Reconstruction of the spread and behaviour of the Waroona bushfire (Perth Hills 68)

6-7 January 2016

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Government of **Western Australia**
Department of **Parks and Wildlife**

This report was compiled to inform the Waroona Bushfire Special Inquiry, and is based on information available to the fire behaviour reconstruction team up to 14 March 2016.

Further information about meteorological aspects of the Waroona bushfire is available in a report prepared by the Western Australian Regional Office of the Bureau of Meteorology.

Version 1.1

Date of issue 6 April 2016

Cover image: View from Mt William to the east north east showing widespread defoliation due to crown fire on the morning of Thursday 7 January 2016.

Summary

The Waroona bushfire (Perth Hills Fire 68) was ignited by lightning in the Murray River valley south-east of Dwellingup and was detected at 0630 hr on Wednesday 6 January 2016. Burning under prevailing E to NE winds the fire made a series of major runs to the west, eventually burning to the Indian Ocean near Lake Preston. Around sunset on 7 January the fire burned through the town of Yarloop resulting in the loss of two lives, destruction of more than 100 homes and severe damage to other buildings and infrastructure. The fire burnt a total area of 69165 ha including 31180 ha of freehold land, making it the second largest individual fire in the south-west since the Dwellingup fire of January 1961. The fire was notable for its size and complexity, for the scale and duration of suppression operations, and for its significant social and economic impacts on the community of south-west Western Australia.

This report reconstructs the development of the Waroona bushfire from the time of detection on 6 January to midnight on 7 January based on four distinct phases of fire development.

The initial phase of fire development took place in open forest and areas subject to current bauxite mining activity. Initial attack on the fire was hampered by steep and inaccessible terrain along the Murray River valley, and by rapid escalation of fire behaviour in long unburnt forest fuels during the late afternoon.

During Wednesday evening the fire made an unexpectedly rapid run under ESE winds through a complex fuel mosaic of remnant native forest, rehabilitated bauxite pits and current mining activity. This phase of fire development was characterised by extensive spotting, and may have been facilitated by further lighting ignitions from pyro-cumulonimbus activity during the late afternoon. Fire threatened the town of Waroona and spread rapidly through the agricultural landscape of the coastal plain.

During Thursday the fire grew on a broad front under the influence of ENE winds and spread down the Darling escarpment near the Wagerup bauxite refinery and east of the town of Yarloop. This phase of fire development was characterised by extensive crowning in fuels unburnt for 20 years or more and two further pyro-cumulonimbus events.

The McArthur Forest Fire Danger Index was High to Very High for most of 6 and 7 January, increasing to Severe for a period over parts of the fireground on the evening of 7 January due to a combination of increasing wind speed and falling dew point. Fire behaviour was greater than might be expected under these conditions on account of very dry fuel profiles, long unburnt and heavy fuels, and areas of steep slope.

There is a need to better understand the interactions between weather, fuels, atmospheric conditions and extreme fire behaviour associated with the formation of pyro-cumulonimbus.

The circumstances and impacts of this fire highlight the importance of fuel management in bushland in and around settlements, as well as across the broader landscape. This includes fuel management in the complex mosaic of vegetation age and structure that arises following bauxite mining operations in State forest.

Overview of the fire

The Waroona bushfire (Perth Hills Fire 68) was one of two fires ignited by lightning in the Murray River valley south-east of Dwellingup in the Lane Poole Reserve. Burning in jarrah forest, Perth Hills Fires 68 and 69 were detected on satellite imagery by Department of Parks and Wildlife personnel at 0630 on Wednesday 6 January 2016. Fire 69 was suppressed during the initial response at a size of 11 ha. Fire 68 was unable to be contained at initial attack due to inaccessibility and steep terrain, despite a sustained effort by ground forces and water bombing aircraft. During the afternoon of 6 January the fire spread west across the Murray River valley and escalated rapidly in size and intensity. During the evening the fire continued spreading rapidly to the west through the Alcoa mining envelope, comprising a mosaic of jarrah forest, and rehabilitated and non-vegetated mining pits, haul roads and other infrastructure. Later that evening the towns of Waroona and Hamel, and adjacent areas of agricultural land on the Swan coastal plain came under threat. By the early hours of 7 January, the fire had extended west across the coastal plain burning through a mosaic of agricultural land and remnant bushland. After sunrise on 7 January, the southern flank of the fire, which was burning in the jarrah forest mosaic on the Darling plateau, became an active head fire that spread in a west south west direction under the influence of ENE-NE winds. The fire remained active throughout the day with an extensive and complex perimeter that included agricultural land, State forest and other reserves, and major industrial infrastructure at the Wagerup alumina refinery and adjoining Willowdale minesite. Around sunset on 7 January, the wind veered to the east and increased in speed. Under hot, dry conditions, the south-eastern flank positioned to the north and east of the town of Yarloop became an active head fire that spread rapidly west, causing severe damage to the township of Yarloop and resulting in the loss of two lives.

The Waroona bushfire burnt a total area of 69165 ha including 31180 ha of freehold land, making it the second largest individual fire in the south-west since the Dwellingup fire of January 1961. The fire was notable for its size and complexity, for the scale and duration of suppression operations, and for its significant social and economic impacts on communities in the Shires of Waroona and Harvey. Impacts of the fire were experienced more broadly across the south-west as result of temporary closure of the South West and Forrest Highways during a busy holiday period, and closure of the railway line linking Perth and Bunbury. The fire also caused extensive damage to the electricity transmission grid with more than 1000 poles destroyed. Many thousands of hectares of forest and commercial plantation were fully crown scorched and defoliated by high intensity fire with significant and long-lasting implications for biodiversity, ecosystem health and vitality, water catchments and future forest productivity.

The process of reconstructing the spread of major bushfires provides a valuable opportunity to identify and analyse factors that contributed significantly to fire behaviour, and to learn lessons that can inform future policy and management practice. Well documented fire reconstructions are valuable for training, and for evaluating the performance of fire behaviour prediction systems and tools (Cheney 2010, Cheney et al. 2012, Burrows et al. 2015). Fire reconstruction can also contribute to better understanding of fire behaviour, particularly by identifying unusual phenomena that are not explained readily by existing theory and modelling approaches (Peace et al. 2015).

This report reconstructs the development of the Waroona bushfire from the time of detection on 6 January to midnight on 7 January. In order to meet the reporting timeframe of the Special Bushfire Inquiry commissioned by the Western Australian Government we have chosen to focus on this period when the fire grew most rapidly, setting the scene for impact on Yarloop during the evening of 7 January. Reconstruction of fire spread from 8 January onwards may be undertaken at a later stage, subject to demonstrated need and the availability of resources.

Examination of response and recovery actions to manage the impact of the fire on the community and environment are outside the scope of this report but are the subject of a Major Incident Review process.

Methods

Structure of this report

This report is divided into four parts:

1. An overview of the fire environment in the general area affected by the Waroona bushfire including topography, vegetation, land use and previous fire history.

2. Description of antecedent climate leading up to January 2016 and an overview of weather and atmospheric conditions during 6 and 7 January.

3. Chronological description of weather, fuel conditions and fire behaviour during four time periods representing different phases of fire activity:

   Phase 1 - 0630 to 1900 on 6 January
   Phase 2 - 1900 on 6 January to 0930 on 7 January
   Phase 3 - 0930 to 1830 on 7 January
   Phase 4 - 1830 to 2400 on 7 January

   Observed fire behaviour is compared with predictions from fire behaviour guides, and unusual weather phenomena identified through observations and reported by field observers are described.

   The reconstructed spread of the fire is presented using two maps showing fire isochrones and the direction of spread indicated by field observations of leaf freeze. Isochrones and leaf freeze are presented on a tenure map base (Appendix A), and on a on a base image showing categories of crown damage determined from high resolution aerial photography (Appendix B).

4. Synthesis of major findings drawn from the fire reconstruction

Data sources for climate and weather

The large size of the fire and variability of topography within its perimeter made it necessary to draw on weather observations from a number of locations to properly characterise conditions on the fireground. These observation sites are managed by several different agencies including the Bureau of Meteorology (BoM), the Department of Agriculture and Food Western Australia (DAFWA) and Alcoa. These sites include:

- BoM automatic weather stations at Dwellingup (-32.71° 116.06°, 267 m asl) and Collie East (-33.36° 116.17°, 200 m asl) which are located approximately 15 km north and 70 km south of the fire respectively, and represent conditions on the Darling plateau. Wind speed and direction are measured at 29 m height above forest canopy at Dwellingup and 10 m height above ground at Collie East. Dwellingup data are plotted as 30 minute observations.
- DAFWA automatic weather stations at Harvey (-33.06° 115.85°, 20 m asl), Logue Brook (-32.99° 115.85°, 200 m asl) and Waroona (-32.85° 115.89°, 20 m asl). Wind

speed and direction are measured at 3 m height at these stations, with a multiplier of 1.3 applied to make these equivalent to 10 m observations.

- Alcoa automatic weather stations at the Minesite (-32.79° 116.05°, 340 m asl) and at the Wagerup Refinery close to the base of the escarpment (-32.92° 115.91°, 40 m asl). Wind speed and direction are measured at 30 m height at the Minesite, and simultaneous observations for 10 m and 30 m heights are available for the Wagerup Refinery. Wagerup data are plotted as 6 minute observations.

Data sources for reconstruction of fire behaviour

Details of vegetation type and the number of years since last prescribed burn or bushfire were accessed from datasets maintained by the Department of Parks and Wildlife Fire Management Services Branch. The anniversary date for time since fire records is 1 July.

Fire spread was reconstructed from incident records which included:

- a detailed fire chronology prepared during a series of workshops attended by personnel representing Parks and Wildlife, Department of Fire and Emergency Services (DFES) and the Shires of Harvey and Waroona
- individual fire diaries and notes
- recollections gathered during interviews (Appendix C)
- maps prepared from field intelligence and aerial surveillance
- photographs and video images taken by personnel on the fire ground
- evidence collected from the fire ground by members of the fire investigation team including observations of crown defoliation, crown scorch, stem charring, fuel consumption and vegetation (leaf) freeze. Vegetation freeze refers to the orientation of scorched leaves, twigs and finer shrub stems following the passage of a flame front. Heat from the flames makes the finer plant material supple and those components that are scorched but not consumed are bent by the wind. On cooling, the vegetation remains ‘frozen’ in the direction of fire spread downwind. Vegetation freeze is a valuable indicator of wind direction at a location, and can be used to locate the position of a fire at the time of a wind change. Freeze can also provide a crude indication of wind strength with more pronounced freeze indicating stronger winds. Vegetation freeze can be variable and difficult to interpret in areas where fire behaviour has been severe and a high proportion of leaves have been consumed, or in areas where fire behaviour has been very mild. Numerous observations of vegetation freeze are generally required to indicate reliably the direction of spread of a large and complex bushfire.

A range of remote sensing products were also used for the fire reconstruction including MODIS and Himawari 8 satellite imagery. Satellite images provide an indication of the active fire and area burnt at time of overpass (only active fire during the night, where only thermal bands are used) when there is no cloud obscuring the image. Post-fire high resolution aerial photography and subsequent classification and patterning of overstorey canopy damage was valuable in reconstructing the fire’s path and aspects of its behaviour. Four band (RGB and NIR) imagery was captured approximately 2 weeks after the fire. Data were captured with 30 cm pixels but for this analysis the imagery was re-sampled to 3 m pixels. The analysis provided a classified image delineating forest areas with green canopy, scorched canopy, defoliated canopy and cleared areas (gravel pits, roads, etc.). Ashbed from burning logs was also clearly visible and was categorised with the cleared areas. Analysis was performed in ENVI® image analysis software and processing was performed using decision tree analysis. The result was a high resolution map of canopy damage categories.

