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Abstract

Natural and human disturbance and climate change pose major challenges for resource management. This is relevant in natural forests where conflict can occur between water provision and industrial logging where conversion of old forests to young, fast-growing stands can dramatically reduce streamflow and water yield. We modelled changes in stream run-off and hence water yield from a forest catchment in response to clearcut logging with projected climate change (using a Representative Climate Futures [RCFs] approach). We focused on the Thomson Catchment which is the largest single catchment for the city of Melbourne, south-eastern Australia. Within this catchment, we targeted our analysis at montane ash-type eucalypt forests, as these receive the most rainfall and are subject to clearcutting. We used several forest management scenarios to model changes in water yield over time. For our analysis of projected climate change, we employed a range of RCFs that represent 'consensus', 'wettest' and 'driest' scenarios to model the impacts of multiple Representative Concentration Pathways (RCPs). Our initial spatial analysis revealed that 42% of the ash-type eucalypt forests in the Thomson Catchment have been logged. Under historical and continued logging, stream runoff decreases by 40,211 ML by 2090 compared with a hypothetical baseline if logging had ceased in 1995 and 34,059 ML if logging continues beyond 2019. These losses exceed the projected impacts of climate change under the consensus and wettest scenarios, but the driest scenarios are projected to exceed these losses, consisting of 49,998 ML and 69,474 ML for RCP 4.5 and RCP 8.5, respectively.

We suggest native forest logging be excluded from the Thomson Catchment because of decreasing stream flows due to climate change and an increasing water demand due to human population growth. This study provides a quantitative approach for highlighting how resource conflicts can be magnified under climate change.

Keywords

Climate change, clearcutting, forest policy, watersheds, resource conflict, south-eastern Australia, montane ash forest

1. Introduction

Climate change is projected to exacerbate the risks associated with variations in the distribution and availability of water resources worldwide (WWAP, 2015). Cities and surrounding urban areas are particularly vulnerable (UNDESA, 2016). An estimated 150 million people currently live in cities with perennial water shortage, with climate change scenarios projecting a large increase in this number, possibly up to 1 billion people by 2050 (Revi et al., 2014). Competing and escalating demands for water will lead to increasingly difficult allocation decisions, creating conflict among various uses of ecosystem services (Foley et al., 2011; WWAP 2015). Natural resource management will need to accommodate the impacts of climate change and other challenges to maintain, or genuinely achieve, more efficient, socially and ecologically sustainable production systems (Stokes and Howden, 2010; Van Vuuren et al., 2011; Whetton et al., 2012; Prober et al., 2017).

The unpredictability of Australia’s weather patterns is projected to increase with climate change (CSIRO and Bureau of Meteorology, 2016). Across southern Australia, there has been a decrease in average annual rainfall since the mid-1970s with further overall declines projected from multiple climate change scenarios (Gerbing et al., 2015; Hope et al., 2015). Water supply providers are expecting that stream-flows into reservoirs supplying urban areas will decline over the long term (Howe et al., 2005). The capacity of catchments to supply water will become increasingly important, particularly in the context of competing demands from other sectors utilizing catchment areas for non-water harvesting purposes, such as logging of forested catchments for timber and pulpwood production (Hamilton, 2008; Schyns et al., 2017).

Industrial logging is permitted across a number of forested catchments supplying water to the city of Melbourne (Australia’s second largest city), and surrounding urban areas (Viggers et al., 2013). These catchments are considered an important source of pulpwood for paper manufacturing and sawlog for timber production (Flint and Fagg, 2007). It has long been recognized that logging has negative impacts on water yields (Langford and O'Shaughnessy, 1980; O'Shaughnessy and Jayasuriya, 1991; Vertessy et al., 1998; Vertessy et al., 2001). These impacts result from changes in forest structure and increased levels of evapotranspiration by fast-growing young trees (Feikema et al., 2008). Following disturbance, large numbers of eucalypts germinate following disturbance (Smith et al., 2014). These trees grow rapidly, but the stocking density declines as the forest ages (Ashton, 1976). There is a strong correlation between the age of the forest and the total leaf area index, which produces a marked difference in evapotranspiration and thus streamflow between young and old forests (Feikema et al., 2008). These changes in evapotranspiration and streamflow can persist for many decades (O'Shaughnessy and Jayasuriya, 1991), and may potentially compound the impacts resulting from projected climate change.

Conflict between water yield and industrial logging in Melbourne’s water catchments date back well over a century (Viggers et al., 2013). Logging was excluded from some closed catchments designated in the late 19th century (Langford and O'Shaughnessy, 1980). Additional forest areas were designated as water catchments during the 1960s to increase Melbourne’s water supply capacity, although logging was not excluded from all of these catchments (Viggers et al., 2013). This includes the Thomson Water Catchment, the largest in Melbourne’s water supply system (Melbourne Water, 2019). The Thomson Water Catchment produces the majority of water for the five million people living in Melbourne as well as for rural towns and some agricultural areas (Keith et al., 2017).

In the investigation reported here, we modelled changes in water yield in the Thomson Catchment in response to both the impacts of clearcutting operations and projected climate change. We explored the water yield impacts of three forest logging scenarios. (1) A hypothetical scenario where logging ceased in the Thomson Catchment by 1995. (2) A scenario where actual past logging was coupled with continued logging in the Thomson Catchment. And, (3) A scenario where logging ceases by 2019 in the Thomson Catchment. We compared these changes with a range of projected climate change impacts based on multiple Global Climate Models (GCMs).

While GCMs largely agree on projected temperature increases under the respective Representative Concentration Pathways (RCPs), projected changes in rainfall may vary between GCMs (Flato et al., 2013) and between regions (CSIRO and Bureau of Meteorology, 2015; 2016). To address such variability, several studies have used multi-model ensembles of GCMs presenting a range of projected impacts across catchments and watersheds (Chiew and McMahon, 2002). These include projections of wet, median and dry variants for each of low, medium and high global warming scenarios (Murphy and Timbal, 2008). This generally provides more robust information than any single GCM (Randall et al., 2007). However, each GCM produces different climate projections, making the selection of a reduced sub-set of climate projections problematic (CSIRO and Bureau of Meteorology, 2015). Selections can be influenced by biases such as the exclusion of GCMs of lower reliability for a particular region (Ruane and McDermid, 2017). This may preclude consideration of low likelihood, but high impact, future regional climates that can be significant for adaptation planning. One way of capturing a range of projections is through the Representative Climate Futures (RCF) method (Whetton et al., 2012), which assesses each of the GCMs in terms of their respective capacity to represent projected climate change impacts across specified regions.

2. Methods

2.1 Study area

Our study area was the Thomson Catchment, which covers approximately 48,700 hectares and lies ~125km east of the city of Melbourne (Figure 1). The catchment provides water to the Thomson Reservoir, which was completed in 1983. The large storage capacity of the reservoir was intended to capture surplus water in wet years for subsequent use in dry years (Viggers et al., 2013). The terrain across the catchment is steep and deeply incised with elevation ranging from 300 m to 1,565 m above sea level. Mean annual rainfall ranges from 1000mm to 2500mm across the catchment, with higher elevations receiving the highest rainfall (Peel et al., 2000).

The Thomson Reservoir is the largest reservoir of the Melbourne Water Supply system, with a capacity of 1,068 billion liters or 59% of Melbourne's total water storage capacity (Melbourne Water, 2017). The Thomson Reservoir is solely reliant on streamflow from its surrounding catchment and supplies water to other reservoirs. The Thomson Reservoir receives the highest streamflow compared to other reservoirs throughout the water supply system. The Thomson Reservoir receives around 202,930 ML per annum or 41% of total water inflow across Melbourne's major water catchment system (Melbourne Water, 2019).

