase in ember intensity immediately upwind from the house.

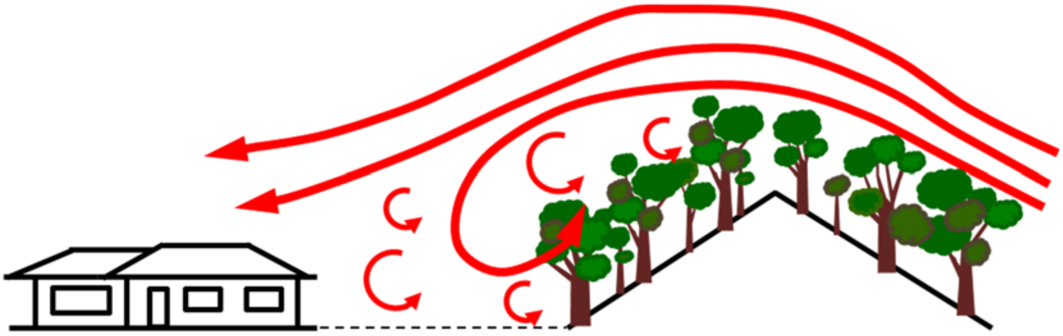

Figure 7: A situation that would be assessed as an ‘upslope’ effective slope in AS 3959. However, in this situation the winds (red arrows) over the ‘upslope’ effective slope have separated from the surface and have formed a lee eddy.

Moreover, the Standard stipulates that rate of spread of negative slopes is modified using equation (4), which we have noted can significantly under-predict rate of spread. This has implications for calculation of fire line intensity, which in turn is used to derive flame length and radiant heat exposure. More will be said on this point in later sections.

3.3. Distance from vegetation

The distance between a site and the classified vegetation is used in the Standard to calculate radiation view factor and atmospheric transmissivity, both of which act to attenuate radiant heat exposure. According to AS 3959, a site that is more than 100m distant from vegetation is classified as BAL-LOW (no construction requirements). However, Chen and McAneney (2004) report that in the 2003 Canberra fires the majority of homes in Duffy were lost beyond a separation distance of 40m. In Duffy no homes lay closer than 37m to the nearest edge of the forest, and homes were lost at a maximum distance of 674m from the forest edge. In fact, 50% of the houses lost in Duffy were more than 100m away from the forest edge (Chen and McAneney, 2004).

3.4. Direct flame contact

While the effect of direct flame contact is acknowledged in AS 3959, it is done so through consideration of whether flame length is sufficient for flames to contact built assets (Midgely and Tan, 2006) and through the BAL–FZ classification, which characterises flame contact as an equivalent radiant heat flux exposure threshold of more than 40 kWm^{-2}. However, building components, particularly those with high surface area to volume ratios, can cool convectively even while subject to a considerable radiant heat flux. On the other hand, direct flame contact involves a convective heat flux that does not permit convective cooling to occur. Again, it is not clear if these more subtle effects are accounted for in the standard, but the appearance is that they are not.

Furthermore, AS 3959 does not appear to adequately account for situations where wind-blown embers, which perhaps originate from vegetation more than 100m away from the site, set fire to vegetation that would otherwise be considered low threat (i.e. corresponding to a BAL-LOW classification). Figure 8 shows an example of this occurring during the 2016 Fort McMurray fire in Canada. Although, this situation does not strictly comply with the fuel types accommodated in AS 3959, it is clearly conceivable that similar situations could occur in southeast Australia, particularly given the greater propensity for ember generation from eucalypt species.