Images from the BoM Doppler radar at Serpentine were used to examine the characteristics of the convective plume above the fire. Lightning discharge data were obtained from GPATS and Weatherzone.

Data were used to prepare maps with isochrones showing the estimated position and shape of the fire at intervals according to the rate of growth of the fire and the availability of reliable observations of the position of the fire.

Fire behaviour predictions

The Forest Fire Danger Index (FFDI) was calculated using the McArthur Mark V meter with the Drought Factor set at 10. FFDI values presented in tables and figures are based on 30 minute observations. Fire behaviour was predicted using the Dry Eucalypt Fire Model (DEFM) of Gould et al. (2007) with equations programmed into a spreadsheet format (WA Fire Models 2014). Fuel hazard scores and indicative fuel loadings were based on a Jarrah North West type with a fuel age of 10-20 years, and a wind ratio of 3:1. Fine fuel moisture content was predicted using the three models presented in the DEFM with the transition to Model 3 (night) conditions set at 2000 hrs. Two sets of predictions were made for each time period for which a reliable rate of spread observation was available from direct observation of spread, or from reconstructed spread. These predictions reflected:

- the mean fine fuel moisture content, slope and wind speed for the period, or
- maximum conditions based on the 25th percentile value of fine fuel moisture content, and 75th percentile values of slope and wind speed for the period.

Regional fire environment

Landform and topography

The fire extended across the western margin of the Darling Plateau and the Swan Coastal Plain. These broad landforms are separated by the Darling escarpment which rises about 300 m above the plain and has localised areas of steep and rugged terrain, and is deeply dissected by the drainage lines of the Drakes, Samson and Logue Brooks and smaller tributaries.

The Darling Plateau is an undulating lateritic upland at an elevation of 300-340 m above sea level, with occasional higher points exceeding 450 m elevation at Mt William and Mt Keats. The plateau is dissected by the Murray River valley which trends roughly north-south in the area affected by the fire, and has localised slopes up to 20° and outcropping of the basement igneous rock. Summer flows in the Murray River are intermittent and the river itself provides no barrier to the spread of fire. Vehicle crossing points are limited, with more than 20 km separating the crossing at Driver Rd on the southern end of the fire and the Nanga Road bridge.

The Swan Coastal Plain is flat and elevation varies by only a few metres between Waroona to the coast at Preston Beach. The Harvey River drains the central section of the plain between Waroona and the Bassendean dunes of heavily leached grey sand closer to the coast. Between the Bassendean dunes and the coast are younger dunes and a system of seasonally dry lakes, the largest of these being Lake Preston and Lake Clifton.

Climate and weather

The area experiences a Mediterranean-type climate with cool moist winters and warm to hot summers that are typically dry and have median monthly rainfall below 20 mm from December to March. The Darling escarpment creates orographic uplift that leads to increased rainfall on the western margins of the plateau, with mean annual rainfall of 1234 mm at Dwellingup and 992 mm at Waroona over an 80 year recording period. Mean annual rainfall declines steadily with distance east from the escarpment. Rainfall has been declining across much of south-west Western Australia since the mid-1970s and the period since 2000 has seen a number of years with rainfall very much below normal. Mean monthly temperatures are 1-2° cooler on the plateau than on the coastal plain.

During the summer months anti-cyclones move along the southern edge of the continent directing easterly winds across the south-west, accompanied by the development of a west coast trough. Winds associated with this synoptic pattern are predominantly easterly overnight and during the morning, and may be strong and gusty close to the escarpment and on adjacent parts of the coastal plain. A sea breeze from the S to SW is common during the afternoon, with the influence zone dependent on the temperature gradient and strength of the easterly gradient. Summer seas breezes commonly reach the escarpment, and may influence Dwellingup and the Murray Valley under favourable circumstances. Winds typically return to the E and increase in strength after sundown. This weather pattern is normally associated with McArthur Forest Fire Danger ratings of Moderate to High, increasing to Very High (>32) when winds are strong and the air mass is warm and dry.

Vegetation, land use and recent fire history

On the Darling plateau the dominant vegetation type is open eucalypt forest of jarrah (*Eucalyptus marginata*) and marri (*Corymbia calophylla*) with a potential height of 25-30 m. Moister and more fertile sites support extensive stands of bullich (*Eucalyptus megacarpa*) and blackbutt (*Eucalyptus patens*), while skeletal soils associated with the escarpment support a woodland of wandoo (*Eucalyptus wandoo*) and marri. Open forests have an understorey of woody shrubs that can vary from scattered low shrubs (<0.5 m) on harsh sites to dense stands of taller shrubs (>1.5 m) on fertile sites associated with streams and swamps. Fuel structure and loading are influenced strongly by time since fire, and default fuel characteristics are provided for four age classes of the Jarrah North West forest type in Parks and Wildlife Fire Operations Guideline 22.

Most of the forest is public land vested in the Conservation Commission and managed by the Department of Parks and Wildlife as conservation reserve or State forest where timber harvesting may occur periodically. Large parts of the Waroona, Samson and Federal forest blocks in State forest have been mined for bauxite to supply the Wagerup refinery since the mid-1980s. These areas have become highly fragmented by mine pits, haul roads, conveyor lines and other infrastructure. Mining takes place on the lateritic uplands where the depth and grade of ore are superior, and mine pits are dispersed over a wide area rather than working on a single active front. Following mining the pits are ripped and rehabilitated with a seed mix that includes native tree and understorey shrub species. Remnant patches of unmined forest are dispersed throughout the mining envelope, and tend to be in lower lying areas where bullich and blackbutt dominate the overstorey.

Most of the forest burnt on 6 and 7 January had been unburnt for at least ten years, some of it for over 30 years (Fig. 1). Younger fuels resulting from prescribed burning were located east of the Murray River in Young block (6 years old), and west of the river in Nanga block (2 years old). A large area of 6 year old fuel was also located east of the Muja Northern terminal powerline in Driver and Hoffman blocks as a result of a bushfire in December 2009.

The area affected by bauxite mining comprises a mosaic of active operations, rehabilitated pits and patches of remnant forest that has not been burnt since mining operations commenced (Fig. 2). Rehabilitated pits are densely stocked with even-aged saplings, and fuel structure and loading depend on stand age. For most rehabilitated pits time since fire would be the same as stand age, except for those burnt a bushfire in January 2006. This fire started in the Murray Valley and spread westwards through State forest, reserve and the Willowdale minesite before being eventually contained on the eastern side of the Wagerup refinery at a final size of 11090 ha. This fire burnt several hundred hectares of rehabilitated bauxite pits in the southern part of Samson forest block. Experience gained during this fire indicated that rehabilitated stands less than 5 years old were unlikely to support intense fire behaviour due to light and discontinuous fuels, but that older stands could support intense fires with active crowning facilitated by the low and uniform canopy height (Fig. 3). The absence of an overstorey of taller trees means that within-stand wind speeds are likely to be greater than in uneven-aged native forest.

Remnant native forest within mined areas has generally been unburnt for several decades, and fuel ages date from the time that broadscale aerial fuel reduction burning was last undertaken in the 1980s and early 1990s. These stands have abundant surface and near-surface fuels, with very high to extreme fuel hazards and loadings exceeding 20 t ha^{-1}. Remnant stands that include bullich may have a large component of bark pieces in the near-surface fuel layer, and long strands of bark loosely attached to the trunks of standing trees (Fig. 4). Bullich has a similar bark to karri (*Eucalyptus diversicolor*) which has been shown to have potential for long distance spotting because of its low terminal velocity and slow burn-out time as a firebrand (Ellis 2010).

Vegetation on the escarpment includes jarrah forest, wandoo woodland and shrubland fringing rock outcrops. The escarpment is predominantly freehold land, and much of it has been partially cleared and grazed. Fire history on freehold has not been recorded systematically and is unlikely to be a useful indicator of fuel hazard or loading in grazed areas. Annual grasses on the escarpment would have been fully cured in Jan 2016. Bushland to the east and south of Waroona townsite was burnt by an unplanned fire in late January 2015, and a small reserve in the Yarloop townsite immediately west of the South West Highway was burnt by prescribed fire in May 2015.

The coastal plain is predominantly freehold land used for a range of agricultural enterprises including irrigated dairying, horticulture and dryland beef production. An extensive network of irrigation channels and deep drains has been established to service agricultural lands, but over the past decade open channels have been replaced with pipes to reduce water loss from seepage and evaporation (Fig. 5). The eastern half of the coastal plain adjoining the South West Highway has been cleared more extensively than the western half. Vegetation ranges from woodland of jarrah, *Banksia* and *Allocasuarina* on drier sites to Melaleuca swamps in seasonal wetlands. Remnant vegetation on the eastern side is limited to small reserves, roadside verges and drains, much of it in degraded condition and invaded by annual grasses and weeds (Fig. 6).

State-owned plantations of *Pinus pinaster* and *Pinus radiata* have been established on the Bassendean dunes adjoining the Forrest Highway (Fig. 7). West of the highway the Yalgorup National Park includes woodland of tuart (*Eucalyptus gomphocephala*), peppermint (*Agonis flexuosa*) and a variety of coastal shrubland communities. Prescribed burning of native vegetation adjacent to pine plantations has taken place on a limited scale for hazard reduction. Most of Yalgorup National Park had been unburnt for at least 20 years prior to January 2016.

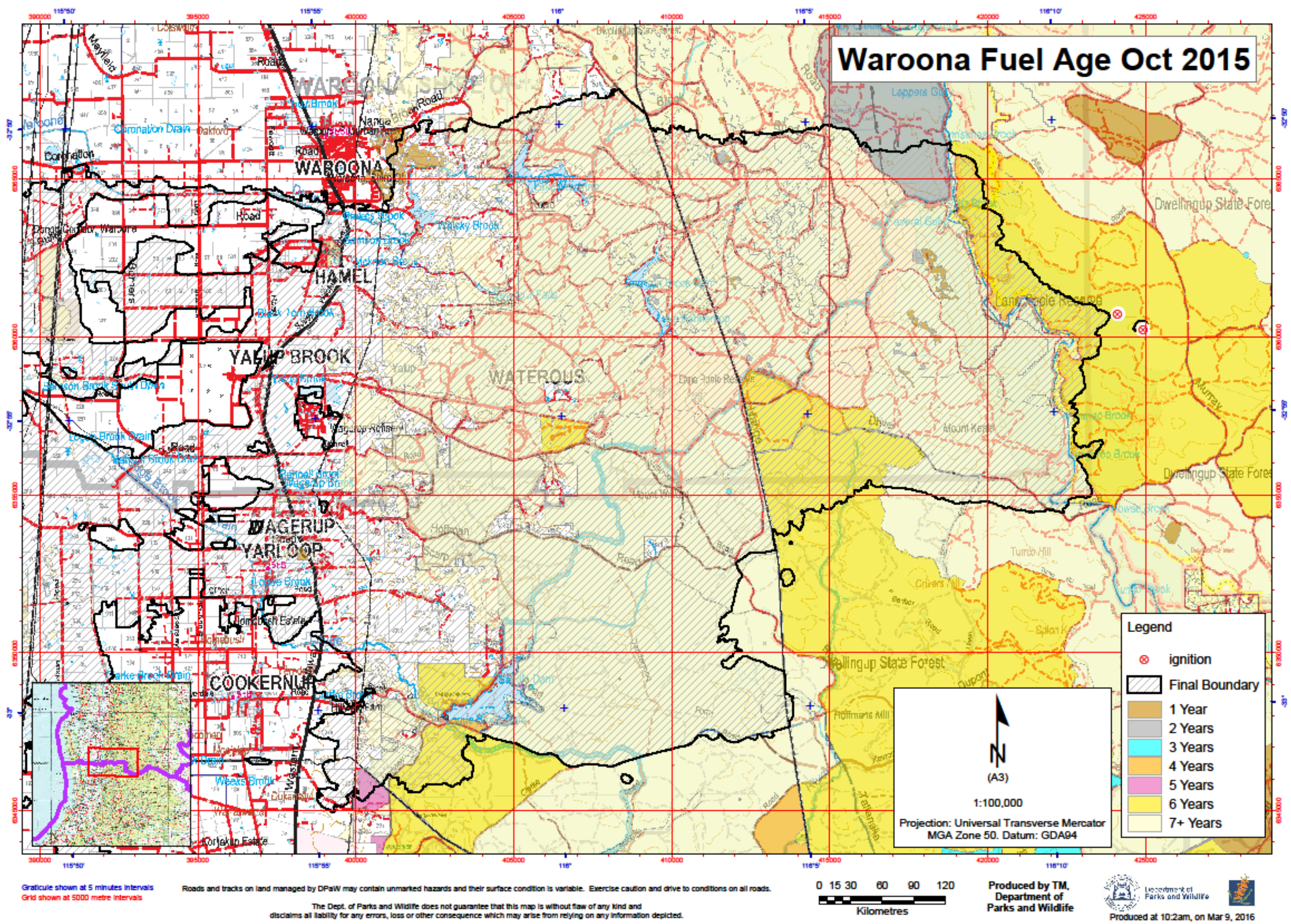

Figure 1. Fuel age at the time of the Waroona fire.