2.2 Land tenure

The majority of the Thomson Catchment is state forest, covering nearly 41,000 hectares or 92% of the catchment. Almost 29,000 hectares or 65% of the catchment area is allocated to logging in areas classified as General Management and Special Management Zones. The remaining area comprises of informal protected areas, such as Special Protection Zones, and dedicated reserves, such as National Parks. The informal protected areas cover 12,000 hectares, or 27% of the catchment. Dedicated reserves, comprising the Baw Baw National Park, cover 3,517 hectares or 8% of the Thomson Catchment (Table 1).

The Thomson Catchment is different to the other large catchments of Melbourne's water catchment system which, since the 1890s, have been designated as 'closed' and designated solely for the purposes of water harvesting (Langford and O'Shaughnessy, 1980). These closed catchments were included in the Yarra Ranges and Kinglake National Parks over a century later (Clode, 2006). The exclusion of logging from these closed catchments was to protect the water supply capacity of those catchments. However, Thomson Catchment was not afforded the same levels of protection and is subject to logging operations (Viggers et al., 2013).

The state forests of the Thomson Catchment are subject to a Legislative Supply Agreement between the Victorian Government and a pulp and paper production company, Paper Australia Pty Ltd (trading as Australian Paper), owned by the Nippon Paper Group (Nippon Paper Group Inc, 2009). This Legislative Supply Agreement is contained within the *Forests (Wood Pulp Agreement) Act 1996* and it binds the Victorian Government to supply Paper Australia Pty Ltd with fixed volumes of pulp logs sourced from the Thomson Catchment and surrounding region for 34 years commencing in 1996 (Parliament of Victoria, 1996). The first Legislative Supply Agreement was passed in 1936 and it required the exclusion of the Thomson Catchment upon its designation as a catchment by 1967 (Parliament of Victoria, 1936). However, a revision of this Agreement in 1961 removed this requirement, thereby committing the Thomson Catchment to supply pulplogs under successive Legislative Supply Agreements (Thompson, 1961).

2.3 Forest types

Several forest types occur in the Thomson Catchment. Sub-alpine (Snow Gum *Eucalyptus pauciflora*) woodland dominate the highest elevations. Montane ash forests, including Alpine Ash (*Eucalyptus delegatensis),* Mountain Ash (*Eucalyptus regnans)* and Shining Gum *(Eucalyptus nitens),* dominate the higher elevation escarpments. Mixed species forests, including Messmate (*Eucalyptus obliqua*), occur throughout the remainder of the catchment. The focus of this study is the montane ash forests because they are located across the higher rainfall areas of the catchment.

Around 18,870 hectares of the Thomson Catchment support montane ash forest (Table 2). Mountain Ash is the tallest of the montane ash forest types and can approach ~ 100 metres in height (Ashton, 1976). Depending on disturbance history, montane ash forests can be even-aged or multi-aged stands (Mackey et al., 2002). The occurrence of high severity fires produces even-aged stands. In contrast, fires of lower severity allow overstory trees to persist, while stimulating a new cohort to regenerate, resulting in multiple age cohorts (Lindenmayer and McCarthy, 1998). Alpine Ash forests occur at a higher elevation than Mountain Ash forests (Mueck, 1990), and are usually monotypic stands (Lindenmayer et al., 1996). Interspersed in smaller patches across these two forest types are Shining Gum forests (Turnbull and Pryor, 1984).

Some areas of montane ash forests across the Thomson Catchment are within nationally significant landscapes, including a site of Global Zoological Significance located around Mount Baw (Mansergh and Norris, 1982). These areas provide habitat for threatened fauna. These include the Critically Endangered Victorian endemic species, the Baw Frog (*Philoria frosti* Spencer) (Hollis, 2004) and Leadbeater’s Possum (*Gymnobelideus leadbeateri* McCoy) (Lindenmayer et al., 2013). They also support the Vulnerable Greater Glider (*Petauroides volans* Kerr) (Lindenmayer et al., 2015).

2.4 Forest management and logging

The main form of logging in montane ash forests is clearcutting (Lutze et al., 1999). Clearcutting within montane ash forests is typically a stand-replacing event (Lindenmayer et al., 2011). All merchantable logs are removed from a cutblock (i.e. a clearcut). A high intensity slash-fire is then applied used to burn part of the debris left behind after the logging (Flint and Fagg, 2007). This creates an ash bed, where the dominant eucalypt species are aerially seeded or replanted. As stands of eucalypt age, the stand gradually self-thin (Ashton, 1976) until the remaining trees reach their top height (Walsh and Entwisle, 1996).

Our spatial analysis of clearcutting across the Thomson Catchment was based on historical logging data from the State Forest Resource Inventory (SFRI) (DELWP, 2007), data on fire disturbance history (DELWP, 2018a), and recent logging data (DELWP, 2018b). Where SFRI data were absent across formal protected areas, such as national parks, we used

Ecological Vegetation Class (EVC) information (DELWP, 2018c). The most significant disturbance in the montane ash forests across Thomson Catchment was the 1939 bushfires (DELWP, 2018a). As of 2019, the most extensive disturbance in the catchment since these bushfires has been logging. A large bushfire occurred in the catchment during January 2019. However, areas of montane ash forest remained largely unaffected (Emergency Victoria, 2019). Approximately 8,190 hectares of forest across the Thomson Catchment is available for logging (MBAC Consulting, 2006).

2.5 Modelling catchment disturbance

Using rainfall and runoff data collected from catchments supporting Mountain Ash forests across the region that were completely or partially burnt by the wildfires in 1939, Kuczera (1987) calculated a generalized relationship between the stand age and streamflow. The yield trend exhibits a long-term recovery with average yields approaching a stationary value by about age 100-150 years. The approach specifies a general equation for a post-1939 bushfire yield curve and estimates its parameters using available streamflow data:

$$\boldsymbol{g(t) = L_{max}K(t-1941)e^{[1-K(t-1941)]}}, \quad \boldsymbol{if\ t \geq 1941} \qquad (1)$$

where g(t) is the reduction in average annual yield (mm) following the 1939 bushfire, and L_{max} and K are yield parameters. L_{max} is the maximum yield reduction (mm) following the fire and *t* is the year of analysis (Kuczera, 1987). This relationship has wide error bands, indicating uncertainty around the absolute impact on water yield (Feikema et al., 2008).

The equation was modified to calculate the total stream runoff for ash montane ash forests, whereby the reduction in average annual yield was subtracted from water yield from an ecologically mature forest:

$$\boldsymbol{Y = M - L_{max}K(t-2)e^{1-K(t-2)}, if\ t \geq 2} \ (2)$$

where *Y* is the water yield (ML/ha/year), M is the water yield from ecologically mature forest, L_{max} is maximum yield reduction below that of ecologically mature forest, *t* is time in years since disturbance and *K* is reciprocal of time taken for maximum yield depression, which was set at 0.039 (Read Sturgess and Associates, 1994). The maximum yield impact for Mountain Ash forest following disturbance for previous studies across the region is a loss of 6.15 ML/year (Kuczera, 1987; Peel et al., 2000). The Kuczera equation does not include an initial yield increase immediately following stand mortality from fire or logging, where there is an initial increase in water yield for the first two years and evapotranspiration is reduced (Feikema et al., 2008). Pre-disturbance water yield was modelled on water yields from ecologically mature Mountain Ash forest. Water loss associated with the area of younger ash trees resulting from the 1939 bushfires and previous logging up to 1995 was added to the AWRA-L v6 modelled runoff for the period 1986-2005. We spatially divided the catchment into units corresponding with age and the model was simulated for each unit.