Figure 8: Video stills from the 2016 Fort McMurray fire in Canada. The forest on the left of the images is approximately 50m away from the houses. The red circles in (a) indicate garden shrubs that have been set alight by embers from the main fire. The circle in (b) shows flames from the shrubs making direct contact with the properties. Source: www.youtube.com/watch?v=PCc1FvZ3g0Q

3.5. Ember attack

As discussed in Section 1.1.2., the likelihood of ember attack is assessed in AS 3959 via an assumed relationship with radiant heat flux. As such, the Standard posits that the risk of ember attack can be effectively removed if the distance between the vegetation and the built asset is greater than 100m. However, Chen and McAneney (2004) indicate that the majority of houses lost in Duffy were lost due to ember attack rather than due to direct flame contact or radiant heat flux. This is consistent with the findings of Leonard and Blanchi (2005). Half of the houses lost in Duffy were separated by more than 100m from the forest edge. Such findings appear to raise significant questions about the way ember attack is considered within AS 3959.

Figure 9 shows a still from video footage taken at Duffy in 2003 as the firestorm impacted the suburb. Of particular note in the image is the complete lack of flames. Instead the image shows a dense swarm of embers moving close to the ground. This image raises significant questions about the assumed relationship between radiant heat exposure and ember intensity that is implied in the Standard. While the NSW RFS guidelines for planning for bushfire protection (NSW RFS, 2006) do explicitly warn against having shrubs close enough to result in direct flame contact to structures, the ember intensity evident in Figure 9 is likely to result in significant loss in any case.

Figure 9: Ember storm impacts Duffy, 18 January 2003. The image is a still taken from the footage captured by Channel 9 cameraman R. Moran.

The ember storm evident in Figure 9 reinforces the fact that the most damaging fire events do not manifest in a way consistent with the traditional assumptions about the way fires spread. Fires that have escalated to such a degree descend upon the urban interface as a violent pyroconvective event made up of thousands of embers and multiple coalescing spot fires, rather than as a contiguous fire front such as is envisaged in the Standard.

The occurrence of ember storms also has implications for APZ requirements. In Duffy homes were separated from the forest by at least 37m. This distance fits with a BAL–29 classification and thus implies, under the current guidelines, that the APZ was of sufficient width for firefighters to offer effective protection of built assets from bushfire attack. Clearly, however, in this case protection measures were not sufficient, as 206 homes and a firefighting appliance were destroyed (Chen and McAneney, 2004).

3.6. Pyrogenic winds

The role of pyrogenic winds and violent pyroconvection are not addressed in the AS 3959. While the Standard does acknowledge the role that winds play in driving embers into vulnerable areas, it does not explicitly recognise the damage that strong winds themselves may cause. The cases of Chapman on the outskirts of Canberra in 2003 and of Marysville in 2009 serve as examples where pyrogenic winds have caused considerable damage. The pyrotornado that skirted the edge of Chapman caused considerable damage in its own right, while strong pyrogenic winds in the vicinity of Marysville brought down several large eucalypts in areas that were unaffected by fire. In the context of this report, it is significant to note that the 2003 pyrotornado originated at a location less than 20km away from the Ginninderry region.

The potential role of pyrogenic winds in causing house damage during bushfires suggests that it might be necessary to incorporate some of the elements covered in the Standard for wind loads for housing (AS 4055 – 2012) into bushfire protection measures.

4. Ginninderry: a case study in bushfire risk

A detailed bushfire management strategy for the Ginninderry region was compiled by Eco Logical (2014). This risk assessment was undertaken in full compliance with the AS 3959 guidelines and included appropriate consideration of asset protection zones. In this section we provide a re-assessment of bushfire risk for the Ginninderry region, this time taking into consideration some of the dynamic aspects of bushfire propagation that are not addressed in AS 3959 and the Planning for Bushfire Protection Guidelines (NSW RFS, 2006). In particular, we will discuss the ramifications of the issues raised in the previous section, for the Ginninderry region.

4.1. Assessment of slope

The Ginninderry region is bordered by the Murrumbidgee River on its west and by Ginninderra Creek on its north. Both of these waterways form steep, narrow corridors along the northwest edge of the subject land. Figure 10 shows the topographic slopes across the area. Of particular note is that a significant proportion of the land to the north and west of the Ginninderry region has a topographic slope greater than 20°. This is particularly true of the land on either side of the Murrumbidgee corridor, with the steepest slopes (i.e. > 30°) coinciding with the northwest tip of the subject land. It is also important to note that the slopes in Figure 10 have been calculated using a 90m resolution DEM, so that the actual slopes should be expected to be slightly steeper than those depicted in the figure.

