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SPOTFIRE UTILISATION PROJECT: IMPLEMENTATION OF THE VLS FILTER

Final report

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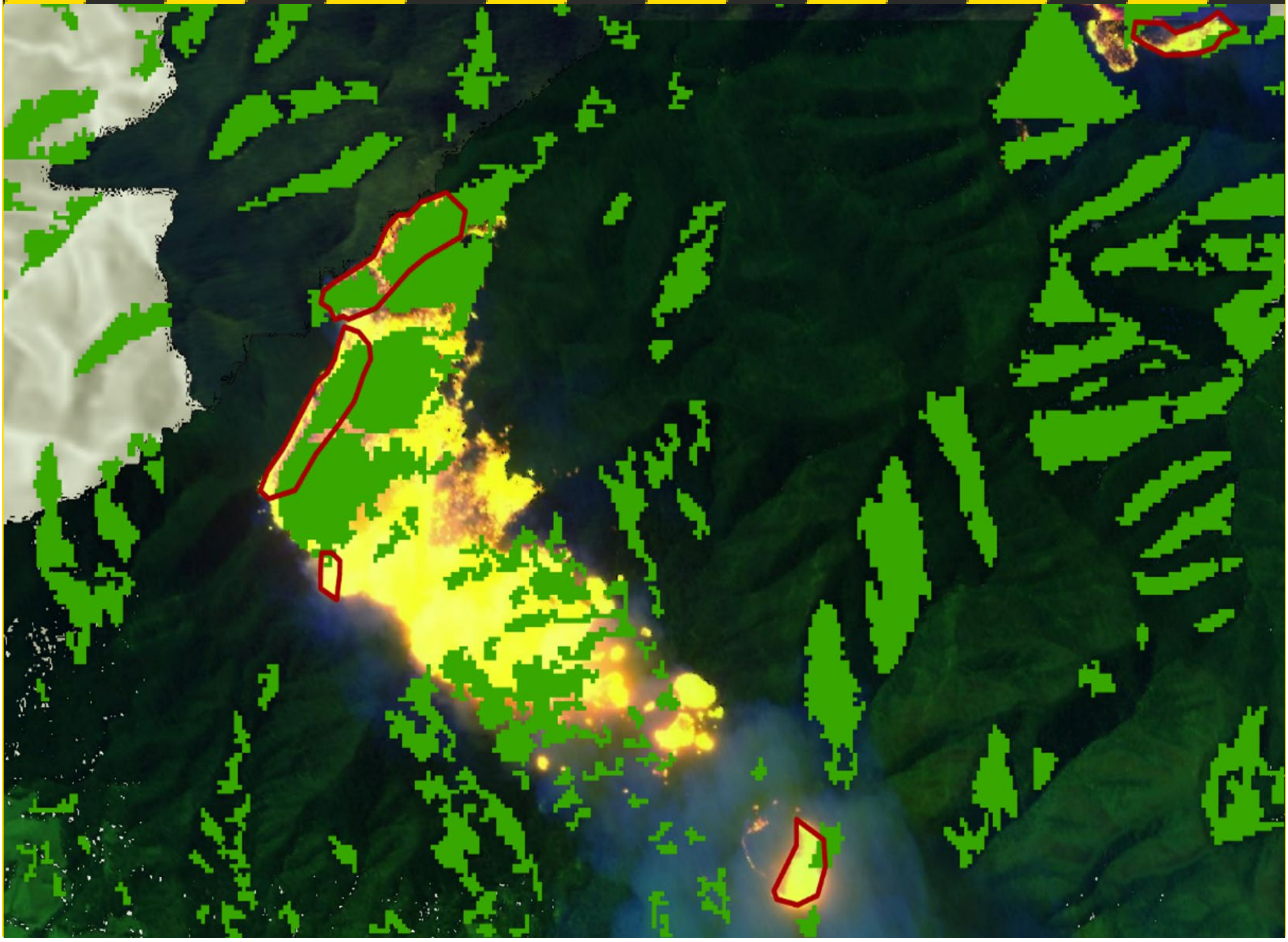
UNSW Canberra



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Cover: VLS filter for NW wind for Yankees Gap Fire, Bemboka NSW. Source: Badlan and Sharples 2021.

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END-USER STATEMENT

Laurence McCoy, *Manager - Predictive Services, NSW Rural Fire Service*

The 2019-20 bushfire season was one of the worst recorded in Australia. The fire season was characterised by periods of extreme fire behaviour with an unprecedented number of extreme fire behaviour events recorded.

Although awareness of Vorticity-Driven Lateral Spread and ensuing extreme fire behaviour is increasing within the fire management community, additional training and dynamic tools to identify high risk locations for extreme fire behaviour will assist fire agencies to improve planning and prioritising suppression, strategies and tactics for future bushfires. This research is an important step for assessing the risk of extreme fire behaviour. It could help to inform fire managers operational decisions ahead of and during fire fighting operations.

The results of the case study applying the products to the Yankees Gap case study was encouraging and we look forward to continuation of this research and trial of the products in an operational setting.

EXECUTIVE SUMMARY

The aim of this research was to produce an operational tool to assist fire agency personnel in assessing the potential for extreme bushfire development. Specifically, this work's intention was to aid in the identification of regions of the landscape that are prone to mass spotting and other dynamic fire behaviour associated with vorticity-driven lateral spread (VLS). The research was divided into three phases: 1) calibration of the slope scale to each DEM, 2) creation of the filter (first and second order) and finally refinement of the filter and, 3) develop training material and ensure filters and related documents are distributed to relevant personnel.

The first-order and second-order wind-terrain filter enables the user to identify parts of the terrain which are susceptible to VLS through its established association with steep or broken leeward facing terrain elements. This is achieved using terrain attributes such as topographic slope, aspect, and profile curvature, as well as environmental variables such as the wind speed and direction. This builds upon the research initially undertaken as part of the original Bushfire Cooperative Research Centre.

This report summarises the three phases of the project, during which time the researchers have gained familiarity and VLS mapping capability with the GIS software "ArcGIS Pro", which is used to create and validate the wind-terrain filters. This facilitated the two main research objectives – to develop and then refine the first order and second order wind-terrain filters so that they may be applied using DEMs of any resolution.

Initially, this involved manual tuning of the first-order wind-terrain filter's parameters to fit a number of calibration events. This tuning was also confirmed through analyses of slope distributions over various landscape domains. These static cases were then validated with real case conditions and the filter compared to areas where VLS was known to have occurred. Scaling thresholds for the 30, 90 and 250 metre resolution DEMs were also evaluated explicitly, and a general linear model has been determined to allow estimation of parameter thresholds for more general DEM resolutions.

The second-order filter was then designed and tested in a similar manner to the first-order filter. The two filters were then merged into a combined operational product, which was also validated using known cases of VLS. Both filters are presented here - separately and as a combined product - for the operational consideration of end-users. End-user feedback was then evaluated to further tailor the operational product to specific operational needs, platforms, and formats. Due to travel restrictions static filters have been produced for immediate use. Development of a dynamic mapping tool is also continuing in which other factors such as the forecast wind speed and direction (and potentially other variables) can be incorporated automatically to provide heightened operational intelligence on extreme bushfire development.

INTRODUCTION

An extreme bushfire is the most dangerous manifestation of a fire and is defined as "a fire that exhibits deep or widespread flaming in an atmospheric environment conducive to the development of violent pyroconvection, which manifests as towering pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) storms" (Sharples *et al.* 2016). These fires are increasingly in frequency and intensity due to changing conditions such as increased drought and global temperatures.