Figure 2. Minesite west of Nanga Rd with remnant jarrah forest, rehabilitated bauxite pit and haul road.

Figure 3. Rehabilitated bauxite pit burnt during the evening of 6 January 2016.

Figure 4. Stand of bullich and blackbutt on Nanga Brook Rd, typical of remnant native forest on lower lying areas within the minesite. This stand has not been burnt for 30 years and has abundant surface and near-surface fuel with a large proportion of bullich bark.

Figure 5. Trees planted along disused open irrigation channel north of Waroona main drain.

Figure 6. Remnant vegetation along Somers Rd west of Waroona.

Figure 7. View to the east from McLarty plantation towards the Darling escarpment.

Weather overview

Antecedent conditions

The trend of below average rainfall in the south west region of Western Australia, particularly since the 1970s and consistent with climate change modelling, is clearly illustrated in Fig. 8 (source: Brad Santos BoM). Local weather conditions leading up to the Waroona fire were derived from the BoM AWS at Dwellingup, some 24 km north of the origin of the fire. Annual rainfall at Dwellingup for 2015 was 780 mm, about 35% below the long term average (1234 mm) and the third lowest rainfall on record.

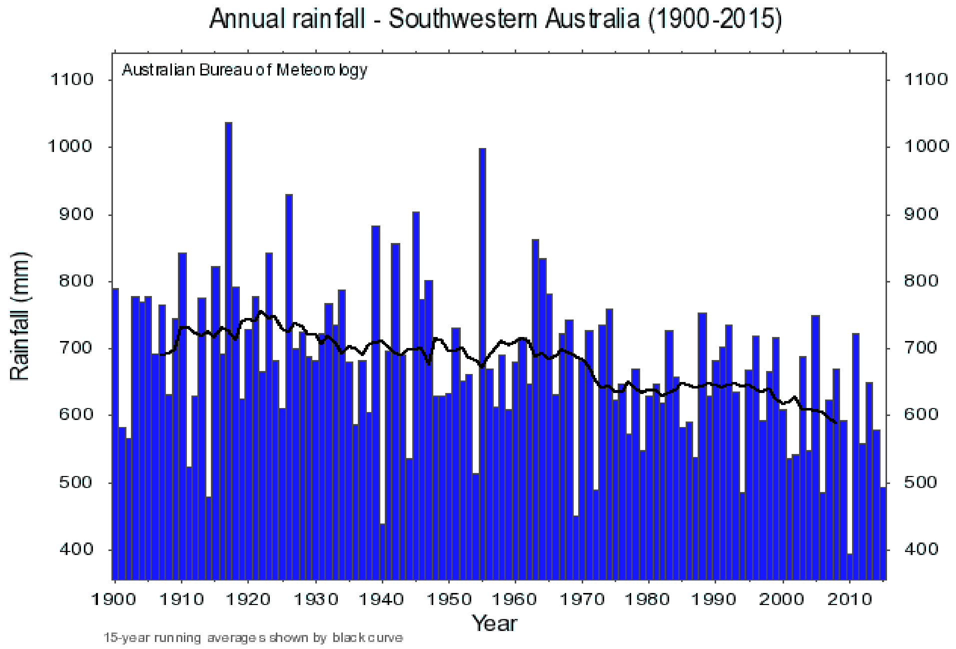

Figure 8. Annual rainfall and running annual average for south-west WA (Courtesy Brad Santos BoM).

The last significant rainfall (>5 mm) recorded at Dwellingup prior to the fire was 24 mm over two days on 5-6 December 2015. Below average rainfall and above average temperatures in spring and early summer 2015/16 resulted in a Soil Dryness Index (SDI, mm) at Dwellingup of 175 on 6 January 2016 (Fig. 9), some 45 mm higher than the previous five-yearly average and equal highest since 1992 for the same time of the year. The SDI as used in fire management (Mount 1972; Burrows 1985) is a measure of regional dryness or 'drought' and ranges from 0 when the surface soil (top 30-40 cm in Western Australia) is saturated (field capacity) to 200 when the surface soil profile is 'bone' dry. A SDI of 175 indicates that surface soil, heavy forest fuels including coarse woody debris and deeper forest fuel profiles were exceptionally dry for this time of year, as was the forest understorey and bark on standing trees. Consequently, the total available forest fuel load was maximal as reflected in a McArthur Drought Factor of 10. Unirrigated paddocks were fully cured.

Synoptic situation

During the summer months, a high pressure system in the Great Australian Bight and the west coast trough are regular features of the synoptic chart for Western Australia and are dominant features of weather experienced in the south-west. Typically, areas east of the trough experience hot, dry winds from the north-east whereas areas to the west experience mild, cooler weather associated with southerly breezes. Atmospheric instability and thunderstorms are common east of the trough line.

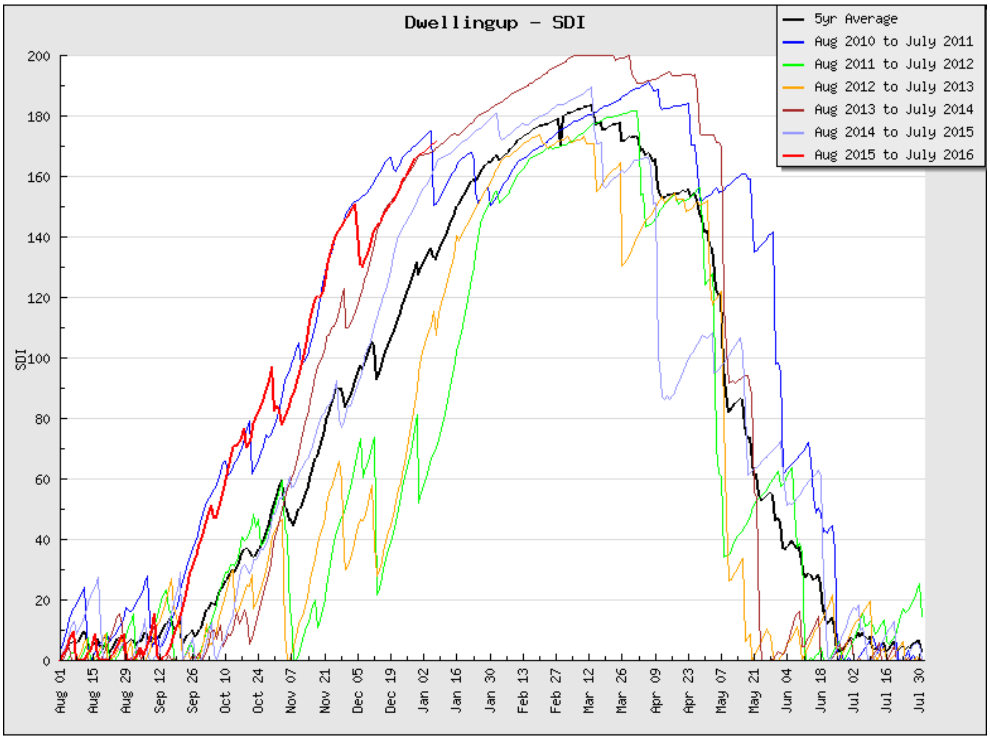

Figure 9. Soil Dryness Index (mm) for Dwellingup showing trend for 2015/16 season (red line) and the five year average (black line).

The formation and movement of the trough is variable and sometimes difficult to predict accurately, but usually the systems move east within a couple days of formation. However troughs can persist for extended periods, particularly in association with hot conditions in the northern interior/Pilbara region of the state. Movement of the weather systems from west to east is accompanied by changing temperature, moisture, wind speed and direction. As the high pressure system moves east, winds back from the east in an anticlockwise direction. If bushfires burning in heavy, dry forest fuels are not controlled in their initial stages before the anti-clockwise movement in wind direction they have the potential to the wind change turns extended flank fires into wide head fires.

The synoptic charts in Figure 10 show the position of the west coast trough and the high pressure system at 0800 hrs 5-7 January. An interesting feature of these charts is the persistence of the west coast trough. Lightning associated with the trough started two fires in the Lane Poole Reserve, one of which developed to become the Waroona fire.

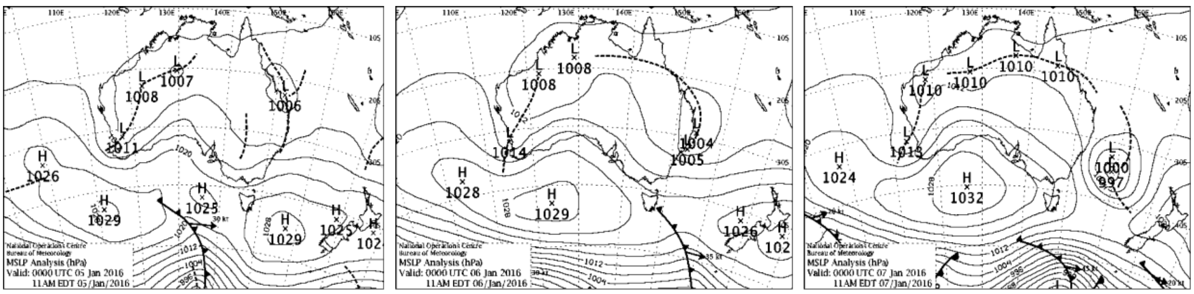

Figure 10: 0800 (WST) daily synoptic (weather) charts for the period of the Waroona fire from 5-7 January 2016. Lightning associated with the trough started the Waroona fire.

Atmospheric stability

Atmospheric stability, or the rate of change of air temperature with altitude, can influence fire behaviour through its influence on the buoyancy or rate of rise (kinetic energy) of the convection column. Extreme or erratic fire behaviour is usually associated with an unstable atmosphere because of the increased kinetic energy or buoyancy of the convection column. Beyond recognising broad associations, understanding of the complex processes and interactions between bushfires and the upper atmosphere is limited and documenting large fire events such as this provides an opportunity to improve our knowledge.