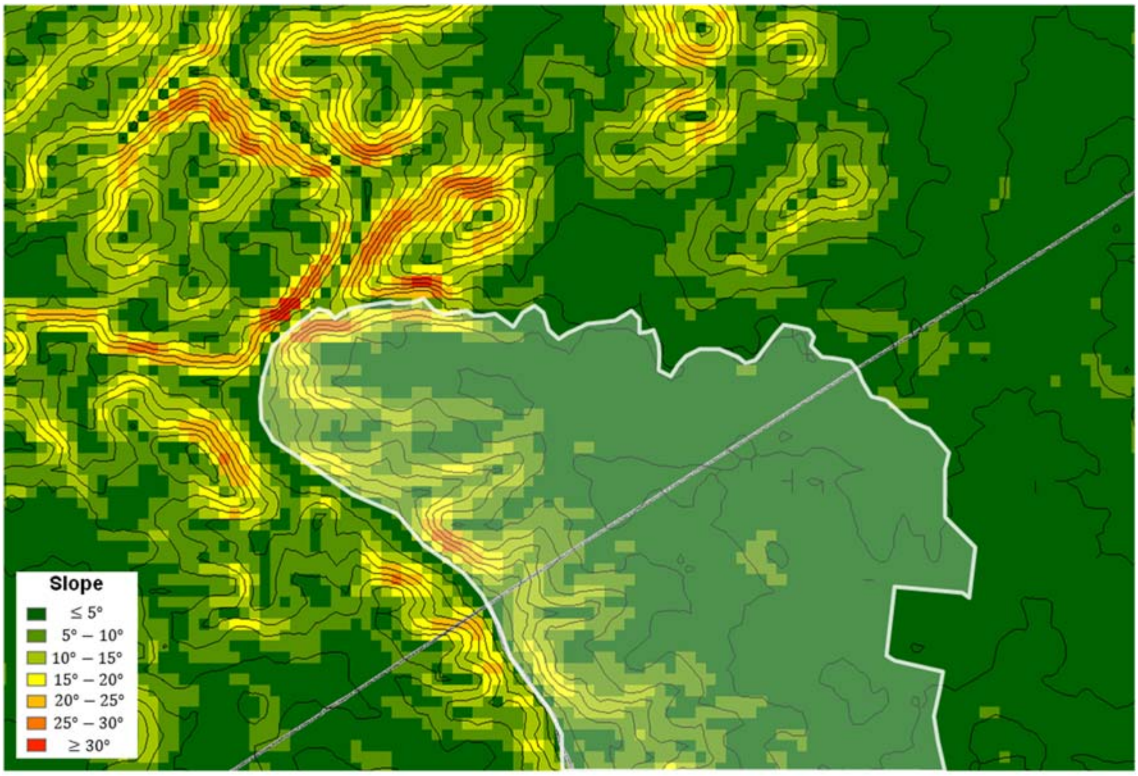

Figure 10: Topographic slope around the Ginninderry region. The land subject to rezoning is shaded white and bound by a white line.

As discussed in previous sections, the Standard only accounts for topographic slopes below 20°. In addition, it assumes that negative slopes modify a fire's rate of spread in accordance with equation (4). This means that the rates of spread assessed under the AS 3959 guidelines could be significantly under-predicted. This under-prediction of rate of spread then has ramifications for the way fire line intensity is assessed; indeed, fire line intensity is directly proportional to rate of spread.