We modelled three forest management scenarios to assess the impacts of past and current forest management and associated logging, together with alternative future management pathways. For Scenario (1), we modelled the water yield where logging ceased in 1995. We used this to quantify the water yield impacts of logging up to 1995, which aligns with the baseline year used in our projected climate change impact modelling. For Scenario (2), we modelled water yield resulting from historical forest management and associated logging, together with a future projection of continued logging, based on previous annual logging rates for the period between 1997 and 2017. For Scenario (3), we modelled the water resulting from historical forest management and associated logging, but logging was to cease by 2019. These projections were modelled assuming no climate change.

2.6 Climate Change and the Representative Climate Futures

A set of Representative Climate Futures (RCFs) can be used across a given region to describe plausible future climates (Whetton et al., 2012). Based on selected climate variables, the RCF consists of a multi-purpose decision-support tool to assist in the application of climate change projections for impact assessment and adaptation planning (Clarke et al., 2011; Whetton et al., 2012). The RCFs were derived from a web-based tool, www.climatechangeinaustralia.gov.au, hosted by the CSIRO Climate Change in Australia project. A four-step process was used in this study, the first step involved generating the RCFs; the second examined and applied the model results; the third identified a representative GCM for each key climate future; and the final step applied of the results in an impact assessment (Figure 2).

Our study focused on rainfall and potential evapotranspiration variables. We selected the Natural Resource Management (NRM) Sub-Zone of South Eastern Australia for analysis, which included the Thomson Catchment. We used the full suite of available GCMs and organized individual GCMs into a ‘consensus’ case, a ‘wettest’ case, and a ‘driest’ case. The ‘consensus’ case consisted of at least 30% or more of a total number of models that were aligned around changes in relation to the baseline climate. We defined the ‘wettest’ case as the climate future resulting in the highest rainfall and least potential evapotranspiration. We defined the ‘driest’ case as the climate future resulting in the least rainfall and highest potential evapotranspiration (Whetton et al., 2012). Each GCM was ranked against a multivariate ordering technique according to the mean, minimum and maximum values (Kokic et al., 2002). For example, the GCM closest to the multi-model mean was selected for the ‘consensus’ case. The RCF outputs were the smoothed average of the GCM grid cells across the NRM sub-zone. These consisted of monthly percentage changes for rainfall and potential evapotranspiration. We applied the delta change factors across local climate information for the NRM sub-zone (Taylor et al., 2018). We used the year 2090 for the analysis because the RCF tool extends to this year and the climate signal would be strongest (Taylor et al., 2018). The GCM selected for the year 2090 was used for all other years. Each modelled year was projected in 20-year increments and this represents the change relative to the base year of 1995 used in the GCMs, averaged ten years either side (1996-2005) (CSIRO and Bureau of Meteorology, 2015).

The Representative Concentration Pathways (RCPs) used in this study were sourced from the pathways described by Van Vuuren et al. (2011), being RCP 4.5 and RCP 8.5. We selected them to represent the highest impact and mid-impact pathways. RCP 4.5 was the most optimistic pathway where evapotranspiration was modelled under the RCFs and radiative forcing was projected to increase (extra energy held in the lower atmosphere due to greenhouse gasses) by 4.5 W/m^2 in 2100, compared to pre-industrial levels. Greenhouse gas stabilisation is achieved with global greenhouse gas emissions peaking by 2040 and then declines. RCP 8.5 projects the highest emission scenario with an additional radiative forcing of 8.5 W/m^2 by 2100 compared with pre-industrial levels, with greenhouse gas emissions continuing to rise (Riahi et al., 2011).

2.7 Rainfall/Runoff Modelling under Representative Climate Futures

We used the lumped conceptual daily rainfall-runoff model, SIMHYD (Chiew and McMahon, 2002), to estimate daily runoff across the montane ash forests in the Thomson Catchment. It has been used to model projected climate change impacts on stream runoff across catchments throughout Australia (Chiew et al., 2009). SIMHYD simulates rainfall filling an inception store, which is emptied each day by evaporation. The excess rainfall is subjected to an infiltration function determining infiltration capacity, with excess rainfall becoming runoff. It models runoff from infiltration excess runoff, interflow, saturation excess runoff and base flow (Chiew et al., 2002). The model was accessed through the Rainfall Runoff Library (RRL) (Perraud et al., 2003). SIMHYD requires baseline input parameters of daily rainfall, potential evapotranspiration and runoff for model calibration.

To run SIMHYD, we used historical daily rainfall and potential evapotranspiration (PET) data from 1986 to 2005 centered on the 1995 base year, along with Daily Runoff data,. We sourced climate data from The Australian Landscape Water Balance model (AWRA-L v6) (Frost et al., 2018). The AWRA-L v6 runs on a daily timestep and 0.05° grid (approximately 5 km) simulating the landscape water balance for Australia from 1911 to

2019. Key outputs from the AWRA-L model include surface runoff, soil moisture, evapotranspiration, and deep drainage. The PET data were calculated according to the Penman (1948) equation as a combination of net radiation (the energy required to sustain evaporation) and vapor pressure deficit (multiplied by a wind function) (Frost et al., 2018). Rainfall data were interpolated from station records and provided on a 0.05° grid across Australia. Streamflow was sourced from surface runoff, baseflow and interflow (Frost et al., 2018).

The SIMHYD model was calibrated against modelled daily streamflow data between 1986 and 2005 from AWRA-L v6. In the model calibration, parameters in SIMHYD were optimized to maximize the Nash-Sutcliffe efficiency of daily runoff (Chiew et al., 2009). We modelled RCF projections by scaling calibrated monthly rainfall and PET data in accordance with the change factor under the respective GCM for the specific projection 20 year periods centered on 2030, 2060 and 2090. Future forest management scenarios were not included in this part of the analysis.

2.8 Comparison of impacts between forest management and projected climate change

The modelled impacts of forest management scenarios were compared with the modelled impacts of projected climate change under the RCFs using 1986-2005 period centred on 1995 as the baseline period. This was the baseline period used in the RCF approach (CSIRO and Bureau of Meteorology, 2015). The baseline runoff we obtained through AWRA-L v6 was partly modelled on the condition and growth stage of the vegetation at that particular time (Frost et al., 2018). Modelling our forest management scenarios with 1995 as the baseline year allowed for consistency in our comparative analysis of projected impacts. We calculated and analysed median differences between the impacts of forest management scenarios and the RCFs.

3. Results

3.1 Disturbance across the catchment

Inclusive of all forest types, approximately 8,250 hectares or 17% of the Thomson Catchment has been logged since the 1939 bushfires. Of this logged area, around 81% is concentrated within the montane ash forests (Figure 3). Clearcut areas in montane ash forests consist of 7,790 hectares or 45% of the montane ash forest area across the catchment. Approximately 4,619 hectares of montane ash forest is now younger than 40 years. Around 3,800 hectares of forest is allocated for logging under a Timber Release Plan, issued by VicForests (2019). Approximately 3,000 hectares or 80% of the gross area proposed for logging in the next five years is montane ash forest.

3.2 Water yield loss resulting from disturbance

The modelled median water yield from montane ash forests for the 1995 baseline period of 1986-2005 was 125,358 ML/yr for the total montane ash forest area of 18,870 hectares. The average age of unlogged montane ash forest for the period 1986-2005 was 56 years, largely as a result of the 1939 bushfires. We modelled an average runoff yield of 6.72 ML/ha/yr from these forest areas, with 4.28 ML/ha/yr in loss in runoff as a result of the average age of the forest at that time. We calculated that old growth montane ash forest would yield 11.0 ML/ha/yr of runoff across this area. Compared with Scenario (1), where logging would have ceased in 1995, we calculated that continued logging decreases runoff by 14,166 ML, 33,679 and 40,211ML for 2030, 2060 and 2090, respectively, assuming no projected climate change impacts (Figure 4). If logging were to cease by 2019, we projected gains in water yield to be 2,606 ML, 21,974 and 34,059 ML by 2030, 2060 and 2090, respectively.