Aerological diagrams provide information about the vertical structure of temperature, moisture (dew point) and winds in the upper atmosphere so can be used to determine atmospheric stability and to provide information about the strength and dryness of winds aloft. The diagrams can also detect layers of warm, very dry air (dry slots) and there is evidence that, under some circumstances, bushfires can induce mixing of dry slots to the surface, significantly influencing fire behaviour. Figure 11 shows aerological diagrams for 6 January constructed from balloon flights at Perth Airport, some 100 km north of the fire and modelled atmospheric profiles on 7 January for the fire ground location (courtesy Brad Santos, BoM).

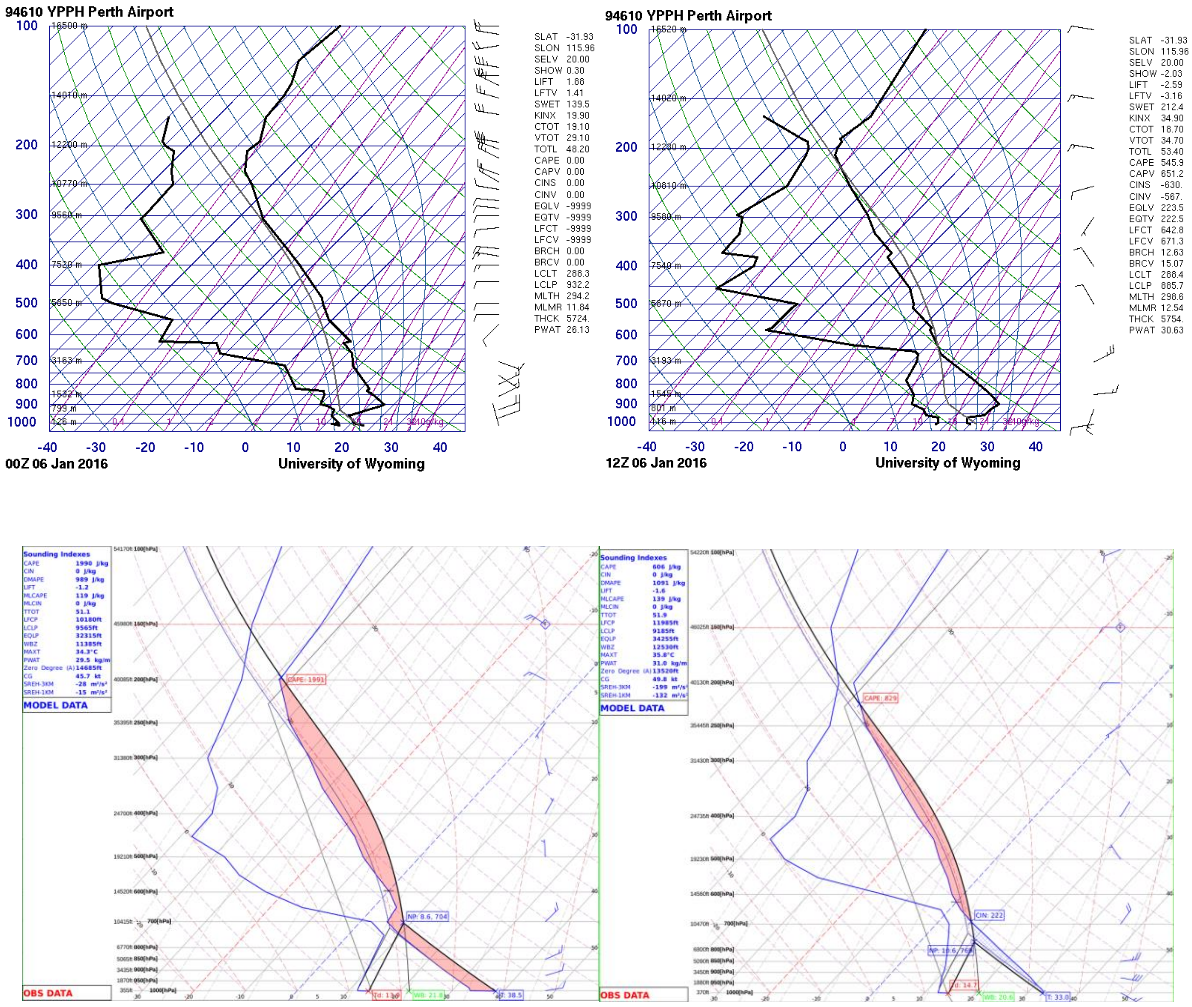

Figure 11: Aerological diagrams for Perth Airport at 0800 hr and 2000 hr on 6 January (upper panel) and modelled atmospheric profiles for the Waroona fire ground at 1400 hr (L) and 2000 hr (R) on 7 January (lower panel)(courtesy B. Santos BoM).

Significant features illustrated in Fig. 11 include:

- 6 January 0800 hrs: surface inversion, stable atmosphere (Lift Index = +1.88; c-Haines = 5.8), with dry air above 3,000 m.
- 6 January 2000 hrs : weak surface inversion, unstable atmosphere (Lift Index = -2.59; c-Haines = 9.6), dry air above 3,000 m.
- 7 January 1400hrs and 2000 hrs: unstable atmosphere (Lift Index = -1.2 and -1.6; c-Haines = 8.3 and 9.1), light to moderate ENE winds to 3,000 m.

The 95th percentile value for the c-Haines at Perth Airport is 8.8. Values above the 95th percentile have been consistently associated with unexpectedly severe fire behaviour in southern Australia (Mills and McCaw 2010).

Fire spread and behaviour

Phase 1 - 0630 to 1900 on 6 January

Weather

Wednesday 6 January was a hot dry day with a maximum temperature of 37°C and minimum relative humidity of 14% recorded relatively late in the afternoon at Dwellingup (Fig. 12). Morning winds were ESE and moderately strong, becoming lighter and more east NE during the afternoon (Fig. 13). Dew point fell steadily during the day to a minimum of 5.4°C at 1630 hrs then increased rapidly as the wind swung to the west south west. The McArthur FFDI peaked at 38 during the mid afternoon then declined as humidity increased and winds became lighter (Fig. 14). The Western Australian Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1985) predicted a minimum Surface Moisture Content of 5% and a jarrah rate of spread index of 130 m h^{-1} at Dwellingup.

Wind speeds during the day were similar at Dwellingup and the Alcoa minesite which is 9 km closer to the fire ground than Dwellingup and measures wind at 30 m height (Fig. 15). After 1900 hr Dwellingup recorded significantly higher wind speeds. No data are available from the Alcoa minesite after 0130 hr on 7 January, because the power system was interrupted by the fire.

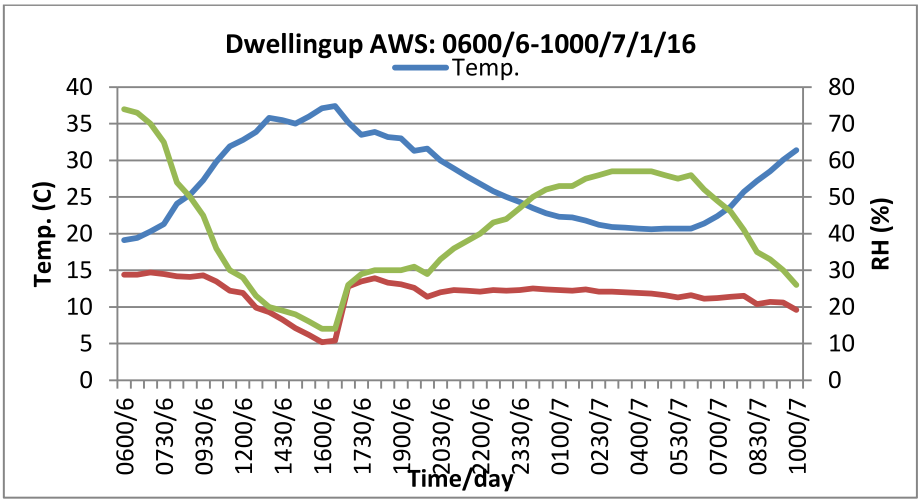

Figure 12. Dry bulb temperature (blue), dew point (brown) and relative humidity (green) recorded at Dwellingup from 0600 hr on 6 January to 1000 hr on 7 January 2016.

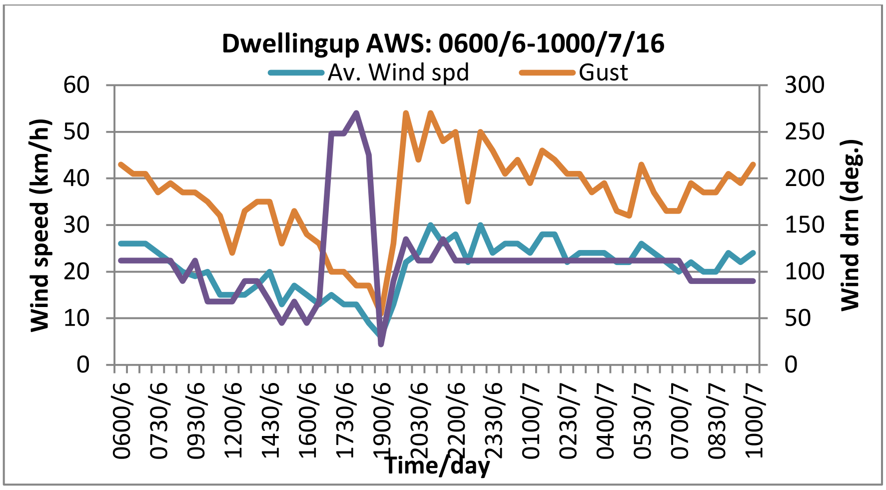

Figure 13. Average wind speed (blue), gust speed (brown) and wind direction (purple) recorded at Dwellingup from 0600 hr on 6 January to 1000 hr on 7 January 2016.

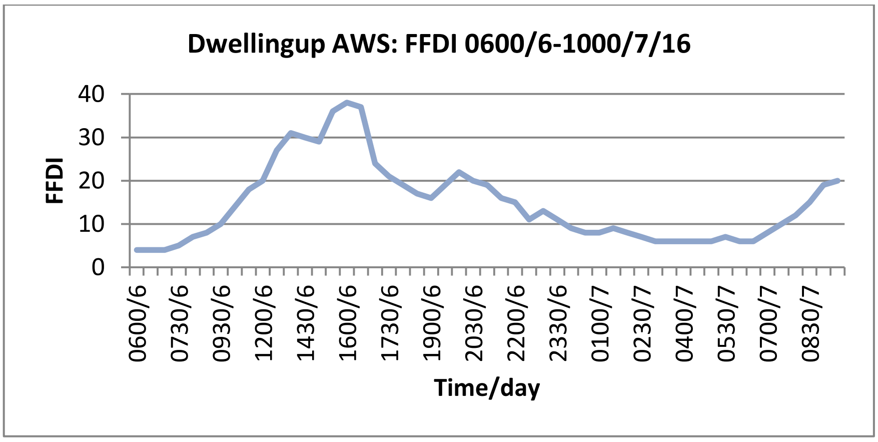

Figure 14. McArthur FFFDI at Dwellingup from 0600 hr on 6 January to 1000 hr on 7 January 2016.