Figure 11 shows a modified version of Figure 6 from the report compiled by Eco Logical (2014). Of note are the green regions in the figure where fire line intensity is predicted to be less than 4,000 kW m^{-1}. According to Sullivan et al. (2014), however, rates of spread calculated using equation (4) with a slope of -30° would be under-predicted by a factor of 6. With reference to Figure 10, the regions circled in blue in Figure 11 are all associated with slopes of around 30° or more. As such, under the assumption of a north-westerly wind, which would render the slopes in question as negative slopes, the fire line intensities in the circled regions are under-predicted by a factor of 6 or more.

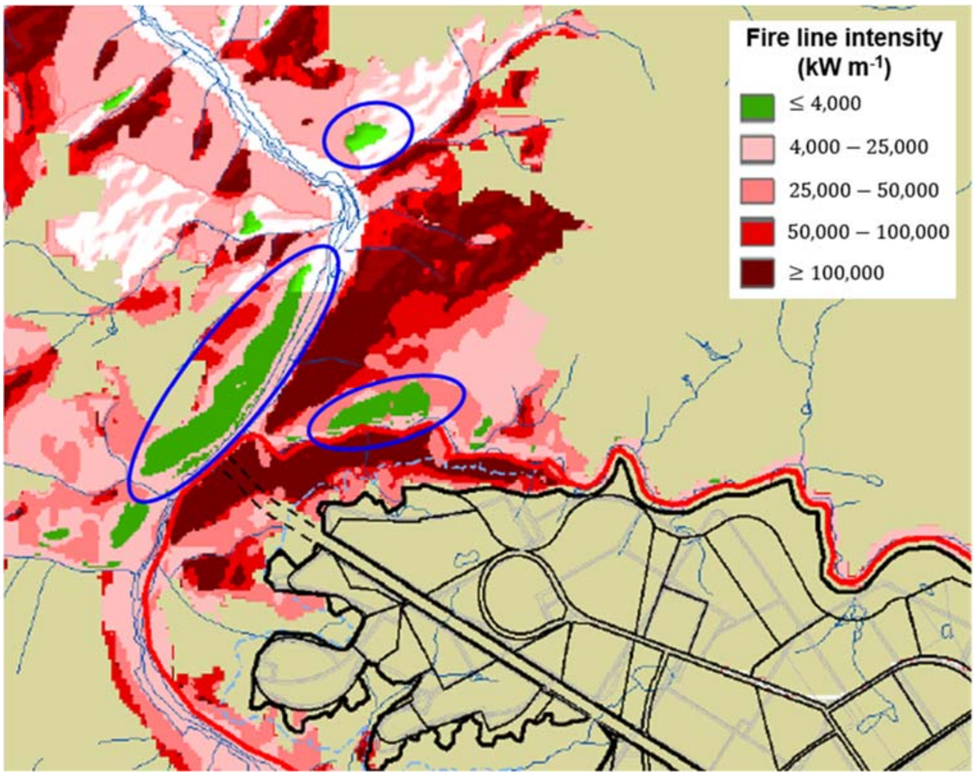

Figure 11: Fire line intensity around the Ginninderry region, as presented in the Eco Logical (2014) report (figure has been adapted). The blue ovals highlight steep, leeward slopes (under northwest winds) where fire line intensity has likely been under-predicted. This figure is a partial reproduction of Figure 6 in Eco Logical (2014).

Moreover, Figure 11 has been derived assuming fire weather conditions that rate as 'Extreme' or worse. Under such conditions, winds would be above the threshold for VLS occurrence and so dynamic fire propagation would be a distinct likelihood. In this case, the leeward slopes circled in Figure 11 would likely coincide with some of the most intense fire behaviour. This likelihood is addressed in more detail in the next subsection.

