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Hydrospatial assessment of streamflow yields and effects of climate change: Snowy Mountains, Australia

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SUMMARY

Hydrospatial analyses of catchment topographic indices for 112 unregulated (unimpaired) gauging stations show that mean catchment elevation is the primary control on annual precipitation, runoff depth, runoff coefficients and evapotranspiration in the Snowy Mountains. Catchments with mean elevations greater than 1850 m show a steep increase in yield over the trend for lower elevation catchments and have runoff coefficients greater than one. Precipitation undercatch because of high winds and winter snowfall is the cause for this unusual situation, with deep accumulations of blown and drifted snow contributing significantly to runoff from small, high elevation catchments. Climate change effects on precipitation, runoff, runoff coefficients and the timing of peak snowmelt discharges vary across an elevational gradient. Annual precipitation shows strongly significant declines of up to 11.0 mm yr^{-1} from 1944 to 2009, with the magnitude of precipitation declines increasing with increasing elevation. Lower elevation catchments show greater sensitivity to drought than higher elevation catchments, exhibiting sharp declines in annual runoff coefficients due to smaller average differences between evapotranspiration and precipitation, and switching from energy (demand) to supply (precipitation) limited water balances. Climate change effects on the timing of peak winter–spring (June to November) snowmelt discharges for the highest elevation gauged catchments in Australia are pronounced with average shifts toward earlier peak discharges of 6.2 and 4.0 days per decade for the Snowy and Geehi Rivers, respectively. A lapse rate model using elevation as a substitute for temperature change highlights the sensitivity of mean annual runoff coefficients in the Snowy Mountains to changes in mean annual temperature, declining by 15% and increasing by 17% per degree centigrade rise and fall, respectively. Runoff coefficient sensitivity is driven by elevation (temperature) driven controls on the proportion of precipitation falling as snow vs. rain, combined with decreasing evapotranspiration with increasing elevation. Temperature (elevation) driven decreases in evapotranspiration resulting from changes in rain–snow precipitation balances, widespread snowpack accumulation and largely treeless catchments dominated by alpine vegetation during cool phases of the last glacial cycle offer a simple but comprehensive explanation for the greater runoff volumes in the Murray-Darling basin from the SE Australian highlands preserved by palaeochannels considerably larger than present river systems.

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1. Introduction

Atmospheric carbon dioxide and methane concentrations are now at their highest level for the past 800,000 years and are the primary cause for a 0.85 °C increase in global mean surface temperatures from 1880 to 2012 (IPCC, 2013). The recent increases in global temperature are greatest in northern hemisphere high latitudes, with average Arctic temperatures increasing at almost double the global average over the past 100 years, resulting in substantial declines in the extent, duration and thickness of seasonal sea ice and seasonally frozen ground (IPCC, 2013). Snow cover across the northern hemisphere has declined since the mid-20th century (IPCC, 2013) and in mountainous regions globally, spring and summer snow cover and glacier mass balances have declined (e.g. Diaz et al., 2003) and shifts toward earlier snowmelt runoff have been well documented (e.g. Adam et al., 2009). All of

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these changes are consistent with the effects of enhanced global warming resulting from anthropogenic forcing (Rosenzweig et al., 2008; IPCC, 2013).

Globally, there have been relatively few studies that have examined relationships between streamflow yields along elevation and temperature gradients that control the partitioning of precipitation between rain and snow (Dingman, 1981; Singh and Bengtsson, 2003; Hunsaker et al., 2012). Dingman (1981) found that elevation was the single most dominant variable controlling water yields, low flows, flood flows and the coefficient of variation of annual flow for 59 catchments ranging in size from 5.4 to 1984 km^2 in New Hampshire and Vermont, USA, with slope and aspect having only second-order effects. Singh and Bengtsson (2003) found reductions in snow covered area under warmer climates in the Himalaya region lead to larger percentage increases in catchment evaporative losses in snow as opposed to rain dominated basins because of the lower evaporation from snow covered areas (Bengtsson, 1980). Hunsaker et al. (2012) investigated changes in snowmelt runoff and water yield along elevation and temperature gradients in California's southern Sierra Nevada in eight experimental catchments with areas ranging from 0.49 to 2.28 km^2. Their results showed that increases in runoff with elevation were associated with changes in the partitioning of precipitation between rain and snow combined with the delayed onset of spring increases in evapotranspiration in higher elevation snow-dominated as opposed to lower elevation mixed rain and snow catchments (Hunsaker et al., 2012). Hunsaker et al. (2012) also suggested that climate warming of 2 °C could cause a 19–38% decline in mean annual runoff coefficients, with lower elevation catchments exhibiting the largest percentage declines.