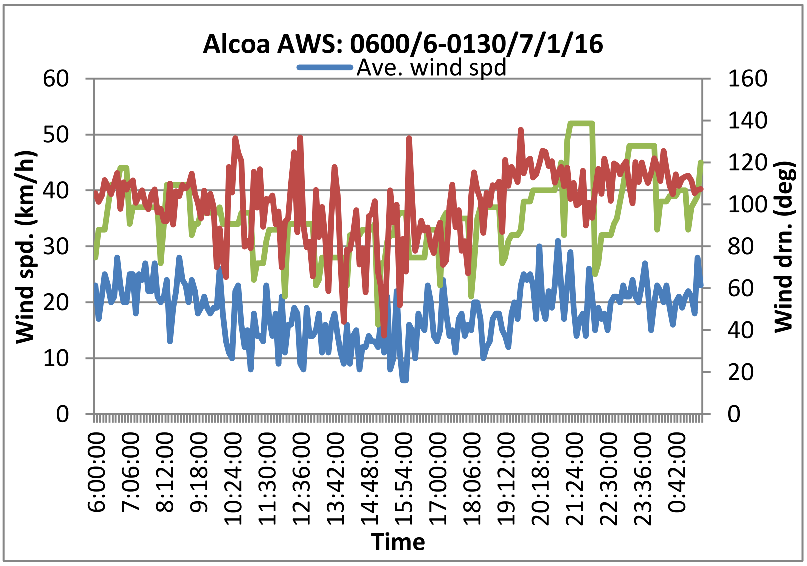

Figure 15. Average wind speed (blue), gust speed (green) and wind direction recorded at the Alcoa minesite from 0600 hr on 6 January to 0130 hr on 7 January 2016.

Fuels

The fire developed initially in open forest of jarrah and marri on the eastern side of the Murray River valley in 6 year old fuels dating from a spring 2009 prescribed burn in Young forest block (Fig. 1). Reports from Perth Hills District personnel indicate that the 2009 prescribed burn was of moderate intensity and consumed surface and near-surface fuels on the uplands, but that much of the steep west-facing aspect of the valley burnt patchily or not at all (M. Pasotti, pers. comm.). Fuel hazard and loading on these slopes may therefore have been considerably greater than indicated by the nominal fuel age of six years. Observations made by members of the fire investigation team near the origin of Fire 68 on 29 January supported this view, with an absence of bark charring on jarrah trees and a continuous and deep layer of surface fuel. In contrast, unburnt fuels near the origin of Fire 69 on the upland landform had considerable bark charring and a shallower surface fuel layer, as would be expected for 6 year old fuel.

West of the Murray River fuels were considerably older, ranging from 10 to 37 years since last fire. Much of the State forest within this phase of the fire run was through current mining activity that included active pits and expanses of recently cleared forest. As the fire progressed further west of Nanga Rd it encountered an increasing proportion of older rehabilitated bauxite pits densely stocked with jarrah and marri saplings (Fig. 3).

Fire behaviour

Lightning activity during the evening of Tuesday 5 January ignited two fires west of Murray Rd in Young forest block. These were first detected on satellite imagery by Parks and Wildlife personnel at 0630 on Wednesday 6 January. The eastern-most fire (Fire 69) was burning in open forest on a gentle slope above the 300 m contour at -32.89° 116.19°. First arriving crews reported mild fire behaviour with flame heights less than 2 m and this is supported by post-fire observations of char, defoliation and crown scorch height. The origin of Fire 69 was confirmed to be a mature marri tree struck by lightning with an obvious scar on the trunk (Fig. 16). Ground forces concentrated initial attack on Fire 69 because the prevailing easterly winds made it necessary to contain this fire before personnel could safely commence attacking Fire 68 which was further to the west. Fire 69 was contained at 1143 hr at a size of 11 ha.

Figure 16. Lightning struck tree at the origin of Fire 69.
Arrow points to fresh scarring on the trunk.
(Photo: Peter Moore, Parks & Wildlife Dwellingup)

The point of origin of Fire 68 was approximately 3 km west of Murray Rd in moderately steep terrain of the Murray River valley at -32.89° 116.17°. At 0815 hr the Parks and Wildlife spotter aircraft reported the fire to be 8 ha in size and burning with a rate of spread of 50-100 m h^{-1}. Aerial attack with water bombing aircraft commenced shortly afterwards with the aim of restricting the development of this fire until Fire 69 was contained and a direct attack made with bulldozers and ground crews on Fire 68. By 1000 hr the fire was reported to be spotting. Direct attack by ground crews and machines was hampered by the inaccessibility of the fire, the presence of large numbers of dead trees and the escalating intensity of the fire (Fig. 17 &18). Rock outcropping presented difficulties for bulldozers attempting to track the edge of the fire. By 1330 hr the fire had crossed the Murray River and was spreading west south west through steep and inaccessible terrain, with an estimated size of 160 ha.

The reconstruction of spread indicates that by 1450 hr the fire had reached the active bauxite mining operations in Keats forest block (Appendices 1 and 2).The reconstructed rate of forward spread of the fire between 1140 hr and 1450 hr was 1105 m hr^{-1} with a corresponding mean fireline intensity of about 12000 kW m^{-1} (Table 1). The predicted rate of spread ranged from 815 m h^{-1} to 1608 m h^{-1} depending on whether inputs represented the mean or maximum conditions of fine fuel moisture content, slope and wind speed.

Between 1450 hr and 1906 hr the rate of spread increased to a mean of 1320 m h^{-1} over the 4.25 hour period. A period of very rapid spread occurred between 1800 hr and 1906 hr when the observed rate of spread was 3272 m h^{-1}, exceeding the predicted rate of spread by a significant margin even when the maximum input values were applied. This period coincided with the fire encountering an area of un-mined forest in proposed national park between King Jarrah Formation and Nanga Rd last burnt in 1978 and carrying 37 year old fuel. The fire spread uphill on slopes of up to 12° for a distance of 1-1.5 km through the 37 year old fuel. Field inspection and aerial photography indicate sustained periods of crown fire with flame heights in excess of 30 m.

Abundant firebrands generated by intense fire behaviour in the long unburnt fuel are likely to have contributed to mass spotting during the early evening.

Table 1. Observed and predicted forward rate of spread (FROS), fireline intensity and McArthur Forest Fire Danger Index (FFDI) for spread periods from 1130 hr to 1906 hr on Wednesday 6 January. Values are mean and (maximum) for observations and predictions. Weather observations are from the Alcoa minesite.

Time period	**Wind speed (75%) (km h^{-1})**	**Wind gust (Max) (km h^{-1})**	**Temp (Max) (°C)**	**RH (Min) (%)**	**Slope (Max) (deg.)**	**SMC (Min) (%)**	**Obs. FROS (Max) (m h^{-1})**	**Pred. FROS (Max) (m h^{-1})**	**Obs. Intensity (kW/m)**	**FFDI (Max)**
1140-1450	14.3	31	34.3	23.5	+3	4.9	1105	815	12155	26
	(17)		(35.8)	(18)	(+6)	(4.2)	(n/a)	(1608)		(33)
1450-1906	15.0	33	35.8	23.2	+1	4.8	1320	800	14520	27
	(17)		(37.2)	(14)	(+5)	(3.7)	(3272[a])	(1814)		(40)

[a] FROS observed from 1800 hr to 1906 hr.

Figure 17. View from the origin of Fire 68 west across the Murray River valley. Note the slope, evidence of intense fire behaviour and presence of numerous dead trees that pose a risk to firefighters.

Figure 18. Aerial view of Fire 68 spreading west towards the Murray River at 1149 hr on 6 January. Camera is pointing north east, with the river in the foreground. (Photo: Alf Lorkiewicz, Parks & Wildlife Bunbury)

Figure 19. Pyro-cumulonimbus cloud visible at 1934 hr on 6 January from Dwellingup, about 19 km north of the headfire position at that time. (Photo: Allan Clarke, Parks & Wildlife Dwellingup).

By 1730 hr a large pyro-cumulonimbus cloud had formed above the fire, with the plume moving towards the south-west (Fig. 19). Numerous ground lightning discharges were detected by sensors from 1612 hrs onwards, peaking between 1830 hr and 1930 hr. Discharges were detected mostly on the southern side of the fire but a smaller number were also detected west of the fire towards the escarpment. Lightning activity ceased after 2038 hr.

Phase 2 – 1900 hr on 6 January to 0930 hr on 7 January

Weather

Overnight the temperature declined to a minimum of 21°C and relative humidity increased to 57% (Fig. 12). Dew point remained relatively constant between 11°C and 12°C throughout the night. A secondary peak in FFDI of 22 occurred around 2000 hr as the ESE wind re-developed and increased in strength to up to 30 km h^{-1} with gusts to 54 km hr^{-1}. Winds remained consistently from the ESE overnight with average speeds from 24-33 km h^{-1} and gusts to 56 km h^{-1}. These dry windy conditions would have provided little opportunity for overnight recovery of fine fuel moisture, and DEFM models indicate that fine fuels would have stabilised at a moisture content of 11-12%.

Fuels

From Nanga Rd west to the escarpment the fire spread through a complex mosaic of active mining operations, mining infrastructure, rehabilitated bauxite pits and remnant native forest. Much of this area carried fuels older than 20 years, apart from along the southern flank which abutted the January 2006 fire.

Once the fire reached the edge of the escarpment it encountered a mixture of remnant woodland and pasture. The northern flank of the fire encountered one year old fuels immediately east of the Waroona townsite which resulted from the January 2015 bushfire. Fuels on the coastal plain included fully cured pasture, irrigated pasture and remnant woodland and swamp vegetation along drains and road verges.

Fire behaviour

By 1900 hr the headfire was up to 2 km west of Nanga Rd. Aircraft returned to base overnight with the result that information about the location and behaviour of the fire was reduced greatly and limited to field observations often made from a considerable distance away. This was compounded by the complexity of accessing and navigating the minesite. Estimates of the rate of spread of the fire are therefore based on a reconstruction of spread made using limited field observations, post-fire observation of leaf freeze and interpretation of patterns of crown scorch and defoliation from aerial photography.

The headfire continued spreading towards the west-north-west and maintained a rapid rate of spread estimated to have been around 2000 m h^{-1}. The pattern of crown damage indicates little moderation in the rate of spread of the fire over the next four hours. Mass spotting appears to have been an important mechanism that allowed the fire to maintain uninterrupted spread through the minesite despite the presence of wide haul roads, powerline easements and pits. There is also evidence of a number of independent ignition points that may have arisen from long distance spotting or have been ignited by lightning strikes associated with the pyro-cumulonimbus event earlier in the evening. The reconstruction map indicates a concentration of spot fires reported at 2340 hr between Lake Navarino and Lake Moyanup and directly east of Waroona townsite (-32.85° 115.97°). A distinct band of defoliated forest extending westwards from Lake Kabbamup along the valley of the Sampson Brook is also visible on the high resolution air photography, several kilometres south of the main fire. The pattern of crown defoliation suggests a separate run of fire arising from an ignition just west of the Sampson dam wall (-32.88° 116.01°), but it is not possible to determine whether this was caused by lightning ignition or spotting.

The reconstructed rate of spread of the fire from 1900 hr to 2300 hr is considerably faster than the predicted rate of spread by a factor of at least twofold (Table 2). Possible reasons for this underprediction include the contribution of mass spotting to fire propagation, and the presence of extensive areas of rehabilitated forest that are prone to crowning and greater wind influence than the native forest.

Shortly after 2100 hr reports indicated that the Waroona townsite was under sustained ember attack and that a number of spot fires had begun to develop in pasture and bushland on the escarpment east of the town. An experienced Parks and Wildlife firefighter despatched from the Dwellingup office to gather field intelligence reported that the fire impacting Waroona appeared to be well advanced and separate from the main fire front which was further to the north and still burning in the minesite.

By 2130 hr a tongue of fire is reported to have crossed the South West Highway between Waroona and the small locality of Hamel about 1 km further south. This tongue of fire appears to have originated from the multiple spot fires around Lake Moyanup and from spot fires starting downwind of the fire run in the Sampson Brook. The area where the fire crossed the highway is the convergence of the Drakes and Samson Brooks and it is likely that the alignment of the incised terrain and the prevailing winds contributed to channelling of the wind and the path of the fire.

Table 2. Reconstructed and predicted forward rate of spread (FROS) and fireline intensity for spread periods from 1130 hr to 1906 hr on Wednesday 6 January. Values are mean and (maximum) for observations and predictions. Weather observations are from the BoM Dwellingup station.