3.3 Projected Climate Change Scenarios

Our RCF analysis resulted in three GCMs selected each for RCP 4.5 and RCP 8.5 (Table 3). All GCMs projected increases in potential evapotranspiration for the Year 2090 but they varied in their respective rainfall outputs. Under RCP 4.5 for 2090, the Consensus GCM IPSL-CM5B-LR projected a 10% decline in rainfall and 7% increase in potential evapotranspiration. Under RCP 8.5 for 2090, the Consensus GCM IPSL-CM5B-LR projected a 1% decline in rainfall and 18% increase in potential evapotranspiration. Under RCP 4.5, the wettest GCM GISS-E2-R-CC projected a 6% increase in potential evapotranspiration and a decline of 1% in rainfall by 2090. The wettest GCM, FGOALS-s2, under RCP 8.5 projected a larger increase in rainfall of 21% and the largest increase in potential evapotranspiration of 24%. The driest GCMs under RCP 4.5 and 8.5 project declines in rainfall of 22% and 26%, respectively, with increases of 12% and 20% for potential evapotranspiration, respectively.

3.4 Modeled water yields under Representative Climate Futures

Our modelling using SIMHYD resulted in a total of 181 model runs and 181 objective function evaluations. We optimised the model to a Rosenbrock method, resulting in a Nash-Sutcliffe Criterion for Calibration score of 0.901. Our analysis revealed a median water yield of 6.72 ML/ha/yr for the period 1986-2005. The median runoff under modelled AWRA-L v6 input data was 6.55 ML/ha/yr. We projected the modelled median water yield from the total area montane ash forests for the 1995 baseline period of 1986-2005 to be 126,787 ML/yr.

The SIMHYD runoff under RCP 4.5 and RCP 8.5 was projected to decline under the Consensus and Driest RCFs, with the wettest RCF showing little change under RCP 4,5 and an increase under RCP 8.5 (Figure 5). For 2090, the median declines projected by the consensus GCMs under RCP 4.5 and 8.5 were 25,301 ML and 23,077 ML, respectively. The median declines were greatest under projections by the Driest GCMs, with water yield reductions of 49,998 ML and 69,474 ML, respectively. Under RCP 4.5, we projected only a limited change in water runoff for the wettest GCM for 2090, with a small decrease of 478 ML. However, the wettest GCM under RCP 8.5 projected an increase in median runoff of 18,798 ML/yr. The greatest increase to water runoff is projected under RCP 8.5 for the wettest case, with an increase of 28,157 ML in 2060.

3.5 Comparison of disturbance impacts with projected climate change

The impacts of logging exceed those of projected climate change by 2090 under the wettest and consensus RCFs. The impacts of logging exceed the projected climate change impacts of the ‘consensus’ RCF by 14,910 ML and 17,133 ML by 2090 for RCP 4.5 and RCP 8.5, respectively. For the ‘wettest’ RCF under RCP 4.5, logging exceeds the projected climate change impact by 39,733 ML. For the ‘wettest’ RCF under RCP 8.5, the projected increase in runoff is less than the loss incurred by logging by 21,413 ML. Under RCP 8.5 ‘wettest’ RCF, the increases to runoff would mitigate reductions incurred by logging. The ‘driest’ RCFs exceed the impacts of logging, with further losses of 9,787 ML and 29,263 ML for RCP 4.5 and RCP 8.5, respectively.

4. Discussion

There is considerable potential for conflicts associated with the use of natural resources such as timber and water (Luo et al., 2018). We conducted a spatial and temporal analysis of the effects of logging on water provision in a forested catchment and compared these with the impacts of future climate change projections. Our analyses focused on a critical part of the water supply for the city of Melbourne, the second largest city in Australia. We targeted montane ash forests in our study because they receive some of the highest rainfall and they are where the majority of logging occurs. Our analyses indicated that logging in montane ash forests may have a greater impact on annual water yield compared with the impacts of a number of climate futures. Given the Thomson Catchment contributes over 40% of total stream runoff across the water supply system for Melbourne, this has significant ramifications for both water security and wood supply. Thus, our investigation is an example of resource prioritization. That is, competition for land and forest for wood products versus water provision. In the remainder of this paper we discuss the key implications of our findings then conclude with policy recommendations for forest and water management.

4.1 Relationships between logging and water yield

A series of studies in the montane ash forests of Victoria have demonstrated how timber harvesting can influence water yields in logged catchments (O'Shaughnessy and Jayasuriya, 1991; Vertessy et al., 2001) (reviewed by Viggers et al., 2013). Logging disturbance removes mature stands of trees which are replaced by fast-growing young trees. Such changes in forest structure and tree replacement lead to increased levels of evapotranspiration in regenerating stands (Feikema et al., 2008). This is because there are strong relationships between the age of the forest and the total leaf area index, leading to large differences in evapotranspiration and thus streamflow between young and old forests (Feikema et al., 2008).

Our analyses indicated that logging operations after 1995 in montane ash forests across the Thomson Catchment could result in an annual median loss of over 14,000 ML in water yield by 2030. Continued logging as per current management plans, would lead to greater annual losses of ~ 14,000 ML, ~34,000 ML and ~40,000 ML by 2030, 2060 and 2090, respectively. Relative to the water yield if logging had ceased in the Thomson Catchment by 1995, there would be estimated annual median losses of 9%, 18% and 20% of the montane ash forest catchment yield for the years 2030, 2060 and 2090, respectively. Based on an average consumption of 161 liters of water per person per day (Melbourne Water, 2018), this loss in water yield resulting from historical and forecast future logging equates to the loss of water for nearly 600,000 people by 2060 alone, or more than the total current human population of the Australian State of Tasmania. This projected decline is set within the context of recent declines in streamflow across the Thomson Catchment (Melbourne Water, 2017) and an increasing population for Melbourne, which has grown by 557,000 people in the 5 years to 2017, recently passing 5 million people (ABS, 2018). A report by Melbourne Water (which is the agency responsible for Melbourne’s water supply) has highlighted major concerns about water security for the city by 2030 (Chalkley-Rhoden, 2017).

Past governments in Victoria have generally prioritized the provision of water over wood production with several major water catchments closed to logging and other forms of anthropogenic disturbance (Viggers et al., 2013). The first Legislative Supply Agreement to supply pulplogs from Victorian state forests to the then Australian Paper Manufacturers (APM) facility at Maryvale, featured a clause where the Thomson Catchment was to cease being part of the Agreement by 1967 (Parliament of Victoria, 1936). This clause was removed in the 1961 Amendment of the Agreement and logging continues, with 87% of logging taking place after 1967 across all forest types. Moreover, the current Timber Release Plan for timber harvesting has assigned a further 3,800 hectares for logging across the Thomson Catchment (VicForests, 2019). Our work quantifies the extent of loss of water yield associated with past logging operations and the likely future losses as a result of ongoing logging.

4.2 Impacts of climate change

The Representative Climate Futures' projection presents a range of possible future climate change projections, all of which require consideration in planning for adaptation. The critical advantage of this approach is that it provides simplified projections, while also addressing uncertainty. There are more than 40 GCMs used in the Coupled Model Intercomparison Project Phase 5 (CMIP5) (CSIRO and Bureau of Meteorology, 2015), where each GCM contains its own conditions (Flato et al., 2013). The RCF approach facilitates a selection of a sub-set of GCMs that uses internally consistent data from each GCM and the variables relevant for catchment modelling (Clarke et al., 2011; Whetton et al., 2012). This approach provides a range of climate change projections and their associated impacts on water runoff, while incorporating the internal variables of each of the GCMs.