Extreme bushfires development is driven by a number of factors that can cause small fires to rapidly escalate in size and intensity. Extreme fires exhibit expansive areas of active flaming – referred to as 'deep flaming' (McRae *et al.* 2015). Fires that have regions of deep flaming have also been referred to by other authors as 'areal fires' or 'mass fires'. Factors thay may act as triggers for extreme fires include change of wind direction, strong winds, eruptive fire behaviour, mass-spotting and fire coalescence, and VLS (Badlan *et al.* 2017). The last three of these involve dynamic fire propagation, whereby the fire spread transitions from a quasi-steady to accelerated rate of spread. Dynamic fire behavours are problematic not only because the fires increase their size rapidly, but may also catch people in the vicinity offguard, leading to loss of life and property. VLS has been identified as a driver of extreme fire development in numerous events such as the 2003 Canberra fires (McRae 2004;Sharples *et al.* 2012;Simpson *et al.* 2015), and the Aberfeldy (Quill *et al.* 2015) and the Wambelong fires of 2013 (Dillon 2013). These case studies have been chosen to calibrate and validate the filters.

VLS occurs when steep (or broken) topography and strong winds interact to produce flow separation, creating horizontal vorticity such as a lee slope eddy. The fire's updraft may then stretch and tilt this horizontal vorticity into intense vertical vorticity, which may then cause the fire to spread laterally along the ridge line (Simpson *et al.* 2014;Simpson *et al.* 2013). As lateral spread is associated with intense vorticity, this means that ember generarion is enhanced. These embers are then transported laterally and downwind due to the combined influence of the vertical vorticity and the prevailing wind, potentially resulting in mass spotting and fire coalescence (Sharples *et al.* 2019).

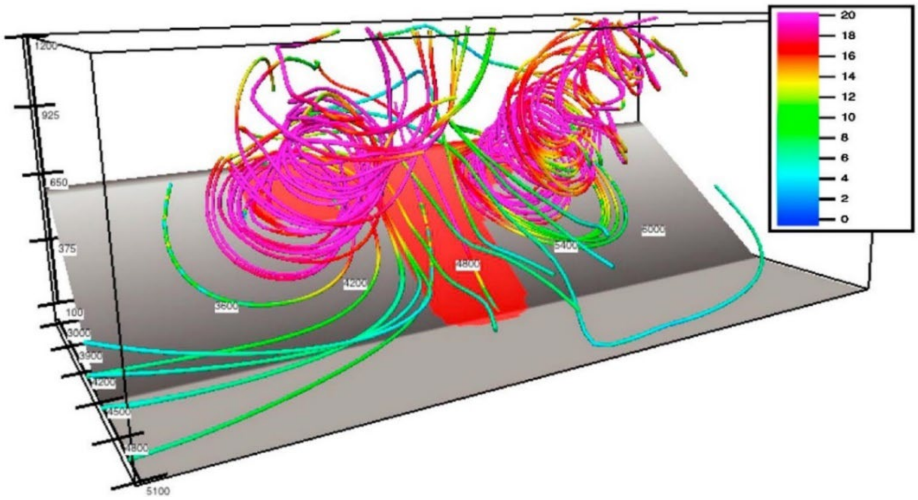

FIGURE 1. SIMULATION OF VLS ACROSS LEEWARD SLOPE, WITH LINES REPRESENTING AIRFLOW. RED SHADING REPRESENTS THE FIRE. WIND IS ALIGNED PERPENDOICULAR TO RIDGE AXIS (SIMPSON *ET AL.* 2016).

This aim of this project was to create an operational overlay that highlights areas of high VLS risk. This was begun by developing static overlays that indicate a single wind direction for an area and then progress to using real-time wind vectors to calculate filters that reflect the changing, dynamic conditions that affect VLS.

The original research by (Sharples *et al.* 2012) used a 250 metre DEM to initially investigate what slope threshold and aspect to use for a given DEM. They found that a minimum slope of 10.5 degrees was necessary to identify VLS using a 250 metre resolution DEM.

However, there are issues with how slopes scale with DEM resolution. This is because slopes get smoothed (i.e., the angle of slope reduces) with decreasing resolution. The threshold for the flow separation required for VLS is usually cited as 20 degrees and this raises the question of "What minimum slope is required for different resolution DEMs?". Further investigations by the authors examined the distribution of slopes in a given domain, using different resolution DEMs. This was repeated for this work (see Section 'Slope Distributions', under Phase 1 Research).

Two filters are required for analysing VLS – a first-order differential of elevation (i.e. the slope). A first-order filter on its own would be sufficient if real topography reflected a hill such as that in Figure 2a. However, is not sufficient in rugged terrain which has 'broken' topography. Ridge lines and bluffs which adjoin VLS-prone slopes, are all part of the VLS-prone landscape. Unfortunately, these ridges are not identified by a first-order filter as this filter only captures slope greater than a certain threshold (but not the top of the ridge, which tends to have gentler slopes (Figure 2b)). Therefore, a second-order is needed to identify the leeward ridgelines (Figure 2c).

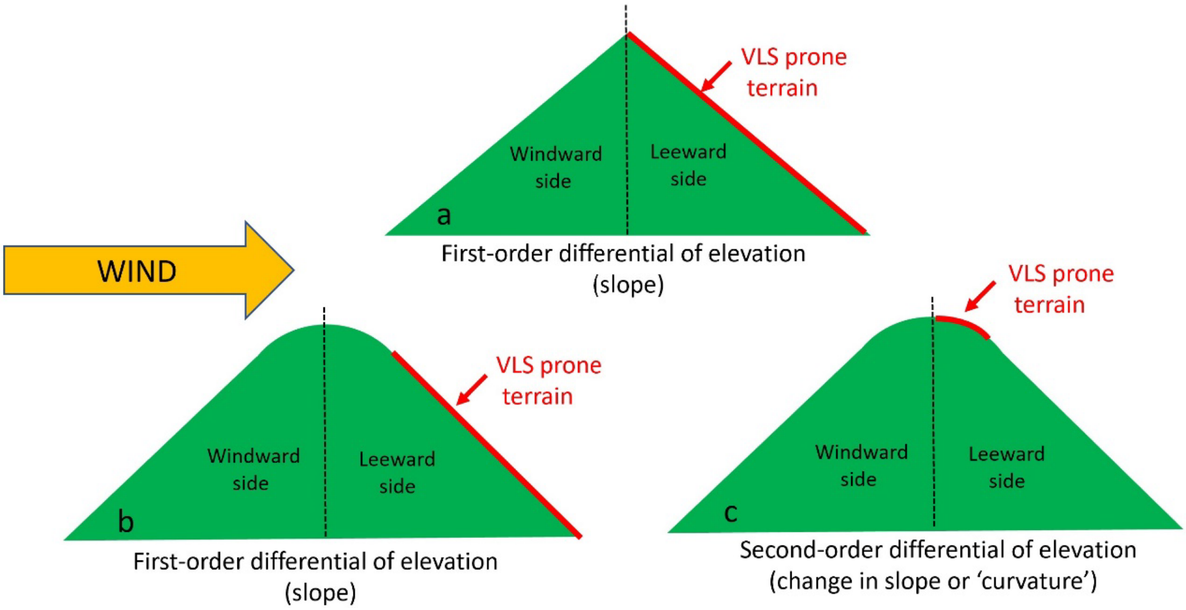

FIGURE 2. FIRST-ORDER VLS FILTERS FOR A) AN 'UNBROKEN' HILL PROFILE, AND A SIMPLE RIDGE PROFILE WITH A FIRST-ORDER FILTER (B) AND SECOND-ORDER FILTER (C).

VLS AND MASS SPOTTING EVENTS

VLS plays an important role in the generation of mass-spotting, which in turn contributes to the escalation of an extreme fire. Figure 3 shows a schematic of a fire which has ignited on the mid-slope of a windward facing slope. This fire initially spreads up the slope in the direction of the prevailing wind. When the fire encounters the ridge line (indicated by the white dashed line), dynamic fire interactions then drive the fuel laterally (VLS) along the ridge line. These regions of lateral spread act as an enhanced source of embers, which are consequently deposited downwind on the lee-facing slope, as a dense ember attack. The resulting dense spot fires then interact, coalesce, and form deep flaming zones.