4.2. Likelihood of dynamic fire propagation

4.2.1. VLS occurrence

As was noted above, the bushfire risk assessment conducted by Eco Logical (2014) assumed fire weather conditions corresponding to fire danger ratings of 'Extreme' or 'Catastrophic'. Such fire weather conditions can only plausibly be attained when winds are stronger than about 35 km h^{-1}, with coincident very high temperatures and very low relative humidity. Hence, the winds considered in the risk assessment were certainly above the threshold required for VLS occurrence. Similarly, the very high temperatures and very low relative humidity that must exist to produce 'Extreme' fire danger rating, would result in critically low fuel moisture content. In fact, based on the dead fuel moisture content model of Cheney et al. (2012), fuel moisture contents would be below 5%, which is the threshold value mentioned in Section 2.2.2. For fuel moisture content below 5%, VLS occurrence will be accompanied by dense spotting and downwind extension of the flaming zone.

Figure 12 shows the Murrumbidgee corridor (looking north) adjacent to the northwest tip of the subject land. The figure shows the steep slopes discussed in Section 4.1, and highlights the steep southeast facing slopes on the western side of the river. Under north-westerly winds, as are assumed in the Eco Logical (2014) risk assessment, the southeast facing slopes would be leeward slopes. The figure also shows that the vegetation on these slopes is forest, which is consistent with the fuel assessment in the Eco Logical (2014, Figure 3) report. Again, the presence of forest fuels meets the requirements for VLS occurrence discussed in Section 2.2.2.

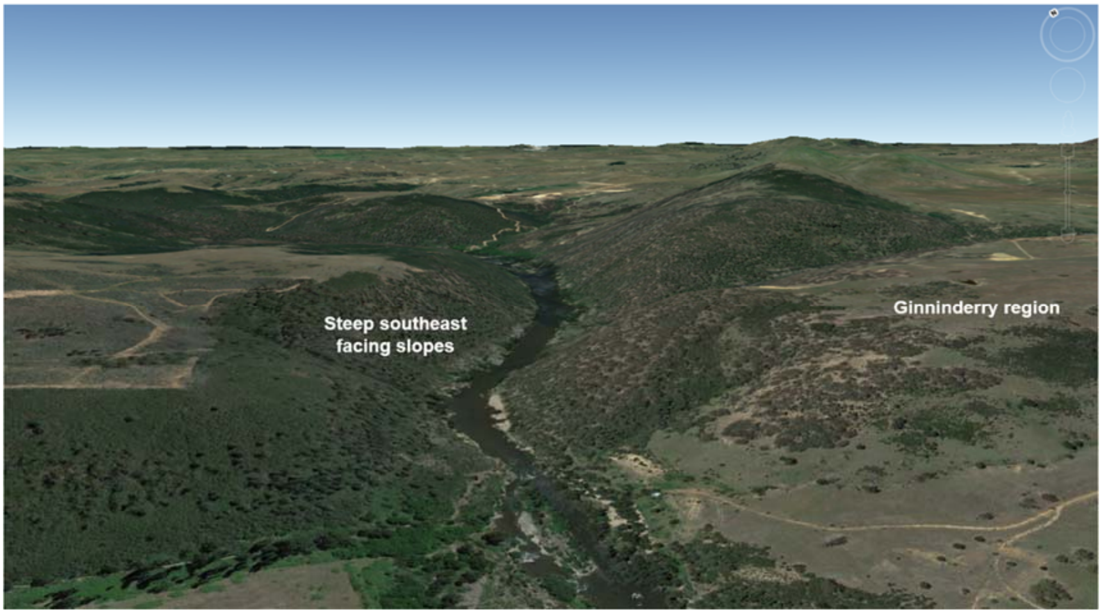

Figure 12: Google Earth image of the terrain to the northwest of the Ginninderry region. The steep southeast facing slopes, which are prone to VLS occurrence under north-westerly winds, are highlighted.

Figure 13 shows the results of applying the wind-terrain filter in equation (5) to the terrain surrounding the Ginninderry area. A north-westerly wind has been assumed in applying the model, which is the wind direction associated with the worst fire weather conditions experienced in the region, and which is again consistent with that used in the Eco Logical (2014) report. The results in Figure 13 indicate that the southeast facing slopes highlighted in Figure 12 do indeed meet all of the requirements for VLS occurrence. In addition, a number of other locations to the northwest of the subject land are identified by the wind-terrain filter as being prone to VLS occurrence. Under extreme fire weather conditions these regions would be highly efficient ember production zones, and would be a likely source of violent pyroconvection.