Our results suggest that water runoff will decline under the 'consensus' and 'driest' representative climate futures. Under a 'no logging' scenario, the resulting increasing age of the forest may negate this impact with increased runoff being returned to the catchment. The scenarios of continued logging risk exacerbating the overall reductions associated with the projected climate, particularly under the 'consensus' and 'driest' RCFs. Further modelling of future logging scenarios under RCFs would provide insight to these compounded impacts.

We have presented a range of representative climate futures but the current trend for runoff across Melbourne's water supply catchments is in decline. The 2017-2018 inflows of 413,000 ML to Melbourne's four major reservoirs, including the Thomson Reservoir, were

33% below the long-term annual average for the period (1913-14 to 1996-97) and 16% below the average for the last 30 years (Melbourne Water, 2018). The influence of this decline is uncertain; whether it is a direct signal from current climate change, a reduction of forest age due to logging and recent fires (Feikema et al., 2013), or a combination of these drivers. Rainfall declines have been observed throughout the region and more broadly throughout south-eastern Australia. Rainfall deficiencies between 2012 and 2018 have affected parts of central and western Victoria. Moreover, there has been clear downward trend in rainfall since the 1990s in southern parts of eastern Australia, and especially in Victoria (Melbourne Water, 2016; Bureau of Meteorology, 2018).

4.3 Previous studies modelling water yield changes in ash forests

Many studies have shown that disturbance in montane ash forests decreases water yield (Langford and O'Shaughnessy, 1980; Kuczera, 1987; Read Sturgess and Associates, 1994; Vertessy et al., 1998; Watson et al., 1998; Peel et al., 2000; Vertessy et al., 2001; Mein, 2008). The majority of these studies were based on disturbance experiments established during the 1950s and 1960s in the Maroondah Catchment (Watson et al., 1998). Ronan and Duncan (1980) projected an average water yield reduction of 140mm or 0.14 ML/ha by 2075, if logging was to have commenced in 1985 across the Maroondah Catchment and a 60 year cutting rotation was then maintained. Later, Read Sturgess and Associates (1994) modelled a number of alternative forest management scenarios across the Thomson Catchment and compared these with current management. If logging had ceased in 1992, around 15,000 ML of water yield would have been returned to the catchment by 2050 (Read Sturgess and Associates, 1994). These studies used either the equation by Kuczera (1987) or other models where water yield was similarly correlated with the age of the forest (Langford and O'Shaughnessy, 1980; Read Sturgess and Associates, 1994).

Reductions in water yield across the Thomson Catchment as a result of disturbance also were examined using the Macaque model (Peel et al., 2000). This model simulates changes in catchment water yield through changes in Leaf Area Index (LAI) and stomatal conductance (Jaskierniak, 2011). The Macaque model estimates that water yield will be most affected by disturbance in montane ash forests (Peel et al., 2000). In a more recent study, the Macaque model was used to model bushfire disturbance across the Thomson Catchment, where a reduction of up to a 23% in water yield was projected under a scenario of frequent bushfires (Feikema et al., 2008; Lane et al., 2010). In a further study, Mein (2008) used the Macaque model and projected water yield losses resulting from logging across the Thomson Catchment, in addition to multiple smaller water catchments where logging is also permitted. If logging were to have ceased in 2009/10, up to 16,000 ML/yr in water yield would have been returned across all water catchments by 2050 (Mein, 2008).

4.4 Caveats

The Kuczera equation is considered to be a useful representation of the potential impacts of forest disturbance on water yield (Jaskierniak, 2011). However, there are challenges in extrapolating the Kuczera equation across a broad range of environmental conditions (Jaskierniak, 2011). The Macaque model can provide more detailed analysis than the Kuczera equation through its representation of physical processes occurring within a water catchment (Peel et al., 2000). However, it is challenging to apply the Macaque model because it contains over 70 parameters and most are default values (Jaskierniak, 2011). Many of these parameters require calibration, but data for them can be difficult to obtain for remote catchments (Jaskierniak et al., 2016), as well as obtaining all of the GCM variables for the respective climate inputs.

A simpler approach has been developed by Jaskierniak et al. (2016) and Benyon et al. (2015), which uses measures of sapwood area derived from basal area and tree stocking density estimates. These inputs provide greater certainty in modelling with strong correlations between predicted and observed streamflow. However, these parameters are reliant on extensive LiDAR mapping to obtain accurate estimates of tree basal area and stocking density. The acquisition of such data was beyond the scope of this study.

The impacts of future fire were omitted from this study because the location, extent and severity of future fire is difficult to predict. Future high severity fire would have similar effects to clearcut logging. Additional fires would add to the effects of logging on water yield. Furthermore, several studies have shown that logged and regenerated montane ash forests are significantly more likely to burn at high severity than intact (undisturbed) stands (Taylor et al., 2014; Zylstra, 2018). These high severity fires are typically stand-replacing events in montane ash forest (Ashton, 1976) and correspond with a reduction in the age of the forest after the fire, leading to a reduction in water yield (Vertessy et al., 2001; Lane et al., 2010). Future fire severity modelling under representative climate futures was beyond the scope of this study.

Development of specific forest growth modelling under projected climate change would provide further insights for future logging and associated forest management. Such modelling could be designed around the GCM variables as well as additional variables, such as the impact of increased carbon dioxide fertilisation on plant growth (O'Leary et al., 2015). A number of models used in agriculture and cropping simulations account for these variables and provide valuable insight as to the impacts of projected climate change on animal and plant productivity (Keating et al., 2003; Meyer et al., 2018; Taylor et al., 2018). These models would allow for the simulation of interactions between projected climate change impacts and future forest management scenarios along with their respective impacts on water runoff.

4.5 Policy implications

Our study has focused on the extent of past and likely future reductions in water yield resulting from future forest management scenarios under representative climate futures across the Thomson Catchment. Trade-offs in economic value associated with different forest uses were not examined in this study. Other approaches are needed to do this, such as integrated economic and environmental accounting (e.g. under the System of Environmental and Economic Accounting [SEEA]; (United Nations, 2012)). Studies using this methodology have been completed for the montane ash forests of the Central Highlands of Victoria (which includes the forest in the Thomson Catchment) (Keith et al., 2017). These studies show that the economic value of the water for Melbourne is 25.5 times greater than the economic value of the timber and pulp produced from logging in native forests. Therefore, on economic grounds, ongoing logging of the Thomson Catchment does not appear to maximize the public good derived from forest catchments.

A primary driver for logging in the Thomson Catchment is its inclusion in the current the *Forests (Wood Pulp Agreement) Act 1996* (Parliament of Victoria, 1996), which forms the Legislative Supply Agreement binding the Victorian Government to supply a minimum of 350,000 m^3 of pulplogs from state forests per annum to Paper Australia Pty Ltd until 2030 (MBAC Consulting, 2006). Pulplogs are delivered to the Maryvale Pulp Mills, which are operated by Paper Australia Pty Ltd. A transition from state forests to plantations was proposed in 2006 by the previous owners of the Maryvale Mills (PaperlinX Ltd), where it committed to using 100% plantation-sourced fibre for its printing and communication papers by 2017 (PaperlinX Ltd, 2006). This commitment was later abandoned by the current owners of the Maryvale Mills who argued for continued access to state forests, including the Thomson Catchment (Poyry, 2011). However, the plantation estate across Victoria has rapidly expanded levels of wood production, and in 2017 provided domestic and export markets with 3.9 million tonnes of hardwood pulp logs (ABARES, 2017). Industry consultants (Poyry, 2011) have advised that it is technically feasible for Paper Australia Pty Ltd to source all of its hardwood pulplog volumes from hardwood plantations.