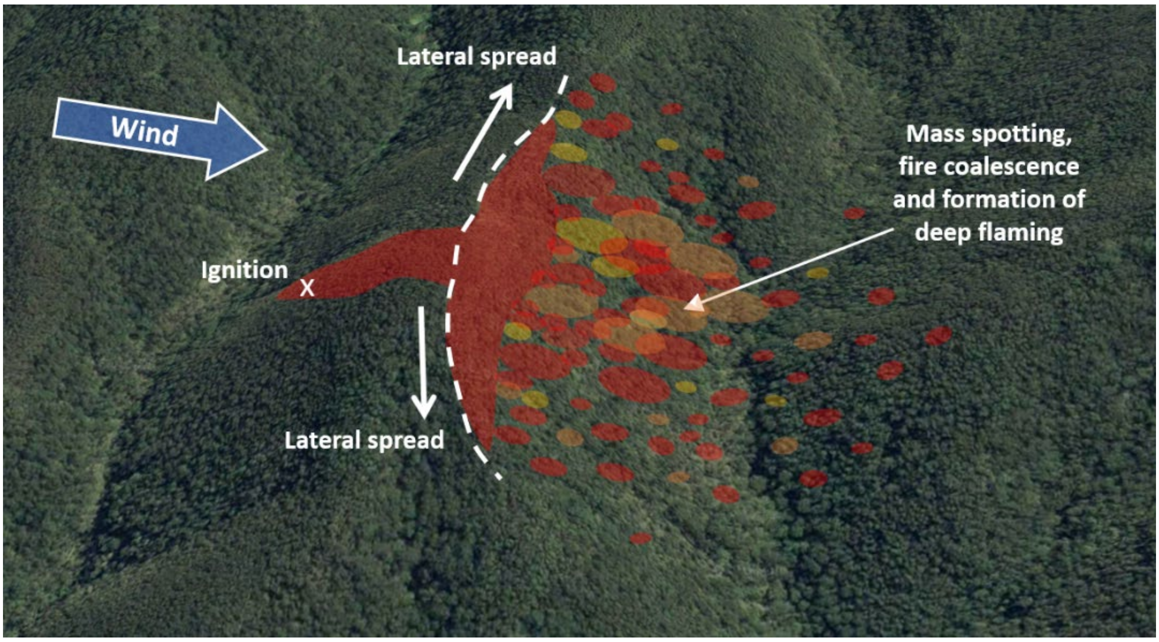

FIGURE 3. SCHEMATIC DIAGRAM ILLUSTRATING A TYPICAL SCENARIO INVOLVING VLS AND ASSOCIATED DOWNWIND SPOTTING, SPOT-FIRE COALESCENCE AND FORMATION OF DEEP FLAMING.

THE VLS TERRAIN FILTER

First-order filter

As described previously, VLS is dependent on the slope and and apect of that slope to the prevailing wind. These conditions may be expressed formally as:

$$\chi(\sigma,\delta) = \begin{cases} 1 & \text{if } S \geq \sigma \text{ and } |\theta - \alpha| \leq \delta, \\ 0 & \text{otherwise,} \end{cases}$$

Where S is the topographic slope, α is the topographic aspect and θ is the direction the wind is blowing **from**. This is the opposite of the standard wind direction and is calculated by subtraction or addition of 180° from the standard wind direction; therefore, a westerly wind has a direction of 90°. σ and δ are the slope threshold and aspect discrepancy respectively. In summary, the first-order filter identifies areas of the landscape with lee-facing slopes where flow-separation is likely to occur (i.e., slope greater than 20°), however the slope threshold will depend on the resolution of the DEM being used. This is addressed by the calibration stage of the research.

Second-order filter

The second-order filter depends on the second order directional derivative of the surface (DEM) and the aspect:

$$\phi(C,\delta)=\begin{cases}1 & \text{if } C<0 \text{ and } |\theta-\alpha|\leq\delta,\\ 0 & \text{otherwise,}\end{cases}$$

Where C is the profile curvature, α is the topographic aspect and θ is the direction the wind is blowing **from**. The profile curvature tool in ArcGIS Pro is used to achieve this. The profile curvature is parallel to the slope, indicating maximum slope. This filter identifies areas of the landscape that are associated with ridge lines, whereas the first-order identifies slopes. Initially this filter is set to identify areas of negative curvature ($C < 0$), which results in identifying typical ridge lines such as those shown in Fig. 2 b and c. However, a study of how thresholds for C might change with resolution may be useful in the future (see Further Work).

DATASETS

The datasets used for this research were from the Shuttle Radar Topography Mission (SRTM)(Farr *et al.* 2007); the 1 second, 3 second-derived (Geoscience Australia 2009) and 9 second datsets with resolutions of approximately 30, 90, and 250 metres respectively.

CASE-STUDIES

To test the slope threshold for the filters, it was first necessary to create some domains based on previous case studies where VLS was noted to play a role in the escalation of the fire. One case-study was chosen for calibration of the slope thresholds (Fig. 4) used for each dataset, with another two added for validation of those slopes afterwards (Figs. 5 and 6).

For calibration

Canberra fires, ACT and NSW, 18th January 2003

Wind direction: NW-WNW 305°

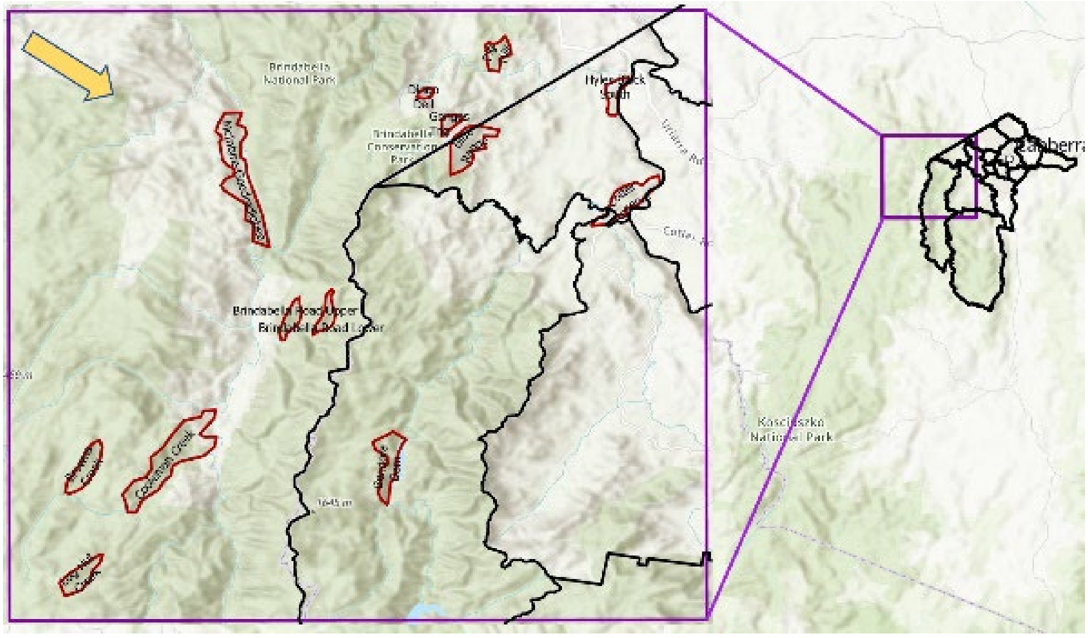

FIGURE 4. MAP OF CANBERRA DOMAIN WITH POLYGONS INDICATING AREAS OF VLS SPREAD. YELLOW ARROW INDICATES DIRECTON OF WIND.

FIGURE 5. MAP OF THE JINGELLIC DOMAIN WITH POLYGONS INDICATING AREAS OF VLS SPREAD. YELLOW ARROW INDICATES DIRECTON OF WIND.