4.2.2. Eruptive fire behaviour

The steep slopes associated with the river corridors to the north and west of the Ginninderry region also raise concerns about the potential for eruptive fire behaviour. Even in the absence of wind the steep slopes in the area would be prone to flame attachment. The red pixels in Figure 14 highlight slopes greater than 20°, as calculated using a 90m resolution DEM. Such slopes would likely exceed the threshold inclination of about 24° required for flame attachment to occur.

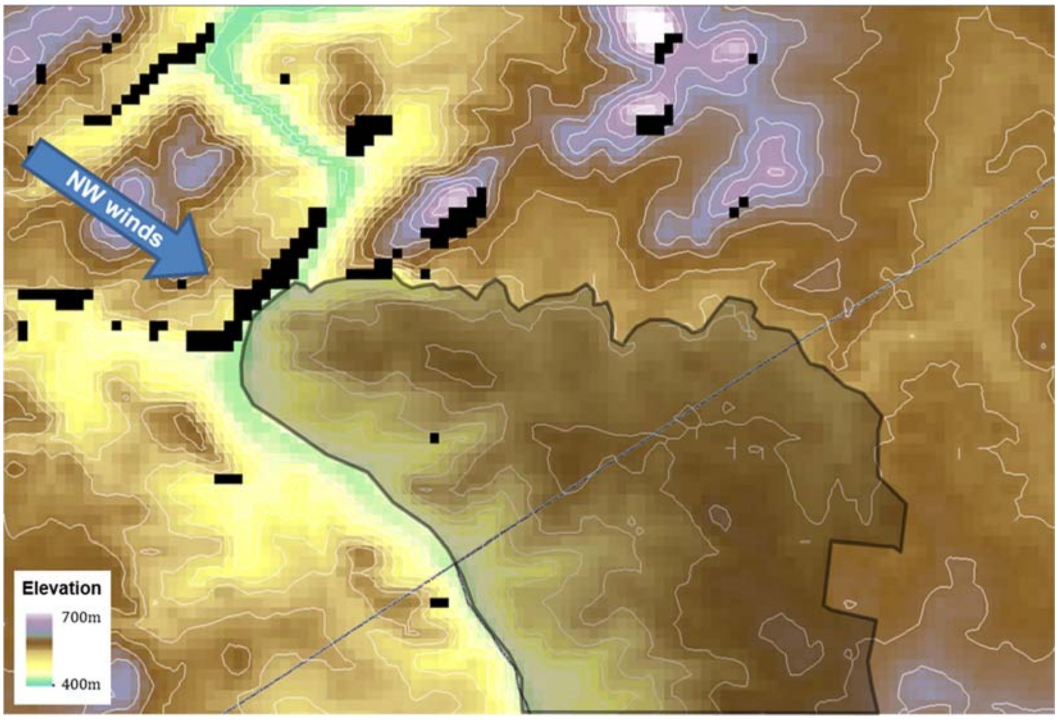

Figure 13: Map of elevation around the Ginninderry region, with the land subject to rezoning in dark shading. The black pixels indicate locations prone to VLS occurrence under north-westerly winds, as determined using equation (5).