Time period	Wind speed (75%) ($km\ h^{-1}$)	Wind gust (Max) ($km\ h^{-1}$)	Temp (Max) (°C)	RH (Min) (%)	Slope (Max) (deg.)	SMC (Min) (%)	Recon. FROS (Max) ($m\ h^{-1}$)	Pred. FROS (Max) ($m\ h^{-1}$)	Recon. Intensity (kW/m)	FFDI (Max)
1900-2100	20.6 (28)	54	30.8 (33.4)	31.7 (29)	0 (+2)	7.7 (5.6)	2000 (n/a)	549 (1391)	22000	21 (27)
2100-2300	27.5 (28)	56	28.8 (28.2)	36.0 (26)	0 (+5)	8.4 (6.9)	2000 (n/a)	661 (1342)	22000	19 (25)

West of the highway the fire entered the Waroona main drain and followed the drain to the north west for two kilometers before crossing Fawcett Rd where the drain turns due west (Fig. 20). Channelling by the drain resulted in a very long and narrow fire shape. Firefighting efforts focussed on restricting lateral spread of the flanks, but efforts to contain the headfire were hampered by the speed and intensity of the fire in the remnant vegetation adjoining the drain. By 0400 hr on 7 February fire had spread to the western side of the Southern terminal powerline and was burning between Coronation Rd on the north flank and Buller Rd on the south flank.

Figure 20. Waroona main drain looking east back towards Fawcett Rd. This area burnt during the early hours of Thursday 7 January.

By 0200 hr on 7 January fire was impacting on the eastern outskirts of the Waroona townsite (Fig. 21), presumably as a result of spotting from the main fire which had spread on the southern side of Lake Navarino. Sparse 1 year old fuels dating from the January 2015 bushfire would have reduced the likelihood of spotfires starting and their potential fire intensity.

Figure 21. Waroona townsite, property at Woodley Heights impacted by spotting from the main fire run early on the morning of 7 January.

Phase 3 – 0930 hr to 1830 hr on 7 January

Weather

Observations at Dwellingup show that the temperature rose steadily throughout the morning to reach a maximum of 40°C at 1530 hr, coinciding with a minimum relative humidity of 11% (Fig. 22). Dew point declined throughout the day to a minimum of 0.6°C at 2130 hr. The Western Australian Forest Fire Behaviour Tables (Sneeuwjagt and Peet 1985) predicted a minimum Surface Moisture Content of 5% and a jarrah rate of spread index of 130 m h^{-1} at Dwellingup.

At Dwellingup the winds shifted from ESE to E around 0700 hr and then remained easterly until after midday when a north easterly influence is evident (Fig. 23). At Waroona the influence of ENE winds became evident after 0900 hr. Observations from Wagerup shows winds southerly in the morning, shifting ENE around 1230 hr with some periods of due northerly wind during the afternoon.

However, satellite imagery, consistent with the scorch pattern, shows clearly that the southern flank of the fire was under the influence of an ENE wind from around 0700 hr on 7 January. This influence was not detected in 30 minute observations at any of the observation sites, but was evident in the 1 minute observations for brief periods. The possibility of localised wind influence over the fireground warrants further investigation. The lack of observations representative of the fireground creates some uncertainty over comparisons between reconstructed and predicted fire behaviour during this phase of fire activity.

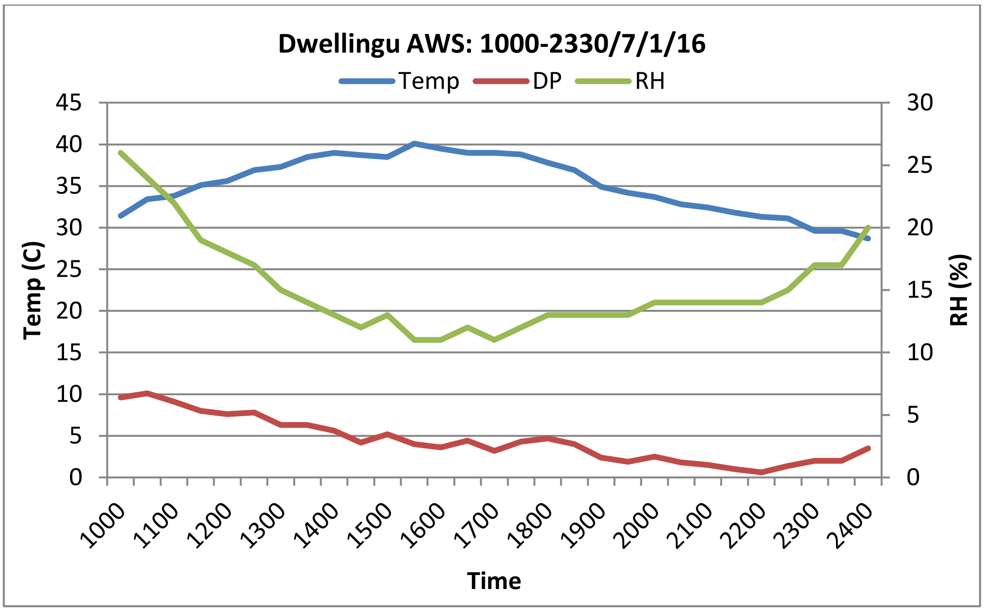

Figure 22. Dry bulb temperature (blue), dew point (brown) and relative humidity (green) recorded at Dwellingup from 1000 hr to 2400 hr on 7 January 2016.

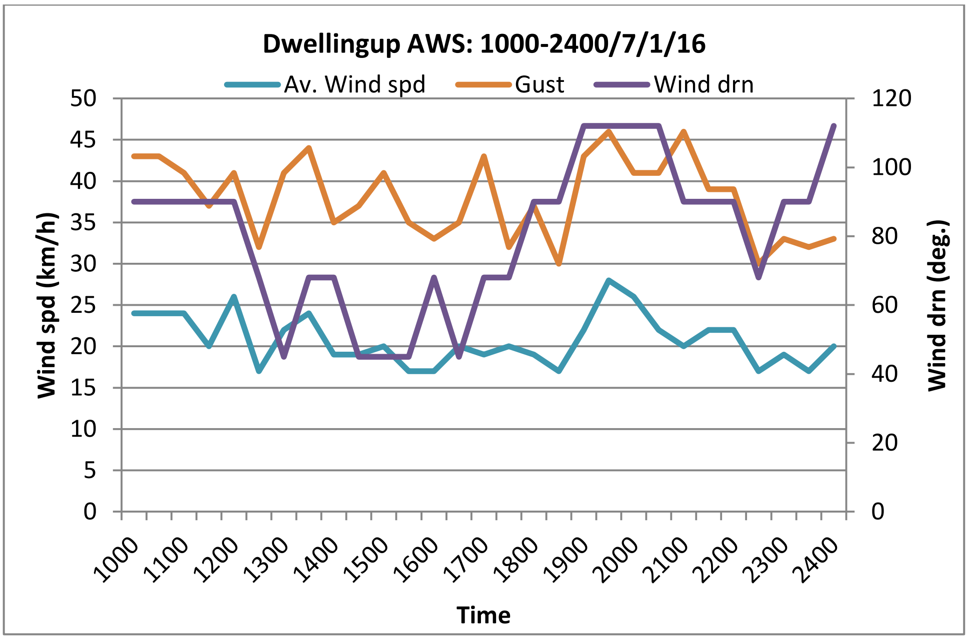

Figure 23. Average wind speed (blue), gust speed (brown) and wind direction (purple) recorded at Dwellingup from 1000 hr to 2400 hr on 7 January 2016.

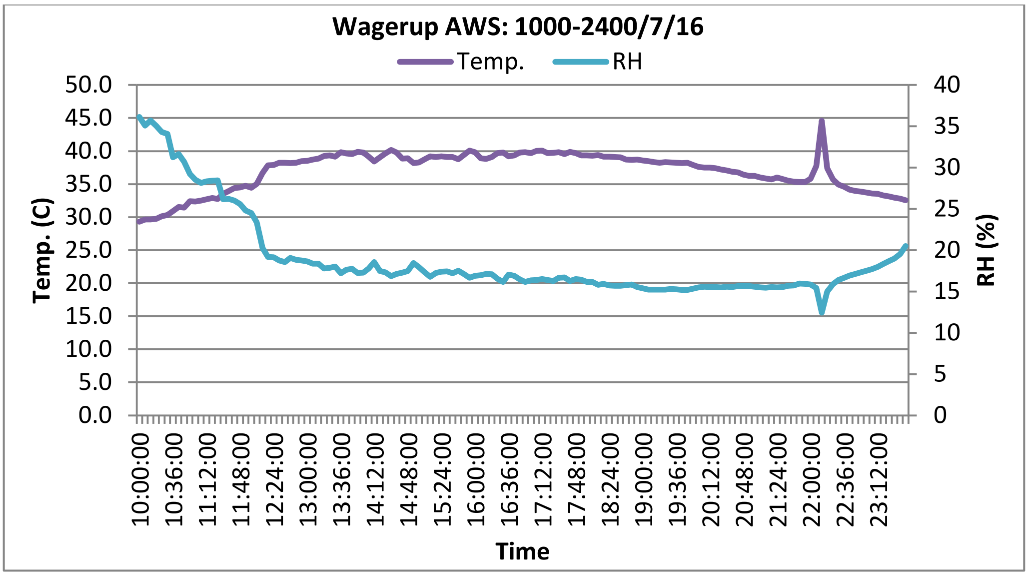

Figure 24. Dry bulb temperature (purple) and relative humidity (blue) recorded at Wagerup Refinery from 1000 hr to 2400 hr on 7 January 2016.

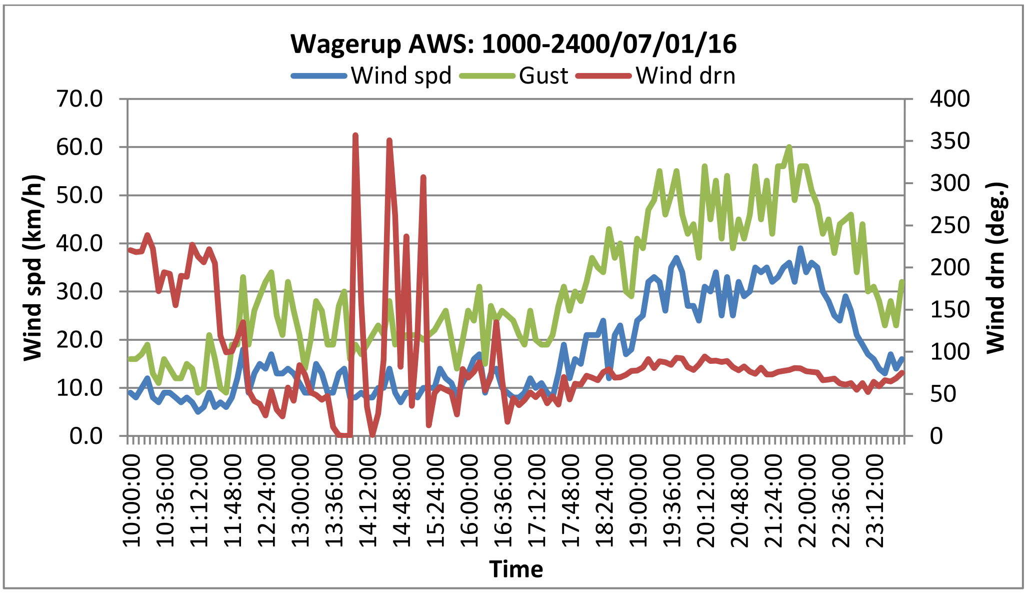

Figure 25. Average wind speed (blue), gust speed (green) and wind direction (brown) recorded at Wagerup Refinery from 1000 hr to 2400 hr on 7 January 2016.