For validation

Aberfeldy Fire, Victoria, January 2003

Wind direction: NW 337.50°

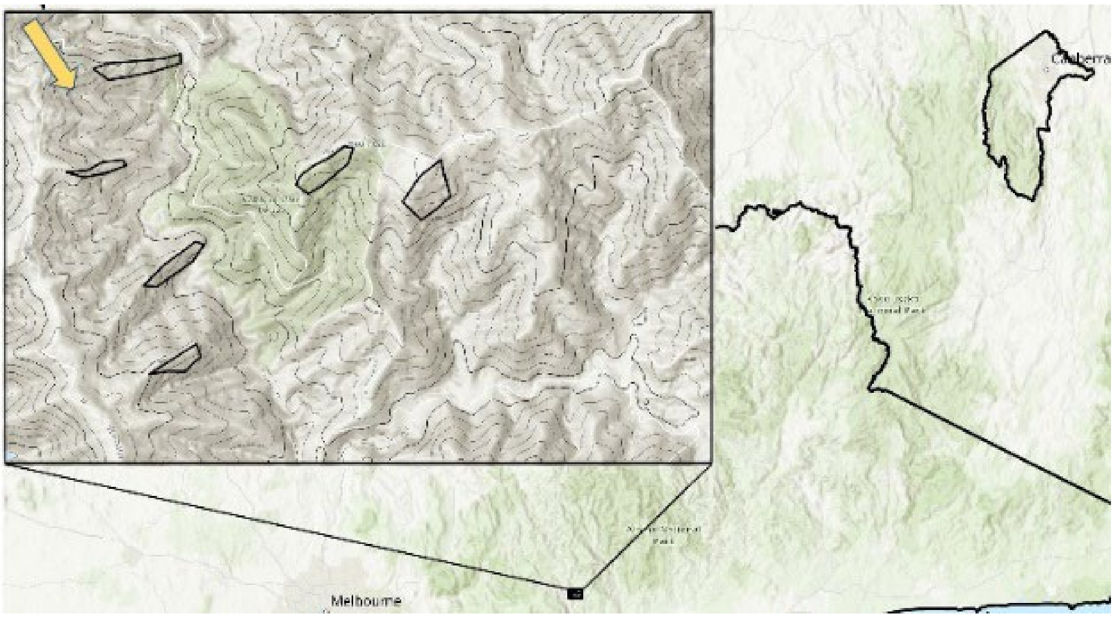

FIGURE 5. MAP OF ABERFELDY DOMAIN WITH POLYGONS INDICATING AREAS OF VLS SPREAD. YELLOW ARROW INDICATES DIRECTON OF WIND.

Wambelong Fire, NSW, 30th December 2013

Wind direction: NW 315°

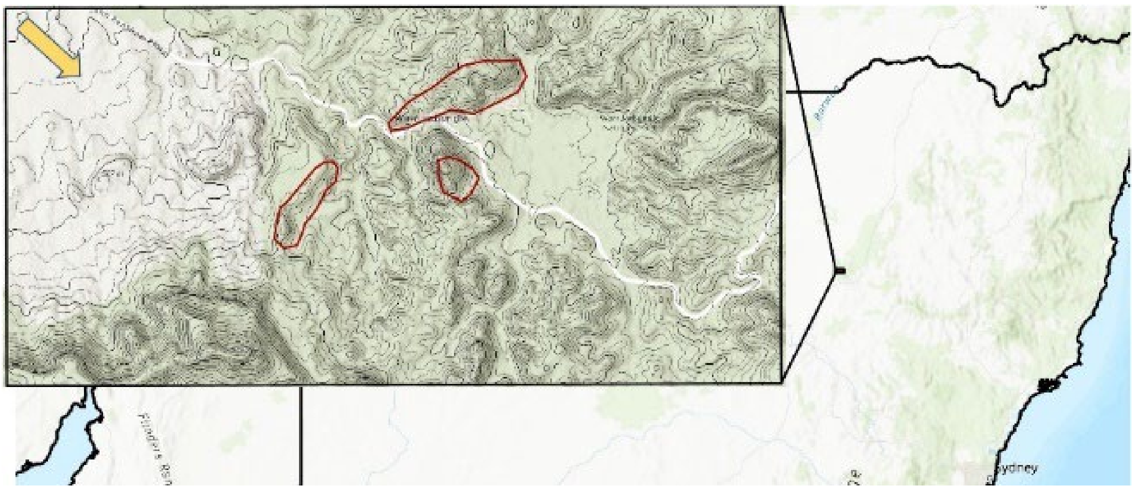

FIGURE 6. MAP OF WAMBELONG DOMAIN WITH POLYGONS INDICATING AREAS OF VLS SPREAD. YELLOW ARROW INDICATES DIRECTON OF WIND.

PHASE 1 RESEARCH

Using ArcGIS Pro software, a first-order filter was made for the Canberra Domain using 30, 90 and 250 metre SRTM DEMs. Three static rasters were created: slope, aspect, and curvature (for the 2nd-order filter). A conditional statement was then used to capture areas that have slopes greater than the chosen threshold and an aspect which is the wind direction ± discrepancy.

CALIBRATION OF FILTER

These first-order filters were then calibrated by manually tuning the filter. This was done by running the filter at with different slope thresholds and varying the aspect from 35 to 45 degrees, and visually assessing whether the filter captured most of the polygons in Fig. 4. As a result, the slope thresholds were then chosen to be 18°, 15° and 11° for the 30, 90, and 250 metre DEM datasets respectively, with an aspect discrepancy of 40°.

Slope Distributions

Another method of determining equivalent angle of slope for a given DEM, was to look at the distribution of slopes in a given area and to look at the equivalent proportions of slope in each DEM. Figure 7 shows the slope distributions for the ACT domain; a 5 metre resolution LIDAR DEM has also been added.

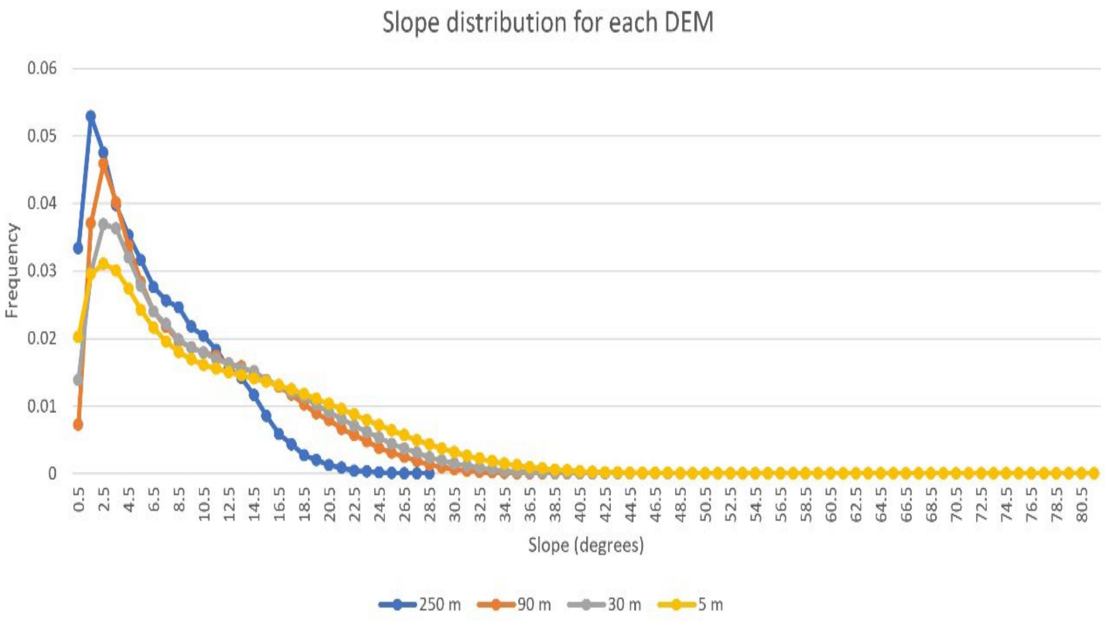

FIGURE 7. GRAPH OF THE SLOPE DISTRIBUTIONS FOR THE 5 M LIDAR AND THE 30, 90, AND 250 METRE SRTM DEMS.