The case of logging in the Thomson Catchment needs to be costed against the increasing demand for water, particularly when rainfall is decreasing (Melbourne Water, 2018). Uncertainty becomes a challenge for future management of the catchment, particularly in the context of representative climate futures. Historical and continued logging risk negating, compounding and/or amplifying, water loss across the Thomson Catchment under representative climate futures. Therefore, a possible set of policy options is to remove logging from the Thomson Catchment and replace wood products sourced from native forests with wood products then sourced from well managed plantations. This would significantly increase water supply to the reservoir. Due to plantations being more intensively managed, the employment lost from the native forest sector would be more than compensated for by employment in the plantation growing and processing sector.

5. Conclusions

Water security in major urban areas is of increasing concern globally. The maintenance of the integrity of forest cover in water catchments is critical to ensuring water security for urban settlements. We have modelled the effects on water yield of future forest management scenarios and the legacies of past forest management in the largest water catchment for the city of Melbourne, Australia's second largest city, and compared these to projected climate change impacts under multiple representative climate futures. Our analysis highlighted the value of removing the negative impacts of logging on water yield. Our investigation highlights the complexity of potential conflicts associated with the use of natural resources such as timber and water, and the impacts of climate change.

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Figure captions

Figure 1. Location of the Thomson Water Supply Catchment

Figure 2. Outline of the Representative Climate Futures method used in the analysis for the South East Australia Natural Resource Management zone. Key classifying climate variables consist of rainfall and temperature, RCPs and the projection year (after Taylor et al., 2018)

Figure 3. Forest age class distribution across the Thomson Catchment (DELWP, 2007)

Figure 4. Water yield runoff for Scenarios (1) Logging ceased in 1995, (2) historic and future logging, (3) Cessation of logging by 2019, based in the equation developed by Kuczera (1987)

Figure 5. Water yield runoff under the Wettest, Consensus and Driest GCMs for RCP 4.5 and RCP 8.5.

Table 1. Land tenure across the Thomson Catchment (forested areas excluding water)

Land tenure	**Description**	**Area (ha)**	**Status**	**% of Total**
State Forest	General Management Zone	27,981	Logging Permitted	63%
	Special Management Zone	747	Logging Permitted	2%
	Special Protection Zone	12,153	Logging excluded	27%
National Park	National Park	3,517	Logging excluded	8%

Table 2. Forest type areas across the Thomson Catchment

Forest Type	**Area (ha)**	**% of Total**
Montane ash Forest	18,871	40%
Mixed Species Forest	24,973	53%
Snow Gum	1,974	4%
Non-Eucalypt	1,312	3%
Undefined	31	0%
Total	47,162	100%

Table 3. Representative Climate Futures for annual rainfall change projected under RCP 4.5 and RCP 8.5 for South East Australia. Case descriptions are listed against their respective Global Climate Models (GCMs) and the classification for modelled years 2090.

RCP	RCF	Annual Rainfall %	Annual Evapotranspiration %	GCM
4.5	Wettest	Little Change -5 to +5	Small Increase 1.0 to 4.59	GISS-E2-R-CC
	Consensus	Drier -15 to -5	Large Increase > 4.59	IPSL-CM5B-LR
	Driest	Much Drier < -15	Large Increase > 4.59	GFDL-CM3
8.5	Wettest	Much Wetter >15	Large Increase > 4.59	FGOALS-s2
	Consensus	Little Change -5 to +5	Large Increase > 4.59	CCSM4
	Driest	Much Drier < -15	Large Increase > 4.59	GFDL-ESM2M

Highlights

We quantified changes in water yields due to logging and projected climate change
Widespread clearcut logging in water catchments reduces water yield
Water loss from logging may exceed impacts under some climate change projections
Water loss from logging may negate additional rainfall under optimistic projections

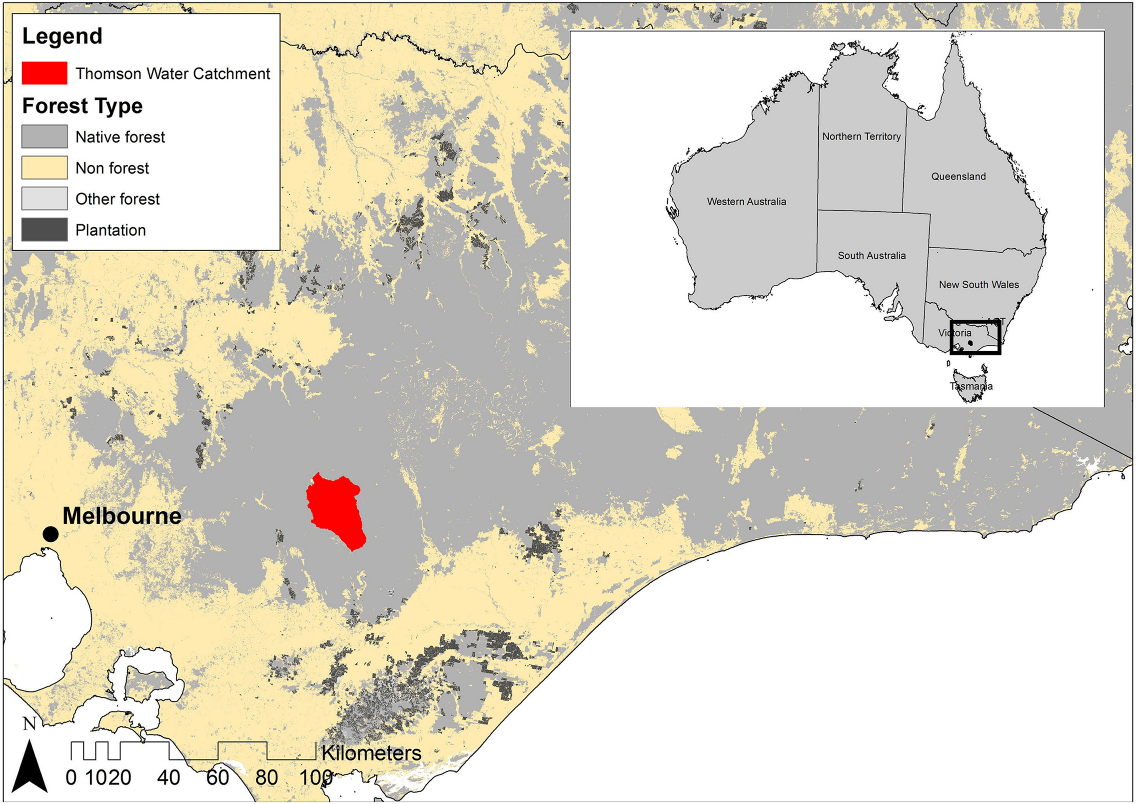
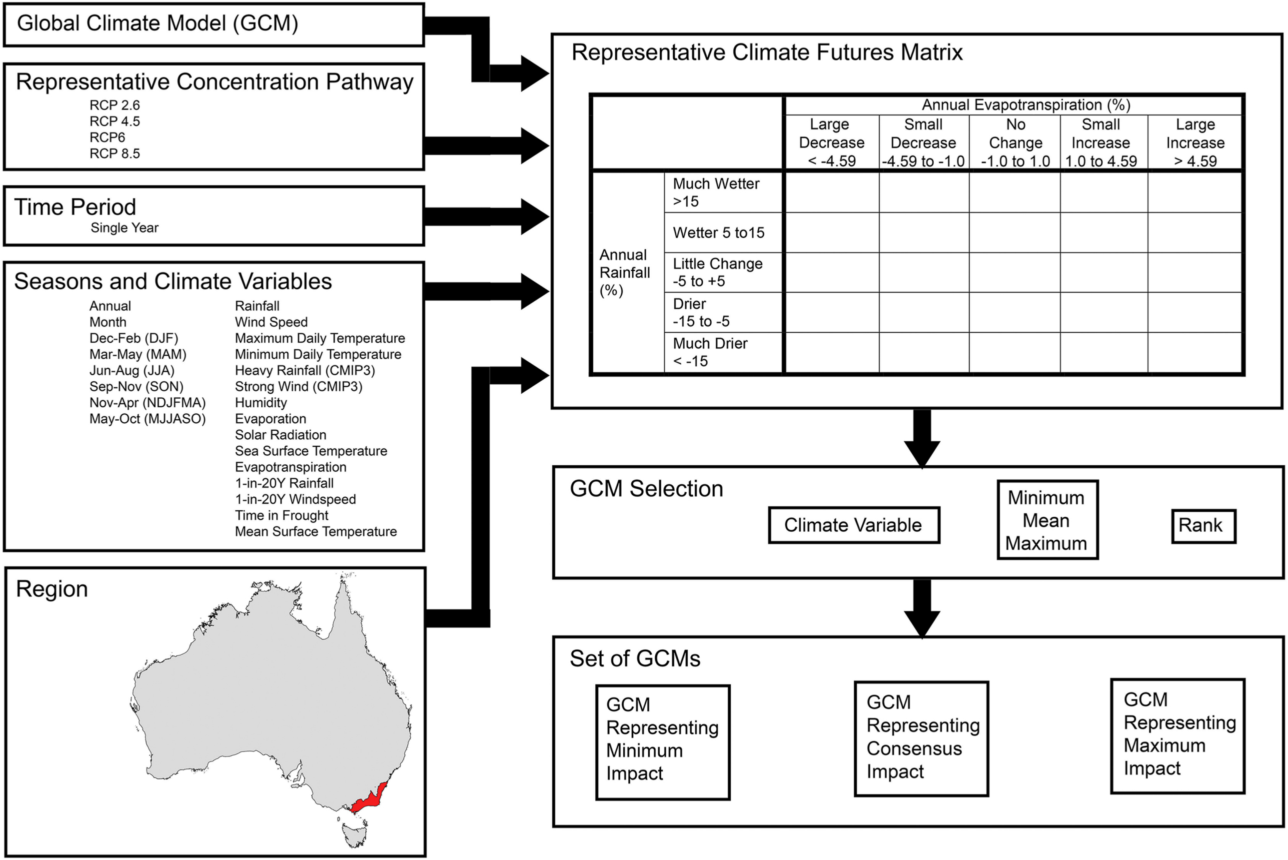