Australia's alpine areas are especially sensitive to changing climates due to their limited spatial extent and low elevation (Hughes, 2003). As such, considerable research has focussed on the likely effects of predicted global warming scenarios on the extent and duration of snow cover (e.g. Hennessy et al., 2003), snow dependent species and ecosystems in the Australian alps (e.g. Hughes, 2003; Gallagher et al., 2009), and whether snow cover records that date to the 1950s contain evidence of the effects of global warming (e.g. Nicholls, 2005; Green and Pickering, 2009). For example, detailed modelling of the duration, extent and depth of snow cover under a range of global warming scenarios has been undertaken by Galloway (1988), Whetton et al. (1996) and Hennessy et al. (2003), with the latest modelling predicting that the area with at least 60 days of snow cover will shrink by 18–60% by 2020 as a result of temperature increases of 0.2–1.0 °C and precipitation decreases of up to 8% (Hennessy et al., 2003). By 2050, predicted changes are more dire, with the area with at least 60 days of snow cover decreasing by 38–96% as a result of temperature increases of 0.6–2.9 °C and precipitation decreases of up to 24% (Hennessy et al., 2003). Instrumented winter–spring (June–September) temperature data from 1962 to 2001 for four high altitude sites in the Snowy Mountains (1480–1957 m above sea level – asl) show increasing trends in maximum and minimum temperatures of 0.020–0.057 °C yr^{-1} and 0.004–0.034 °C yr^{-1}, respectively (Hennessy et al., 2003). Extrapolation of these linear trends in measured data to 2020 and 2050 suggest that the projected temperature increases for the Australian Alps (Hennessy et al., 2003) may indeed be reasonably accurate.

Nicholls (2005) reviewed an extensive literature assessing measured snow course data from Spencers Creek (1830 m asl), Australia's longest and highest elevation snow course record, and undertook an analysis of trends in annual maximum snow depth, spring snow depth, precipitation, temperature and atmospheric pressure. While annual maximum snow depths showed a weak decline, a larger decrease in spring snow depths from 1962 to 2002 was attributed primarily to increasing temperatures during July–September, and to a lesser degree, a small decline in winter precipitation. Green and Pickering (2009) reported a stronger and highly significant decline in snow cover from 1954 to 2007. Their approach differed from that of Nicholls (2005) as they transformed the Spencers Creek snow depth records into metre-days of snow by multiplying snow depth data by the number of days at that depth and summing the result to a single value for each year. Green and Pickering (2009) also report a shift toward earlier spring snowmelt of two days per decade since 1954 for the Spencer's Creek snow course data. Bormann et al. (2012) similarly report a shift towards earlier snowmelt across elevations greater than 1580 m from analysis of satellite imagery. Sanchez-Bayo and Green (2013) attribute a temporal shortening of the Snowy Mountains snowpack of ~3 days per decade since 1954 to increasing temperatures.

While considerable research has focussed on analysis of Australian snow depth records and modelling of trends in snow depth and extent with regard to climate change, less effort has focussed on analysis of hydrological data from Australia's alpine areas (Brown and Milner, 1989). In alpine areas, unregulated catchments with long streamflow records have several advantages over precipitation and snow depth gauges in evaluating the effects of climate change and climate variability on water resources (Beebee and Manga, 2004). First, streamflow and runoff provide an integrated record of the effects of changes in precipitation, snowmelt, temperature and evapotranspiration across spatially extensive areas. Second, streamflow records from alpine areas provide data from areas of rugged topography where meteorological instrumentation and data are often sparse. Third, streamflow and water yields from mountainous areas are of direct economic and social importance to communities, states and nations downstream, and often form the primary focus of interest for governments and water managers.

The Snowy Mountains and wider Australian alps form an extremely important water resource for south-eastern Australia and provide approximately 20% (Brown and Milner, 1989) to 29% (Worboys et al., 2011) of the water yield of the Murray-Darling basin (MDB), Australia's most economically important basin. The Snowy Mountains encompass the five highest peaks in Australia, including Australia's highest peak Mt. Kosciuszko at 2228 m asl, and contain a hydrographic record unsurpassed in Australia. Brown and Milner (1989, p. 317) noted that "There are very few, if any, alpine regions in the world that have such an extensive array of hydrological and meteorologic data available as the Snowy Mountains." For this paper, we have collated hydrologic and hydro-spatial data for 102 Snowy Mountains Hydro-electric Authority (now Snowy Hydro Limited) and 21 Department of Water Resources (now NSW Office of Water) gauging stations representing 1032 station years of data over the period 1944–1970, collected primarily for evaluation and design of the Snowy Mountains Hydro-electric Scheme (SMS). Despite the importance of the Snowy Mountains to water resources in south-eastern (SE) Australia, this data archive has not received the benefit of systematic analysis in conjunction with recently available data such as the Shuttle Radar Topography Mission (SRTM) one arc-second digital terrain model (DTM), and recently available Bureau of Meteorology (BoM) gridded climatic data sets (Jones et al., 2009). Geographic information systems (GIS) based hydrospatial analysis tools such as ArcHydro provide an opportunity for spatially explicit, systematic analyses of this wealth of hydrological data. The aims of this paper, therefore, are to:

i. assess relationships between mean annual runoff depth, catchment area averaged precipitation, runoff coefficients and DTM derived catchment topographic indices;
ii. assess whether effects of recent climatic changes are apparent in long-term streamflow records available for the Snowy Mountains; and,

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