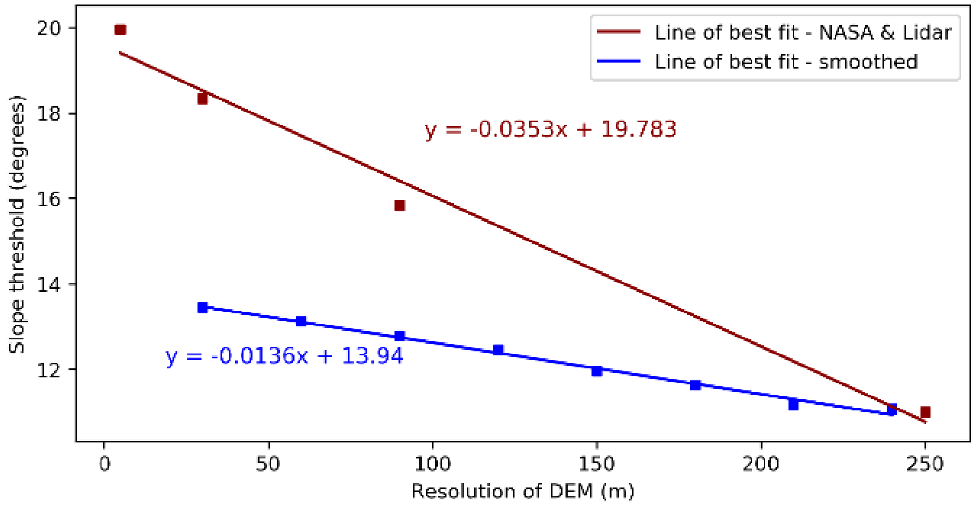

FIGURE 8. CORRELATION BETWEEN VARIOUS RESOLUTION DEMS FOR SRTM AND SRTM-DERIVED DATASETS (NASA & LIDAR) AND MANUALLY SMOOTHED DEMS FROM THE 30 METRE DEM.

The relationship between these SRTM and LIDAR DEMs is shown in Figure 8 (red line). This figure also shows a comparison with DEMs that were created by smoothing (averaging) the 30 metre DEM (blue line). The SRTM datasets are very different to those produced by only smoothing, as they are created using smoothing which involves sophisticated statistical and interpolative methods.

A graph was then produced looking at the equivalent slopes for each SRTM DEM for the Canberra domain to aid in calibration of the filter (Fig. 9). As a result of the probability density graphs, slope threshold values of 10, 16 and 18 degrees were then chosen for the 30, 90 and 250 metre datasets.

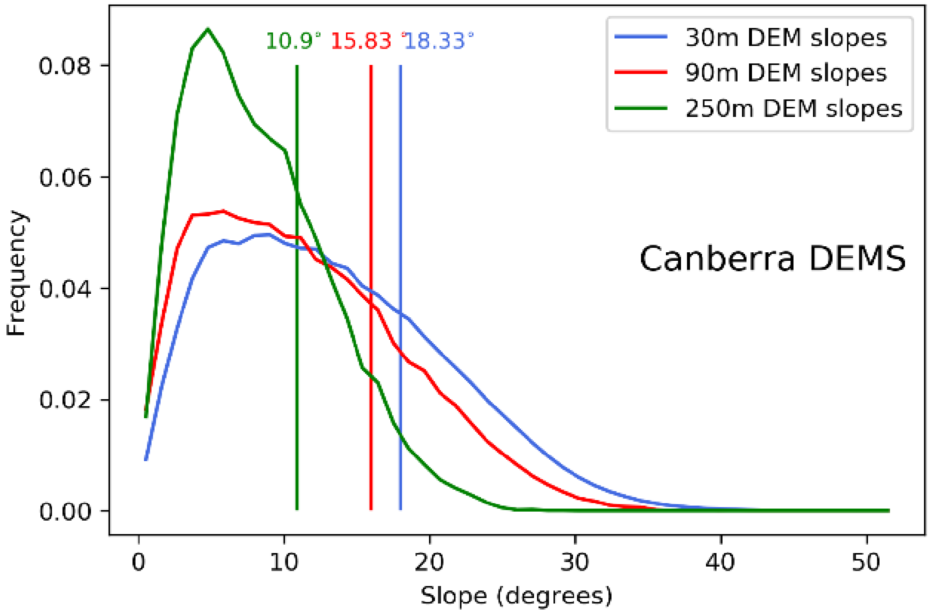

FIGURE 9. SLOPE DISTRIBUTIONS OF THE CANBERRA DOMAIN USING THE THREE SRTM DATASETS. THE VERTICAL LINES SHOW THE EQUIVALENT VALUES OF THE DISTRIBUTION OF SLOPES ABOVE 20 DEGREES.

Comparison of proportion of filter inside polygons to that outside

For the ‘Canberra fires’ domain, the proportion of the area inside a given polygon, which is captured by the filter, was then compared to the proportion of the area outside the polygons covered by the filter. Obviously, although VLS or a fire is not associated with those regions, it does not mean one could not have occurred outside the polygon regions marked. The filter was designed to identify regions of risk, without there being an associated fire and without capturing too much of the landscape.

For the 250 metre filter (first-order)and using a 10 degree slope threshold and a 40 degree aspect, the percentage of the area within the polygon captured by the filter was approximately 32%, whereas the area outside the filter was approximately 9%. As the slope threshold decreases, the filter obviously captures more of the landscape, but will increasingly capture regions that are not a real VLS risk. The aim was to use the highest slope threshold, without loss of information. For the 90 metre data, it was 21% within and 7% outside and for the 30 metre, it was ~19% within and 6% outside. This indicated that the filter captured the areas of VLS risk however, it did not capture too much of the other areas of the landscape, making it a useful tool as it identifies areas within the polygons without complicating VLS assessment by identifying large areas outside. These numbers would change obviously given different landscape and different slope distributions.