Legend
Thomson Water Catchment
Forest Type
Native forest
Non forest
Other forest
Plantation
Western Australia
Northern Territory
Queensland
South Australia
New South Wales
ACT
Victoria
Tasmania
Melbourne
N
0 10 20 40 60 80 100
Kilometers

Figure 1



		Annual Evapotranspiration (%)				
		Large Decrease < -4.59	Small Decrease -4.59 to -1.0	No Change -1.0 to 1.0	Small Increase 1.0 to 4.59	Large Increase > 4.59
Annual Rainfall (%)	Much Wetter >15					
	Wetter 5 to15					
	Little Change -5 to +5					
	Drier -15 to -5					
	Much Drier < -15					

Figure 2

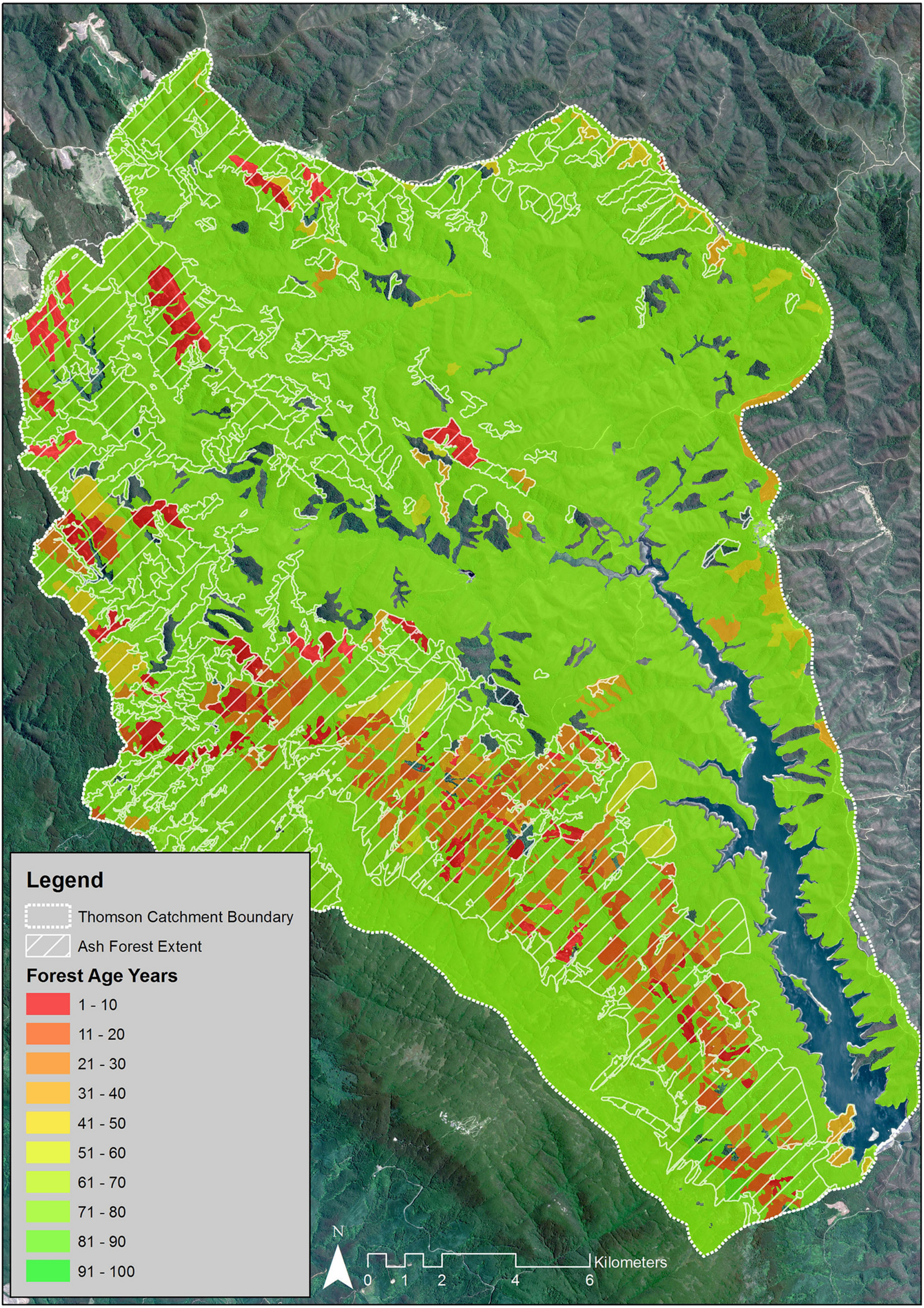
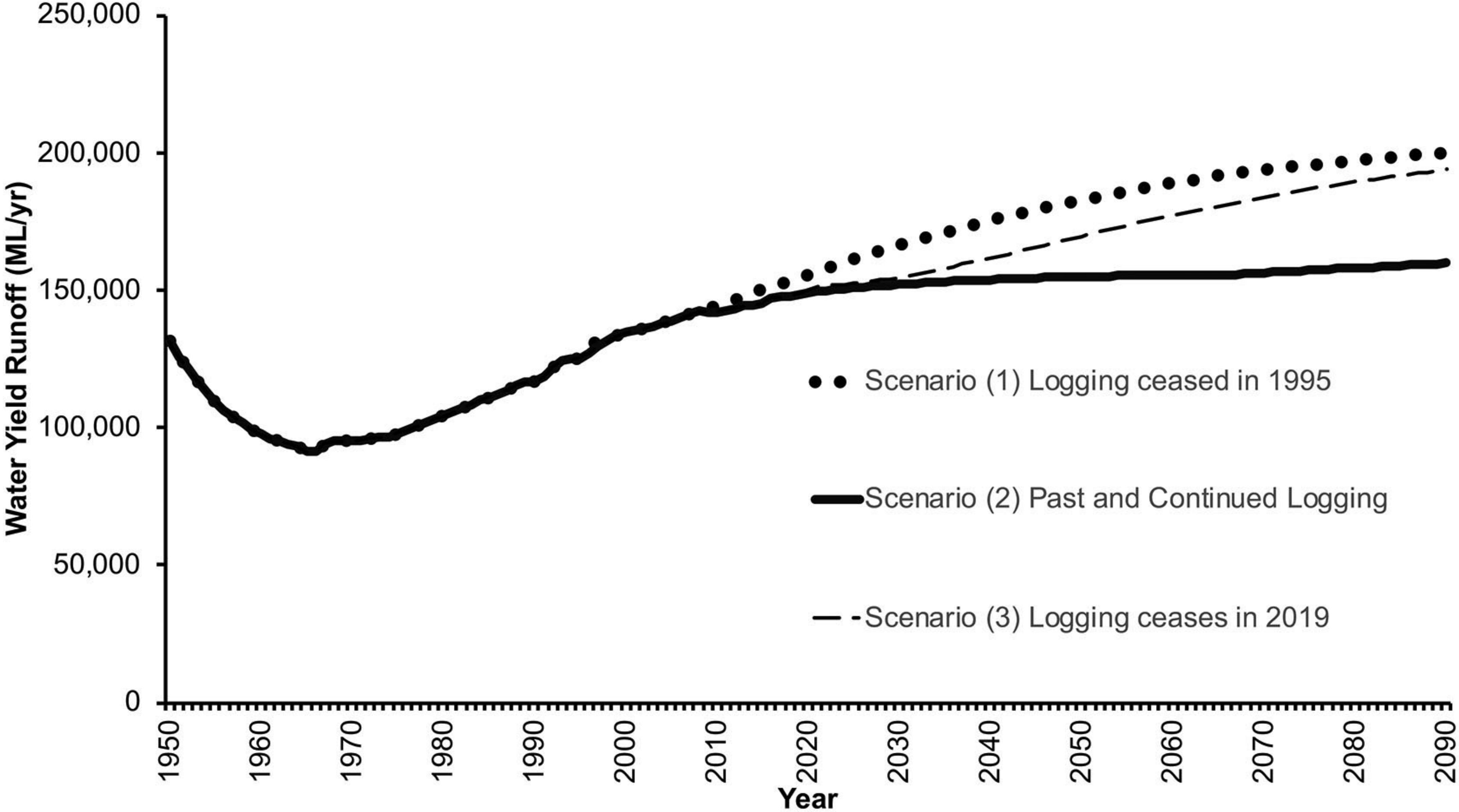