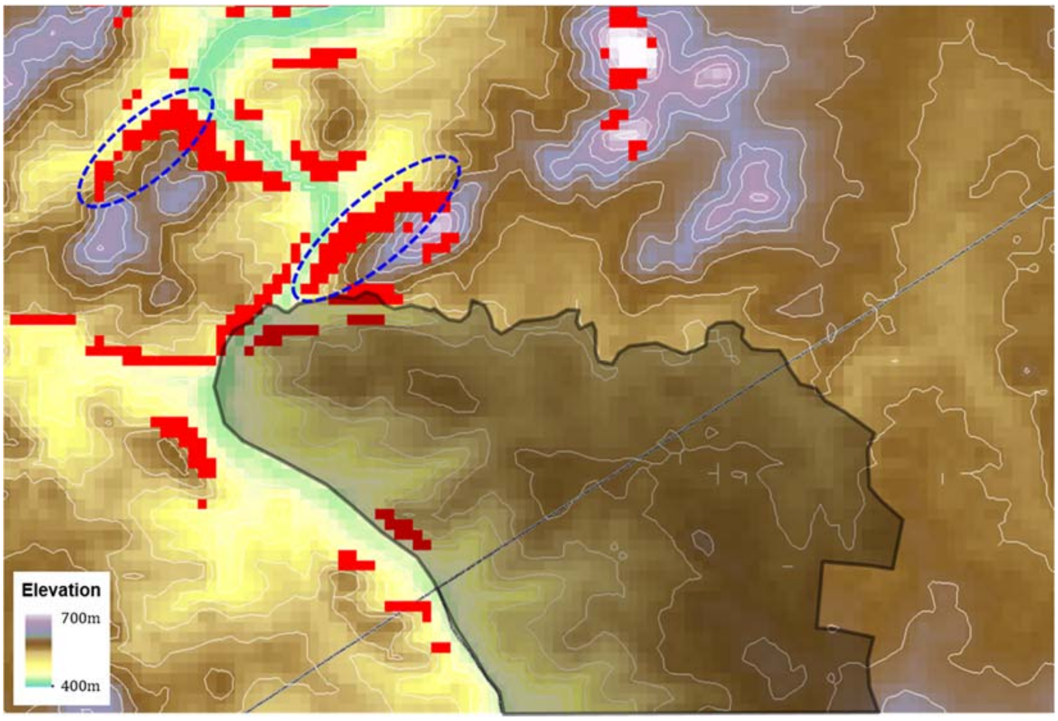

Figure 14: Map of elevation around the Ginninderry region, with the land subject to rezoning in dark shading. The red pixels indicate locations with slopes above 20°, and highlight the potential for eruptive fire behaviour.

As already discussed, given the extreme fire weather conditions that are routinely assumed in risk assessment scenarios, winds should be considered as strong (e.g. > 35 km h^{-1}). Under such conditions, flame attachment could be expected on slopes that are inclined less than 24°. While research is yet to provide definitive guidance on how wind affects the threshold inclination for flame attachment, it should be expected that under strong winds, slopes as low at 20° that are aligned with the winds would experience flame attachment.

The west facing slopes circled in blue in Figure 14 would be of particular concern in the development of fire originating to the northwest of the Ginninderry region. Under strong north-westerly winds and with low fuel moisture content, a bushfire would escalate considerably on these slopes and create extensive regions of intense flaming. Violent pyroconvection would be highly likely under such a circumstance and the land downwind of these slopes would be blanketed with thousands of embers producing multiple spot fires.