VALIDATION OF FILTER

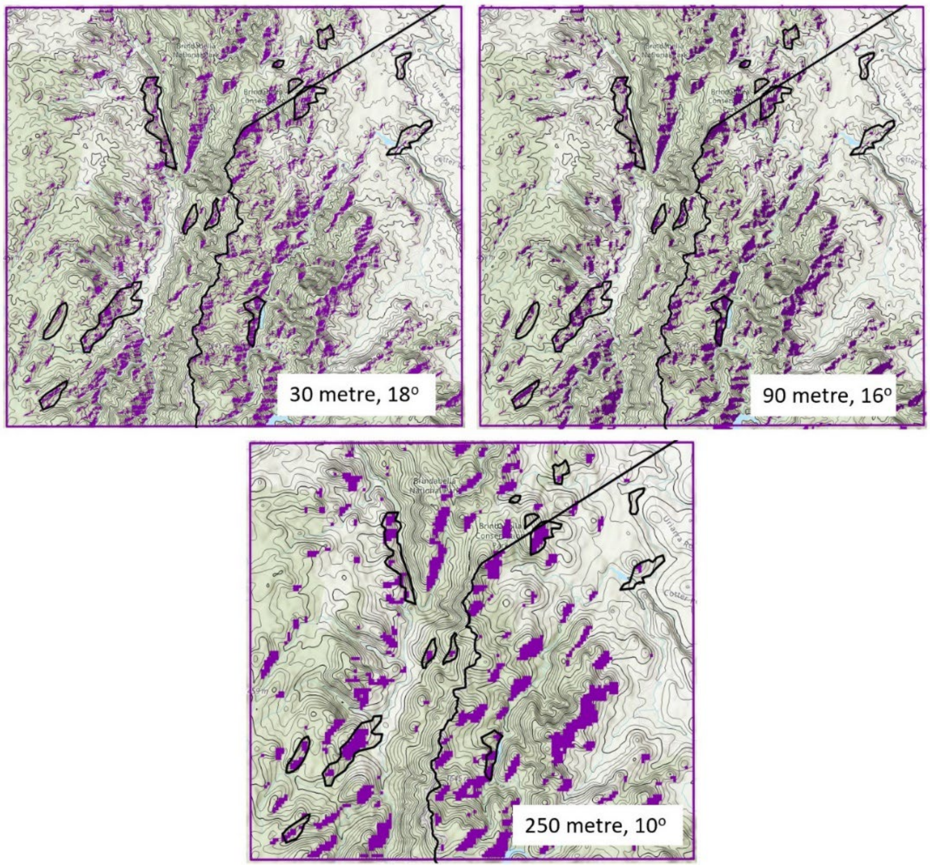

FIGURE 10. THE FIRST-ORDER VLS FILTERS FOR THE 30, 90, AND 250 METRE DEMS, WITH THE SLOPE THRESHOLDS OF 18, 16 AND 10 DEGREES RESPECTIVELY.

Figure 10 shows the first-order filters for the Canberra domain with the three different resolution DEMs. Obviously, the 250 metre filter lacks the detail of the two finer filters but does indicate the general areas at risk of VLS.

All three domains (Canberra, Aberfeldy and Wambelong were then used to validate both the first and second-order filters (Figure 11). This was done by a visual inspection of the polygon areas in each domain to ensure that the filter captured the VLS prone areas, given the wind direction around the time lateral spread occurred.

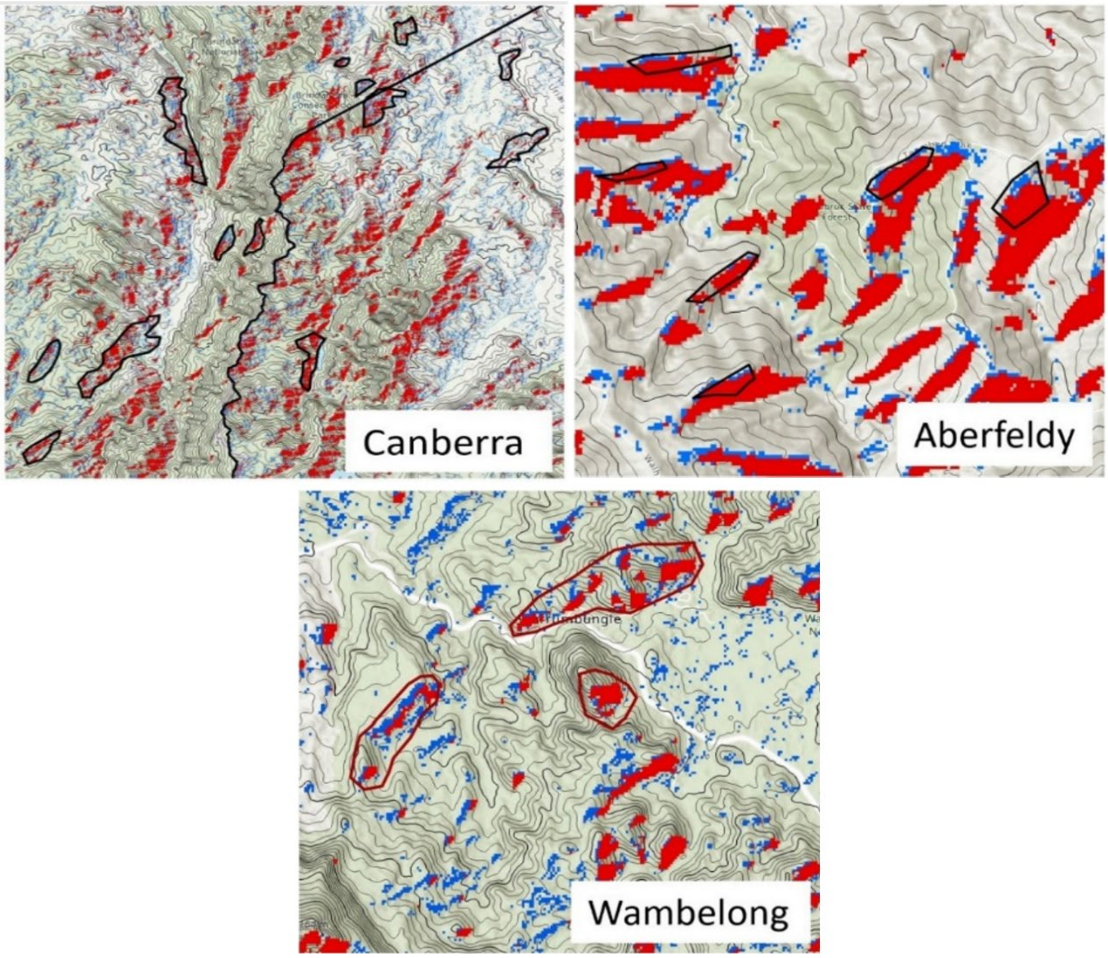

FIGURE 11. FIRST-ORDER FILTER (IN RED) OVERLYING SECOND-ORDER FILTER (IN BLUE) FOR ALL FOUR DOMAINS USING 30 METRE DEM.

As can be seen in Figure 11, the first-order filter (regions in red) did the best in identifying the broad areas for VLS. The second-order filter (blue regions) only gave more information where there were broad ridge lines (i.e. the width of the ridge is much greater than the resolution of the DEM) or in areas of plateaus or bluffs (such as in the case of the Wambelong bluff – LH polygon – where a broad area of blue can be seen on the windward side of the bluff). For ease of interpretation, the domains show the second-order filter overlain by the first-order filter to ascertain how much more of the landscape is captured by the second-order filter.

Note: This method was also unofficially applied to an international event and successfully captures VLS prone areas in the case of the Cerro Grande Fire, Los Alamos, New Mexico, 2010 as well as the 2020 Bridger Hills Fire in Montana (see the training manual (Badlan and Sharples 2021), for more detail).

Noise reduction – removal of isolated pixels

To aid with interpretation of regions with complex terrain where the second-order filter may identify many small areas of VLS risk, a noise reduction mask was also applied to the combined first- and second-order overlay. The method used, identifies where pixels that are adjacent (have faces touching) and then, using a post-processing tool, removes groups comprising less than 10 pixels (for the 30 m DEM). This number is obviously changeable but analysis of the 3 case studies (plus an international example) has shown that removing groups of approximately 8 - 10 removes most isolated pixels without losing essential information. Figure 12 shows the region near the Wambelong fire. The pink areas indicate the combined first and second order filters with the green areas removed as they are less than 8 pixels in size. For the 90 metre and 250 metre datasets, blocks of less than 6 and 4 are used respectively. However, in very 'broken' topography, these could be reduced futher.