Fuels

East of the Muja Northern terminal powerline fuels were jarrah marri forest 6 to 10 years old, with some areas of recent mining activity. West of the powerline fuels were jarrah marri forest mostly unburnt for at least 20 years, including some areas unburnt for up to 37 years. There were also extensive areas with rehabilitated mine pits of varying ages, mostly to the west and south of the minesite conveyor line. South of the Willowdale-Wagerup Rd the vegetation was predominantly native forest, with the youngest fuels being 8 years old in the western portion of Waterous forest block.

Fire behaviour

The aerial photography shows a distinct band of unscorched crowns running in an east to west direction about 1 km south of the junction of the Willowdale mine conveyor and the Muja Northern terminal powerline. This feature is likely to indicate the position of the southern flank of the fire during its overnight run towards Waroona. South of the unscorched band the direction of fire spread indicated by leaf freeze shows a change to the west south west and there is an obvious increase in fire intensity to full crown scorch and extensive defoliation suggestive of widespread crown fire, particularly in the older fuels west of the powerline. This indicates the beginning of a major run by the southern flank of the fire under ENE winds sometime between 0700 hr and 0800 hr. This run continued throughout the morning with a reconstructed rate of spread averaging 1500 m h^{-1} over a period of four hours (Table 3). We have confidence in this reconstruction as it is based on air intelligence and time-stamped photographs of the fire at known locations including Mt William (Fig. 26).

A large pyro-cumulonimbus developed over the fire during the later part of the morning, attaining its maximum development between 1100 hr and 1200 hr when the fire was spreading on a very broad front to the south west through forest unburnt for 20 years or more (Fig. 27 & 28). A second pyro-cumulonimbus cloud developed over the fire during the early afternoon, and was evident on satellite imagery at 1350 hr.

Table 3. Reconstructed and predicted forward rate of spread (FROS) and fireline intensity for spread periods from 0930 hr to 1830 hr on Thursday 7 January. Values are mean and (maximum) for observations and predictions. Weather observations are from the BoM Dwellingup station.

Time period	Wind speed	Wind gust	Temp	RH	Slope	SMC	Recon. FROS	Pred. FROS	Recon. Intensity	FFDI
	(75%)	(Max)	(Max)	(Min)	(Max)	(Min)	(Max)	(Max)		(Max)
	(km h^{-1})	(km h^{-1})	(°C)	(%)	(deg.)	(%)	(m h^{-1})	(m h^{-1})	(kW/m)	
0930-1330	22.5	39	30.5	20.5	+1	4.5	1500	1420	16500	28
	(24)	(50)	(38.5)	(14)	(+5)	(3.8)	(n/a)	(2587)		(37)

Figure 26. View of Mt William at 1140 hr on 7 January, with numerous spot fire ignitions evident in forest on the right hand side of the image. The main fire run has not yet arrived at Mt William. (Photo: Jessica Newman, Parks & Wildlife Bunbury).

Figure 27. Jarrah forest defoliated by crown fire north of Driver Rd at Willowdale during later morning on 7 February.

Figure 28. Pyro-cumulonimbus cloud observed from Dwellingup at 1134 hr on 7 January. The upper part of the plume appears to be under a westerly wind influence. (Photo: Steve Gunn, Parks and Wildlife Dwellingup).

Under the influence of NE winds the southern flank of the fire spread down the escarpment towards the Wagerup Refinery, crossing the South West Highway south of Waroona in a number of places by 1300 hr (Figs. 29 & 30). As the afternoon progressed wind strengths eased and the rate of spread and intensity of the fire reduced. This is reflected in the pattern of crown damage with a shift from defoliation to crown scorch during this period. The escarpment area appears to have been under the influence of northerly winds for periods during the afternoon, based on anemometer observations at Wagerup and the direction of leaf freeze. The 1 minute observations from Waroona record a NNW wind at 1400 hr. This northerly influence had the effect of extending the fire southwards along the escarpment to the east of Yarloop.

Figure 29. Fire crossing South West highway just north of Bancell Rd, 1313 hr on 7 January. (Photo: Jessica Newman, Parks & Wildlife Bunbury).

Figure 30. View north towards Yarloop townsite at 1310 hr on 7 January showing extensive fire activity on the escarpment and several spot fires well to the west of the main fire front. (Photo: Jessica Newman, Parks & Wildlife Bunbury).

Figure 31. Belt of planted trees adjoining a drainage channel, looking east from Somers Rd towards the escarpment. The fire has run as an elongated narrow tongue following the heavier fuel in the planted belt, with minimal lateral spread into eaten-out pasture.

Throughout the day the fire also remained active in agricultural lands on the coastal plain west of Waroona, particularly in the area between Buller Rd and Coronation Rd. The pattern of fire spread on the coastal plain was complex and influenced strongly by factors of land use and the condition of pastures, remnant native vegetation and belts of planted trees (Fig. 31).

Phase 4 – 1830 hr to 2400 hr on 7 January

Weather

Temperatures remained hot for an unusually long time into the evening, exceeding 35°C at Wagerup until 2200 hr (Fig. 24). Relative humidity also remained low and very stable at 15% well into the evening with the falling dew point offsetting any reduction in temperature. After 1700 hr the winds became consistently ESE and increased steadily in strength for the next 2.5 hours rising to a peak around 1930 hr with average winds at Wagerup of 35 km h^{-1} and gusts to 56 km h^{-1}. During the peak conditions the FFDI increased to between 50 and 60, in the lower end of the Severe fire danger rating class.

Weather conditions at Dwellingup followed a similar pattern, although there was some moderation of temperature after 1900 hr and winds were not as strong as at Wagerup near the base of the escarpment.

Fuels

By 1830 hr the south west flank of the fire was burning in freehold land on the escarpment which included extensive areas of remnant native forest, partially cleared lands with pasture, a vineyard and other agricultural enterprises. On the eastern side of Yarloop townsite there were a number of small Crown reserves with a total area of about 100 ha established for a variety of purposes including a rifle range, nature reserve, recreation, road verge and rubbish pit. North of Hoffman Rd and east of the South West Highway were a number of small freehold blocks, many of which retained a considerable cover of native vegetation. Bushland around Yarloop is typically an open forest of jarrah with a dense mid-storey of *Allocasuarina* and a well developed understorey of low shrubs. The recent fire history of this area is not well documented but local knowledge indicates that most of the bushland around Yarloop had not been burnt for at least 20 years, with the exception of a small nature reserve at the southern end of the townsite and west of the highway that was burnt by prescribed fire in May 2015.

Fire behaviour

Personal accounts provided by firefighters present in the Yarloop area during the evening of 7 January indicate that the behaviour of the fire was quite mild as it spread down the escarpment under relatively light winds. This is consistent with the pattern of crown damage which shows incomplete crown scorch and an absence of any extensive defoliation east of the Wagerup-Worsley powerline which runs parallel to, and about 1 km east of, the highway at this point. Up until 1900 hr the possibility of holding the fire along a defensive line constructed east of Yarloop along the powerline appeared realistic.

Shortly after 1900 hr a spotfire was noticed on the west side of the highway burning in a paddock just south of Clifton Rd. A second tongue of fire crossed west of the highway near the northern end of town just south of Boundary Rd a few minutes later. Fire behaviour along the entire south west flank of the fire escalated dramatically around this time as the fire spread into the bushland reserves on the eastern side of the highway and then continued to spread west through Yarloop. The reconstructed rate of spread of the fire from 1830 hr to 2030 hr is 2000 m h^{-1} (Table 4), and undoubtedly there were shorter periods of much faster spread coinciding with wind gusts and fire spread in heavy, continuous fuels. Predicted rates of spread in forest and eaten-out grassland were comparable to the reconstructed rate of spread. The extreme fire behaviour in heavy fuels caused massive spotting that impacted on Yarloop resulting in the ignition of a large number of buildings in a very short time. For the remainder of the evening strong easterly winds continued to push the fire west of Yarloop across the coastal plain for a further 12 km.

Table 4. Reconstructed and predicted forward rate of spread (FROS) and fireline intensity for spread periods from 1830 hr to 2400 hr on Thursday 7 January. Values are mean and (maximum) for observations and predictions. Weather observations are from the Alcoa Wagerup Refinery station.

Time period	Wind speed (75%) (km h^{-1})	Wind gust (Max) (km h^{-1})	Temp (Max) (°C)	RH (Min) (%)	Slope (Max) (deg.)	SMC (Min) (%)	Recon. FROS (Max) (m h^{-1})	Pred. FROS (Max) (m h^{-1})	Recon. Intensity (kW/m)	FFDI (Max)
1830-2030	27.7 (32.4)	44 (56)	38.2 (39.1)	15 (15)	-4 (0)	3.8	2000 (n/a)	Forest 2318 Grass[a] 3566	Forest 22000 Grass[a] 2764	51 (60)

[a] Assumed to be eaten out.

The rapid escalation in fire behaviour experienced at Yarloop during the evening of 7 January was reflected more broadly across the entire western side of the fire including east of Waroona in the Lake Navarino area, and west of Waroona on the coastal plain where the fire made a major run through the McLarty pine plantation and the Yalgorup National Park. This run was interrupted by Lake Preston although spot fires landing on the western side of the lake ignited coastal heathland that continued to burn westwards until reaching bare dunefields. The major break-out west of Waroona caused a significant increase in the scale and complexity of the fire by closing the Forrest Highway, severing both major highway connections and the passenger rail connection between Perth and Bunbury for a number of days.

Synthesis of major findings drawn from the fire reconstruction

Antecedent conditions

The south-west of Western Australia has experienced a consistent drying trend since the mid 1970s, with the past 15 years including notably dry years in 2001, 2006, 2010 and 2015. Rainfall decline has been particularly pronounced in the late autumn and early winter period. Average temperatures have also increased steadily over this period, resulting in greater evaporation and transpiration of moisture to the atmosphere. These trends have important implications for the dryness of forest fuels and for the condition of riparian vegetation and wetlands that have developed during wetter climate phases when seasonal inundation occurred with greater reliability. Fine forest fuels are now drying out earlier in the spring and remaining at low moisture content for an extended period through into the autumn in most years. Dry winters are limiting the opportunity for moisture uptake by larger woody fuels including standing dead trees, stumps and fallen logs with the result that these are available to burn earlier in the spring, and may burn away completely under dry summer conditions. Combustion of greater quantities of woody fuel adds to the total heat output and emissions from forest fires, leads to greater impact on living vegetation and soils, and increases the difficulty of fire suppression and mop-up. The spring of 2015 saw a rapid onset of dry conditions with the Soil Dryness Index rising steeply from early September and trending at near-record dryness (based on 24 year observation period) for the four months leading up to the fire. These conditions would have ensured a very high level of fuel availability.

The long term drying trend for the south-west is also influencing land use and water management practices in the agricultural sector with a shift to dryland farming on the coastal plain and the replacement of open channel irrigation with piped systems for water distribution. This is important from the perspective of bushfire management because it changes the nature of fuel availability across the landscape. Where irrigated pastures and green vegetation might once have limited the opportunity for fire spread on a large scale, this is no longer the case on many parts of the coastal plain. Similarly, seasonal wetlands that may have retained moisture well into the summer period and acted to retard the spread of fires are now drier and prone to burning, including combustion of deep organic soils. The January 2016 fire was the largest to impact on the coastal plain between Perth and Bunbury for many decades, and this should prompt a re-evaluation of the potential for large fires in this landscape.