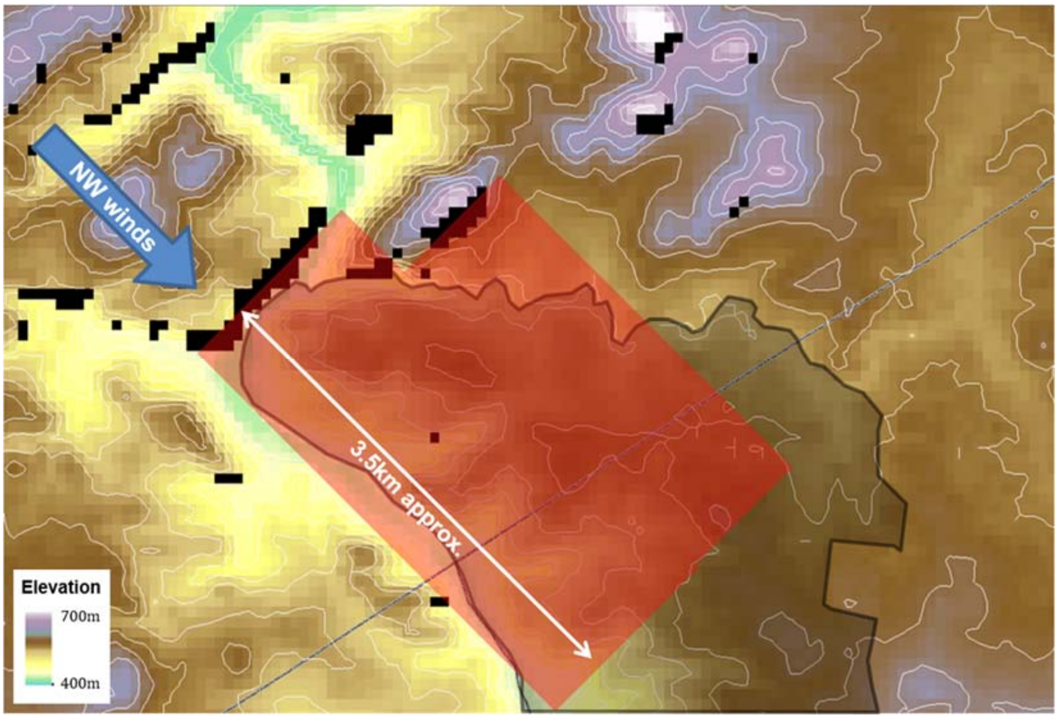

Figure 15: Stylised impact zone for embers generated from VLS prone landforms upwind of the Ginninderry region. A spotting distance of approximately 3.5km has been assumed. This value is conservative for extreme fire weather conditions.

4.2.3. Impacts of embers

The propensity for dynamic modes of fire propagation to occur to the northwest of the Ginninderry region means that fires originating in this area would likely produce dense swarms of embers. Consequently, rather than spreading as a contiguous flame front like that perceived to impact built assets in AS 3959, fires originating to the northwest of the Ginninderry region under extreme conditions would more likely propagate as a series of coalescing spot fires.

The steep southeast facing slope highlighted in Figure 12 would also generate a significant number of embers if VLS was to occur. Figure 15 provides a stylised indication of the area likely to be directly affected by embers in such a case. The red shaded region in the figure depicts the area where embers originating from VLS events would be likely to fall. However, it should be noted that the ember fall distance of 3.5 km shown in the figure is conservative – it is highly likely that under extreme fire danger conditions, embers would travel much further than is indicated in Figure 15.

5. Concluding remarks

The current Standard for construction in bushfire prone areas (AS 3959) and the NSW RFS guidelines for planning for bushfire protection are not consistent with the current state of the science of bushfires. In fact, it appears that for the most part, the methodology underpinning the calculation of BAL espoused in the Standard is that presented by Midgely and Tan (2006)[1]. All of the major advances in our understanding of dynamic bushfire propagation discussed in this report, and how they affect the development of large, destructive bushfires have taken place post-2006. As such, these aspects of bushfire attack could not have been considered by Midgely and Tan (2006).

The main shortcomings of the Standard centre on the following points:

- It is based entirely on the assumption that fires propagate in a quasi-steady manner;
- It is predicated on the notion that the main cause of house loss is radiant heat exposure;
- It factors in the effect of embers in an over-simplistic way via an assumed relationship with radiant heat exposure;
- It offers no consideration of the potential effects of pyrogenic winds.

The failure of the Standard to adequately address the current state of the science means that it will likely significantly under-predict the level of risk from bushfire attack under extreme conditions. Consequently, this raises questions about the adequacy of the design and construction guidelines in AS 3959 and the validity of risk management strategies that use AS 3959 as their basis.

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[1] Strangely, Midgely and Tan (2006) is not listed in the references in AS 3959.

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