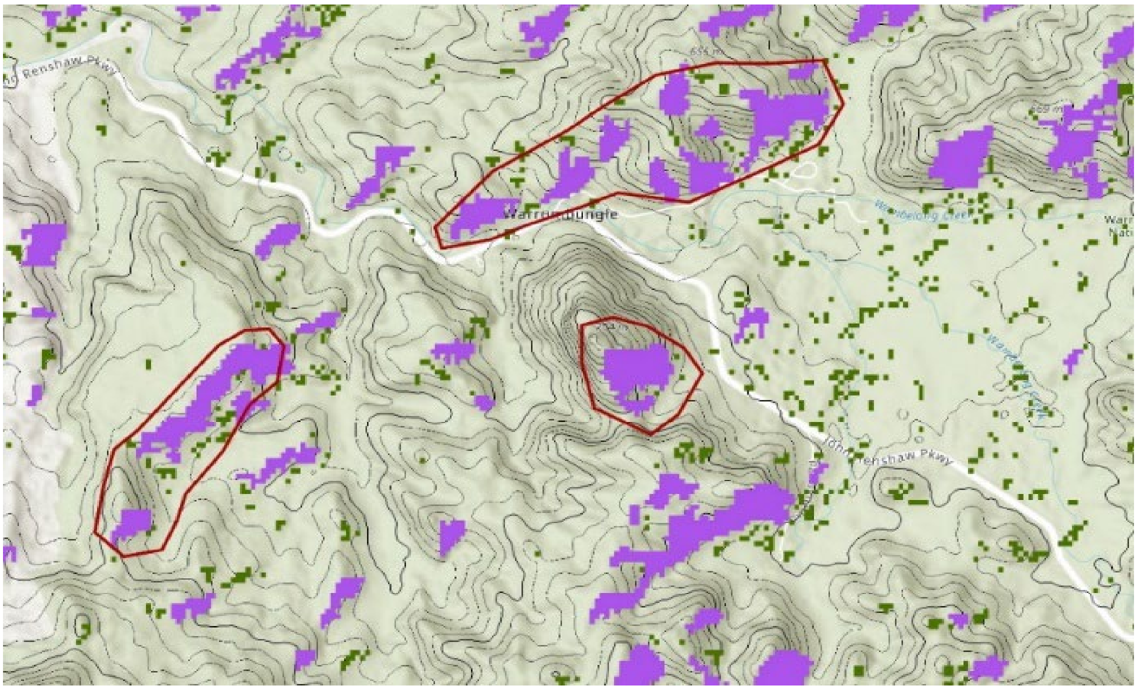

FIGURE 12. VLS FIRST AND SECOND ORDER FILTER (PINK) WITH ISOLATED PIXELS REMOVED (IN GREEN). REGION SHOWN IS NEAR THE WAMBELONG FIRE. POLYGONS SHOW AREAS WHERE VLS WAS IDENTIFIED. CONTOUR LINES ARE EVERY 50 METRES.

OPTIONS FOR OPERATIONAL FILTER OVERLAY

There were therefore some options for the information contained in the final operational filter. Figure 13 shows the various configurations that could have been chosen for the eventual filter.

The options were:

a) the first-order filter only (this shows the main areas of risk),
b) the second-order filter only. While this does identify the ridge tops where the lateral spread ends to be confined. It omits the broader regions prone to the impacts of VLS.
c) first-order and second-order filters as a two-layer overlay
d) combined (union of) first-order and second-order filters
e) Combined filter with isolated pixels removed.
f) The option of removing isolated pixels, to make it easier for interpretation, without loss of the major VLS zones.

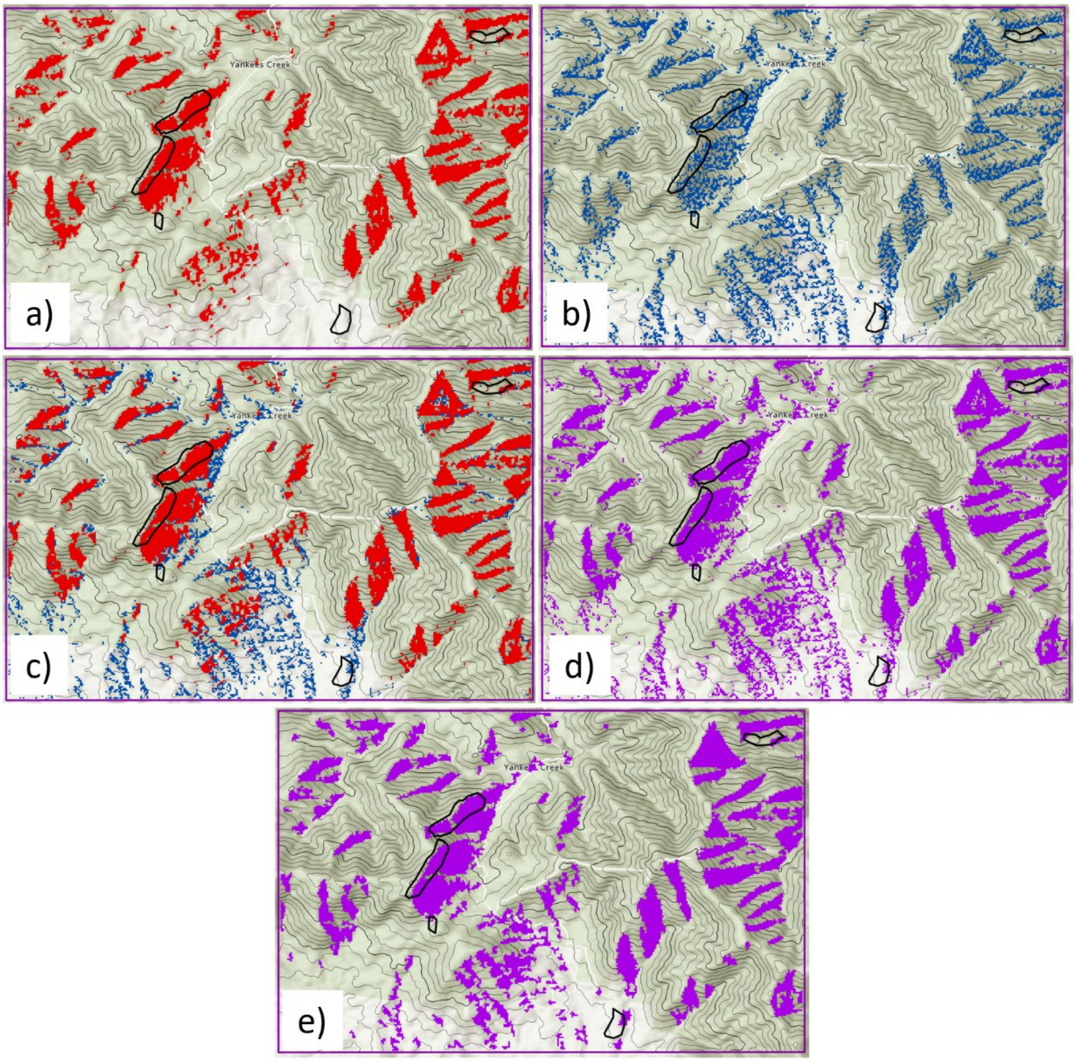

FIGURE 13. VARIOUS VLS WIND-TERRAIN FILTERS APPLIED TO YANKEES GAP FIRE, BEMBOKA. A.1ST-ORDER VLS FILTER B.2ND-ORDER VLS FILTER C.1ST-ORDER FILTER OVERLYING 2ND-ORDER FILTER D. BOTH FILTERS MERGED E. BOTH FILTERS - PIXELS REMOVED

USING THE FILTERS

Yankees Gap fire (Bemboka)

To illustrate the use of the filter, the case study of the Yankees Gap Fire is considered.

1) The fire authorities are informed of a fire with ignition at point ‘x’ (Figure 14 a) on 15th September 2018 at approx. 1320 hrs. Wind is approximately WNW.

2) VLS filter for WNW wind for first and second order filter combined shows the fire near VLS-prone areas (Fig. 14 b).

3) Linescan on 15th September 2018 at approx. 1417 hrs with polygons showing areas where VLS occurred (Fig. 14c)

4) VLS filter overlain to show where VLS occurred and where the filter predicted (Fig. 14d).

This case-study is thoroughly covered in the training manual.

The first and second order VLS filters have been tested for the chosen case studies and have identified areas of high VLS risk, for those examples. However, there are areas of low slopes and broken topography that have experienced VLS but would not be captured by this filter. This is due to the extent of the slope being less than the resolution of the DEM and would need to identify solely by the second order filter. For a balance between accuracy and ease of interpretation, the merged first and second order filters with the removel of isolated pixels was chosen for all the static filters.