Legend
Thomson Catchment Boundary
Ash Forest Extent
Forest Age Years
1 - 10
11 - 20
21 - 30
31 - 40
41 - 50
51 - 60
61 - 70
71 - 80
81 - 90
91 - 100
N
0
1
2
4
6
Kilometers

Figure 3



Water Yield Runoff (ML/yr)
250,000
200,000
150,000
100,000
50,000
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year
Scenario (1) Logging ceased in 1995
Scenario (2) Past and Continued Logging
Scenario (3) Logging ceases in 2019

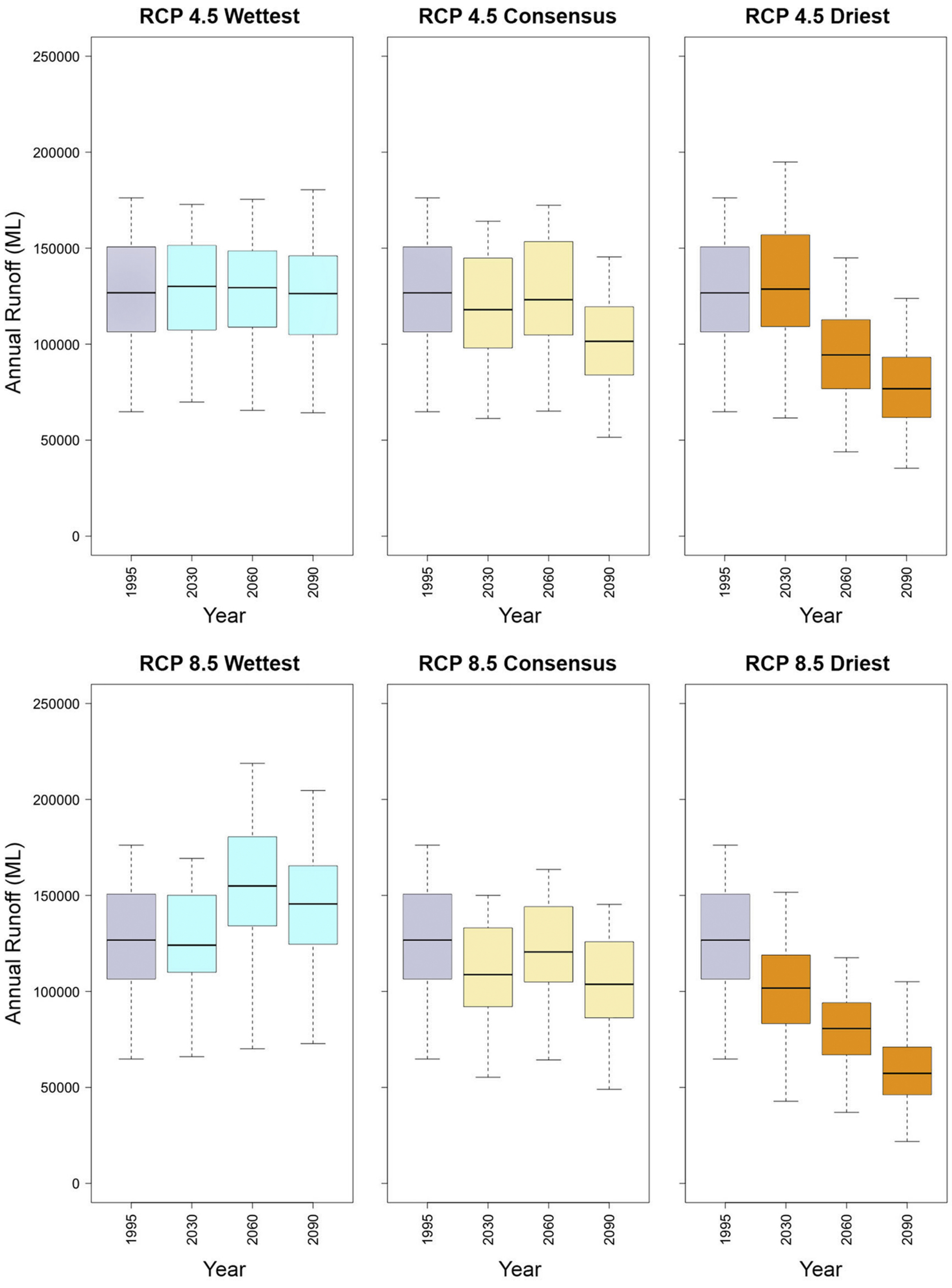

RCP 4.5 Wettest
RCP 4.5 Consensus
RCP 4.5 Driest
RCP 8.5 Wettest
RCP 8.5 Consensus
RCP 8.5 Driest
Annual Runoff (ML)
250000
200000
150000
100000
50000
0
1995
2030
2060
2090
Year

Figure 5