Increased area of long unburnt forest fuels

For most of 6 and 7 January the fire was burning in forest fuels that were at least 10 years old, with sizeable areas of fuel more than 20 years old. The existence of large tracts of old fuel undoubtedly contributed to the rapid spread and high intensity of the fire, and to other phenomena including crown fire, mass spotting and the development of multiple events of pyro-convection.

There was a strong coincidence between long unburnt fuels, positive (uphill) slopes and pyro-convection events on the afternoon of 6 January and late morning of 7 January. These events warrant further study to better understand the relationship between burning conditions at the surface and the development of pryro-convection. There is also an important question regarding the extent to which rate of spread, intensity and spotting are enhanced by the formation of a pyro-cumulonimbus cloud above a fire. Evidence from the fire reconstruction is mixed, with predicted rates of spread falling well short of observed spread between 1800 hr and 1906 hr on 6 January, but corresponding reasonably well with observed rates of spread on the morning of 7 January.

We are unable to fully explain the rapid spread and long distance spotting that took place after 1900 hr on 6 January causing the fire to reach Waroona much sooner than expected. Possible explanations include the presence of numerous patches of remnant native forest unburnt for several decades or more within the mining envelope, and the contribution of further ignitions from lightning caused by the pyro-convection earlier in the afternoon. It is also likely that the moisture content of the older, deeper surface fuel profiles is not increasing significantly over night enabling active fire behaviour to be maintained.

Localised areas of long unburnt fuel adjoining Yarloop clearly played a key role in generating very high fire intensities and mass spotting that resulted in extensive damage to a large number of buildings in the town.

Abundant and long unburnt fuels in road verges and other vegetation corridors also probably contributed to the scale of the impact on the electricity transmission grid by facilitating the combustion of power poles.

Acknowledgements

Personnel from the Department of Parks and Wildlife, Department of Fire and Emergency Services, Shires of Waroona and Harvey provided information used in this reconstruction. Appendix C lists those people who were interviewed as part of the reconstruction work. A number of people provided photographs which have been included in this report and their work is credited where appropriate. All other photographs used in this report were taken by Lachlan McCaw. We thank Theo Menne of the Department of Parks and Wildlife for assistance with GIS and map production for the report, and the Spatial Services Group of the Department of Fire and Emergency Services for making data available.

We also thank Brooke Stephen for making available data from Alcoa weather stations, and staff from the Bureau of Meteorology Perth Regional Forecasting Centre for providing and interpreting a range of weather data and derived products.

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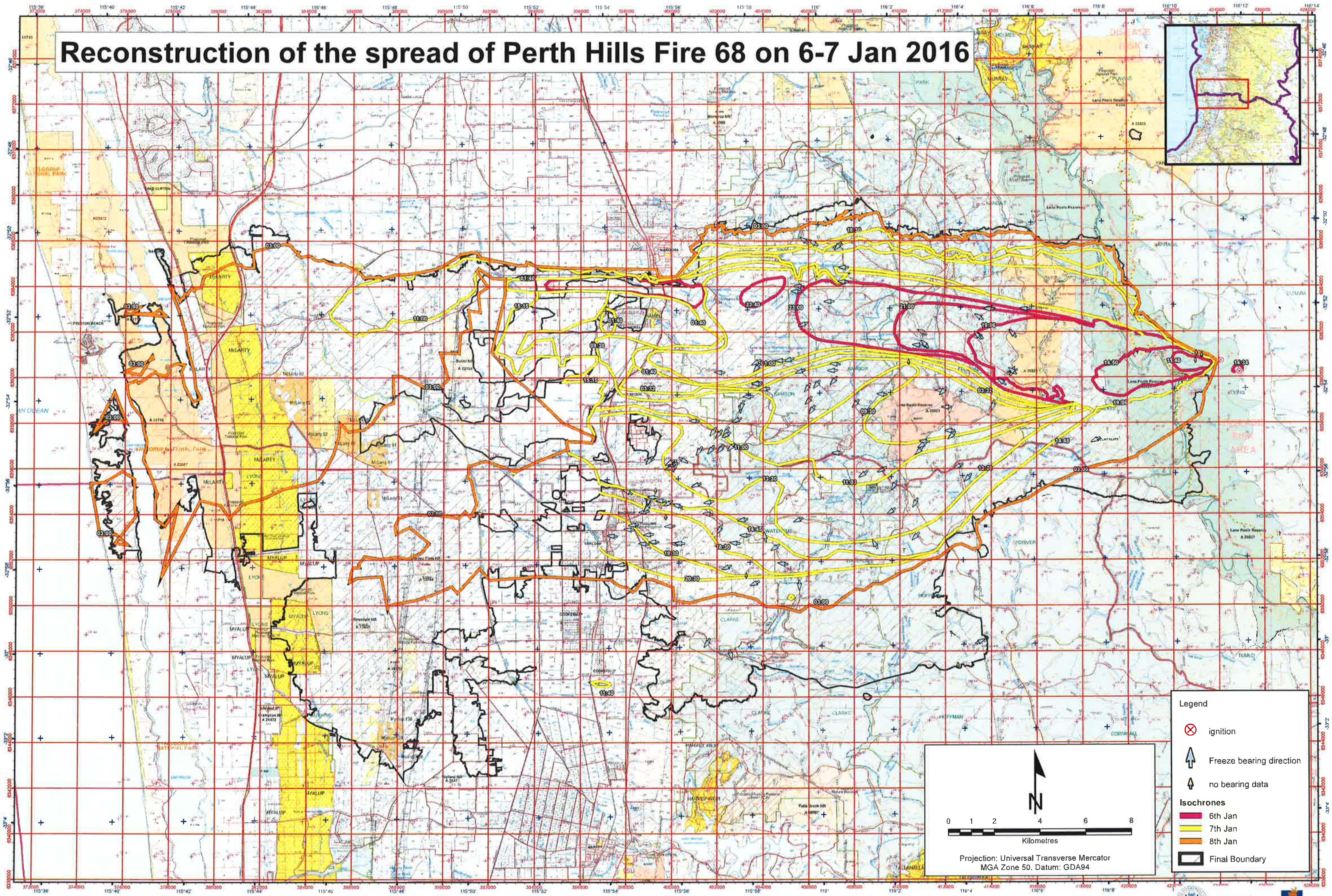
List of Appendices

Appendix A
Reconstruction of the spread of Perth Hills Fire 68 on 6-7 January 2016 overlaid on a land tenure base map.

Appendix B
Reconstruction of the spread of Perth Hills Fire 68 on 6-7 January 2016 overlaid on a base image showing categories of crown damage determined from high resolution aerial photography.

Appendix C List of people interviewed for the fire behaviour reconstruction.



Graticule shown at 2 minutes intervals
Grid shown at 2000 metre intervals

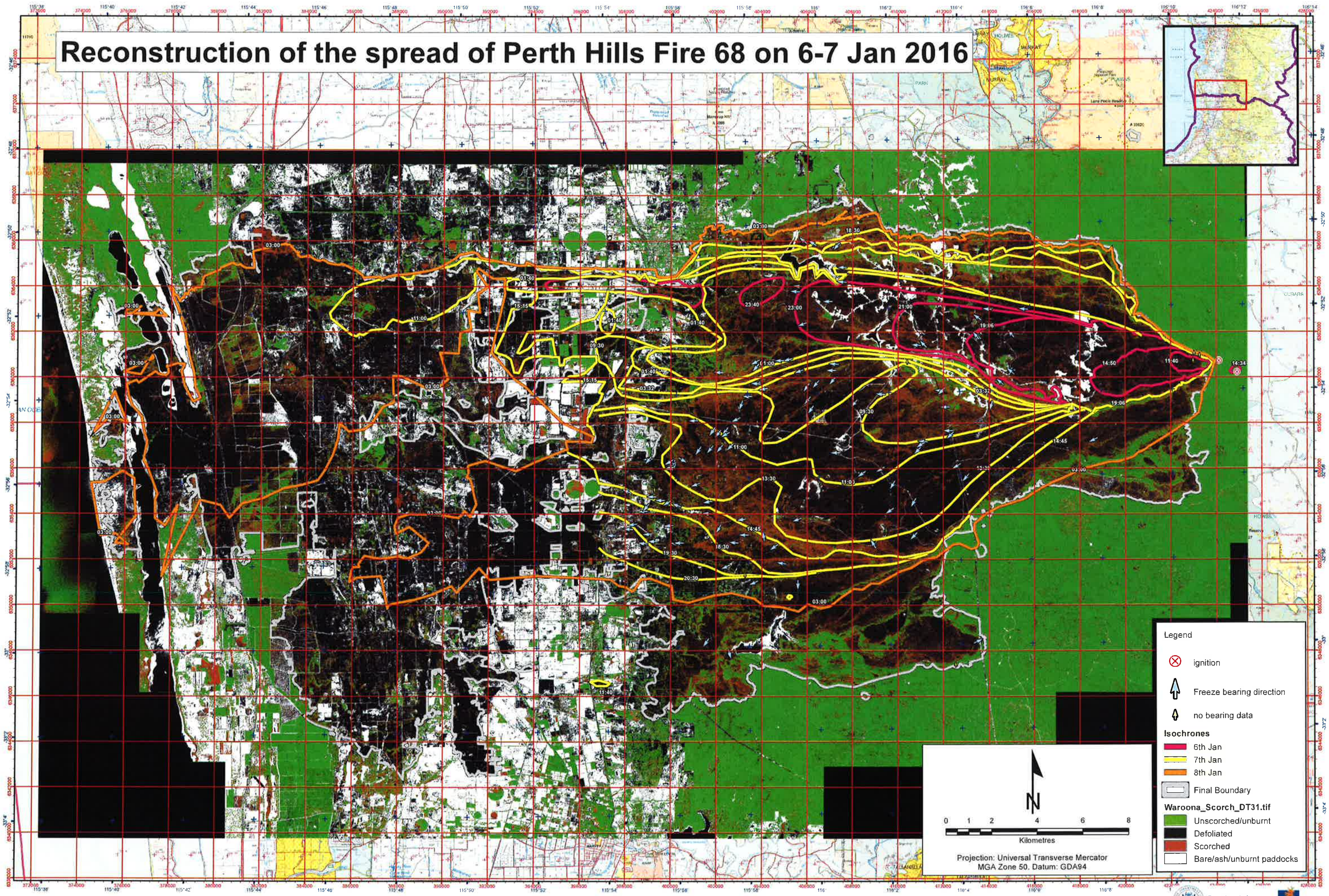
The Dept. of Parks and Wildlife does not guarantee that this map is without flaw of any kind and disclaims all liability for any errors, loss or other consequence which may arise from relying on any information depicted.

Roads and tracks on land managed by DPaW may contain unmarked hazards and their surface condition is variable. Exercise caution and drive to conditions on all roads.

Produced by TM, Department of Parks and Wildlife

Produced at 10:8am, on Feb 29, 2016

Department of Parks and Wildlife



Graticule shown at 2 minutes intervals
Grid shown at 2000 metre intervals

Produced by TM, Department of Parks and Wildlife

Produced at 10:8am, on Feb 29, 2016

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APPENDIX C

LIST OF PEOPLE INTERVIEWED FOR THE FIRE BEHAVIOUR RECONSTRUCTION

Name	Organisation
Department of Parks and Wildlife	Alan Brown
	George Bradshaw
	Mike Cantelo
	Erin Davis
	Tom Conlan
	Trevor Dye
	Ian Freeman
	Steve Gunn
	Bob Hagan
	Carl House
	Greg Mair
	Alan Madgwick
	Jess Neuman
	John Prins
	Chris Roberts
	Brian Smith
	Rob Young
Department of Fire and Emergency Services	Clinton Kuchel
	Antony Nicholas