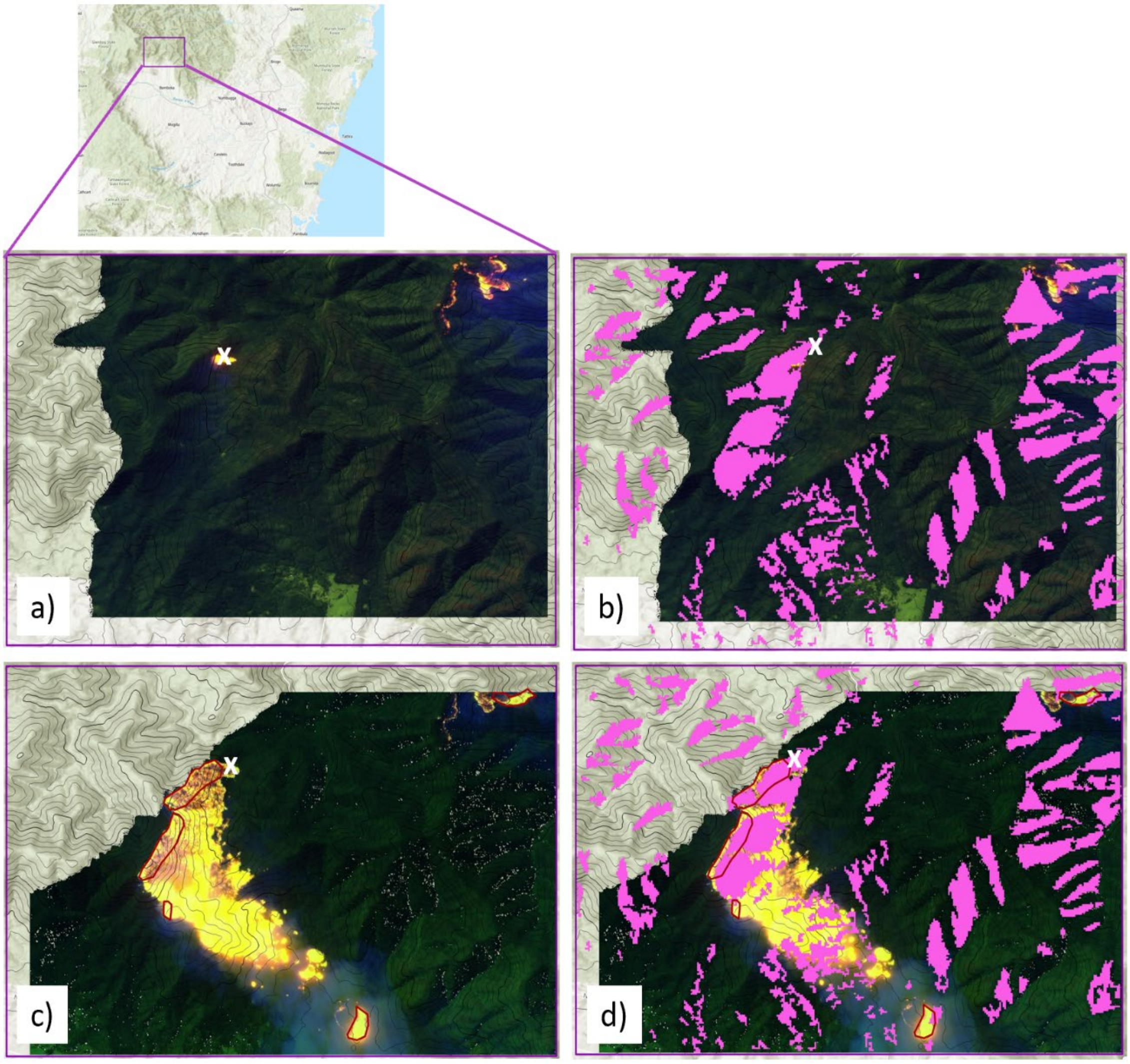

FIGURE 14. YANKEES GAP FIRE 15 SEPTEMBER 2018. A) LINESCAN AT 1320 HRS, B) VLS FILTER FOR WNW WIND, C) LINESCAN AT 1417 HRS, AND D) FILTER AND LINESCAN OVERLAIN.

FINAL VERSION OF VLS FILTER

STATIC FILTER

The version of the filter initially supplied is the static filter. These are produced using a uniform wind direction for each of the main 16 cardinal points (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, and NNW). The filters are produced for each of the following states: New South Wales, Queensland, South Australia, Tasmania, and Victoria. Each filter is supplied in a coarse resolution (based on a 250 metre resolution DEM) and an intermediate resolution (based on a 90 metre resolution DEM). High resolutions may be produced if requested.

The suggestion is to apply the coarse resolution filter initially to identify broad regions where VLS may occur given the synoptic wind direction being forecast. The intermediate filter may then be used to get more detail for a particular area.

The associated training manual (Badlan and Sharples 2021) gives a more comprehensive overview of the filters and guides the reader through two case studies to gain familiarity in use and interpretation.

EVALUATION OF FILTER

Unfortunately, due to the COVID pandemic, and the resultant border closures and travel restrictions, it was not possible to incorporate first-order VLS filter prototype into operational framework or engage in face-to-face meetings as part of the development stage.

However, it was possible to consult with Simeon Telfer (Department of Environment and Water, South Australia), in April 2021 who gave a comprehensive overview of the platform that DEW use and how the filter would be incorporated into operational overlays. We also discussed the method of incorporating real-time wind data into the filter (see further work). Simeon also confirmed the usefulness of such a filter for research and to determine dangerous conditions for fire-prone areas.

Musa Kilnic from Country Fire Authority in Victoria has also provided positive feedback and has shown interest in use of the filter for operational purposes.

FURTHER WORK

STATIC FILTERS

Some additions are planned to the static filter datasets. Firstly, the addition of filters for the southern part of Western Australia is planned as it has experienced a number of extreme fires and would therefore benefit having fiter overlays to allow analysis of fires in the region.

The current collection of filters will also be expanded to allow for a high resolution set of filters which may be of particular use for more detailed analysis of past events and to interpret certain scenarios.

Avenues for future refinement may potentially include calibration of second-order filter with slope, inclusion of other factors such as fuel load and moisture content and, further research into identifying any parts of the landscape where VLS has been noted to occur but has not been identified by the current filter.

DYNAMIC FILTERS

To accommodate the dynamic conditions that affect the likelihood of VLS, it is intended to incorporate the wind forecast used by each state. The approach is to create a Python script that could be run daily to create VLS filters for each wind forecast (usually hourly). As FBANs are trying to decide how the conditions are changing throughout the day, they can apply whichever filter they need, depending on the time of the forecast needed.

Each agency must then also create an area to store all the filters, so analysis of events can take place afterwards if needed, for either training, case study analysis (learned outcomes) or for commissions/coronial inquests.

There are also parts of the landscape where topographic features are not fully captured by the filter, and further research is needed to identify what qualities these regions have. Perhaps the algorithm for those areas may need to be tailored to those areas. This is a refinement of the tool and not necessary for the short-term use of the filter.

CONCLUDING REMARKS

Whilst currently only the static filters are currently supplied, research is continuing into producing a script to generate the dynamic filter. This script may have to be tailored to each state depending on the wind dataset that each state uses. Each state will be required to provide its own script to automate the (daily) generation of the filters.

It is also suggested that all states have access to all the datasets, to allow investigation into notable fires regardless of in which state the fire occurred. This is especially useful for states that have a limited number of cases to study. If there are any areas that have been missed by the filter, please contact us so we can update the filter to include your chosen location. It may also be of use to set up an email group and central repository to enable notifications and distribution of any updates for all fire agencies.

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