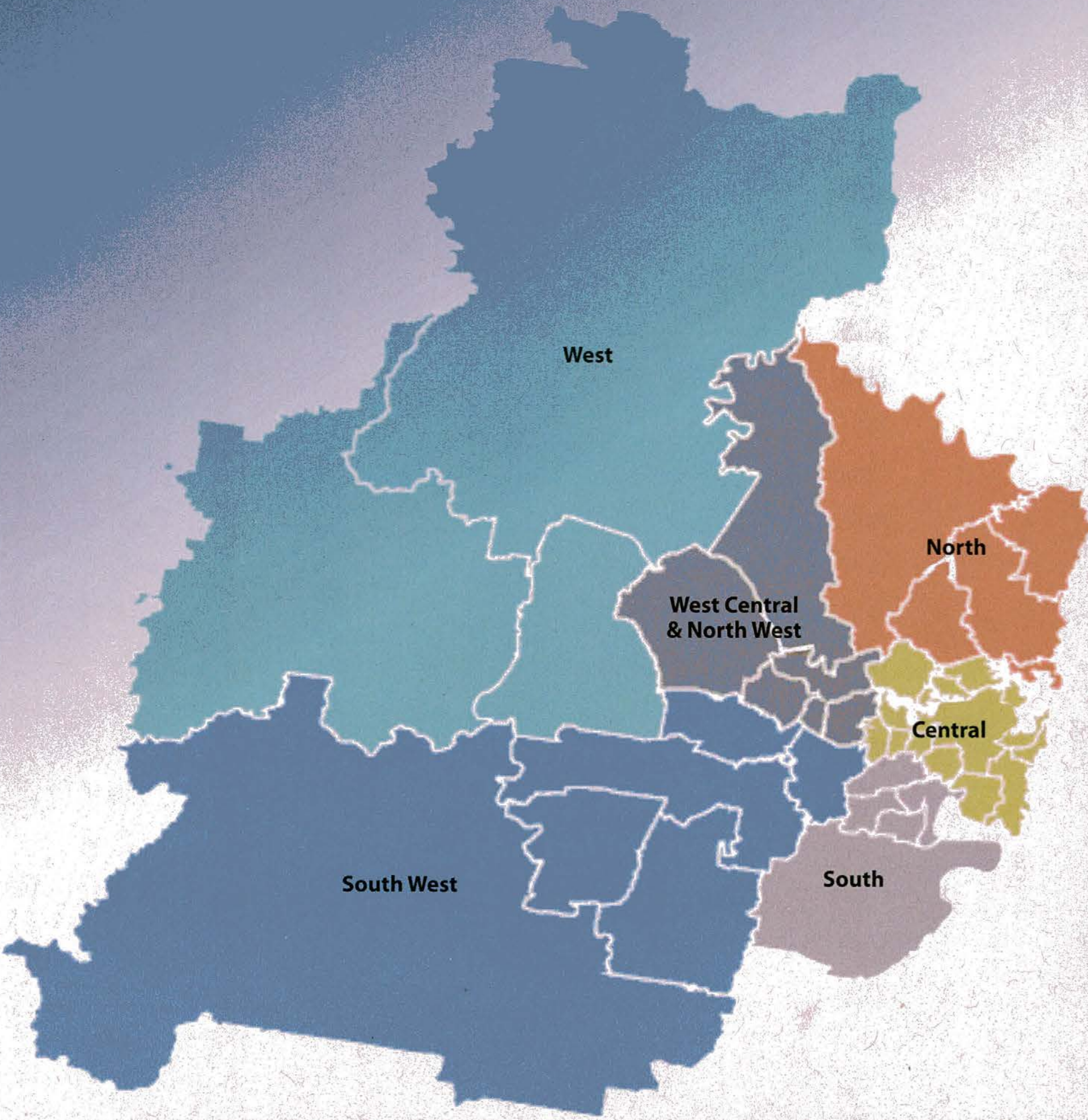
Office of Environment & Heritage

THE SYDNEY CLIMATE STORYLINE



SYDNEY CLIMATE STORYLINE
INTRODUCTION

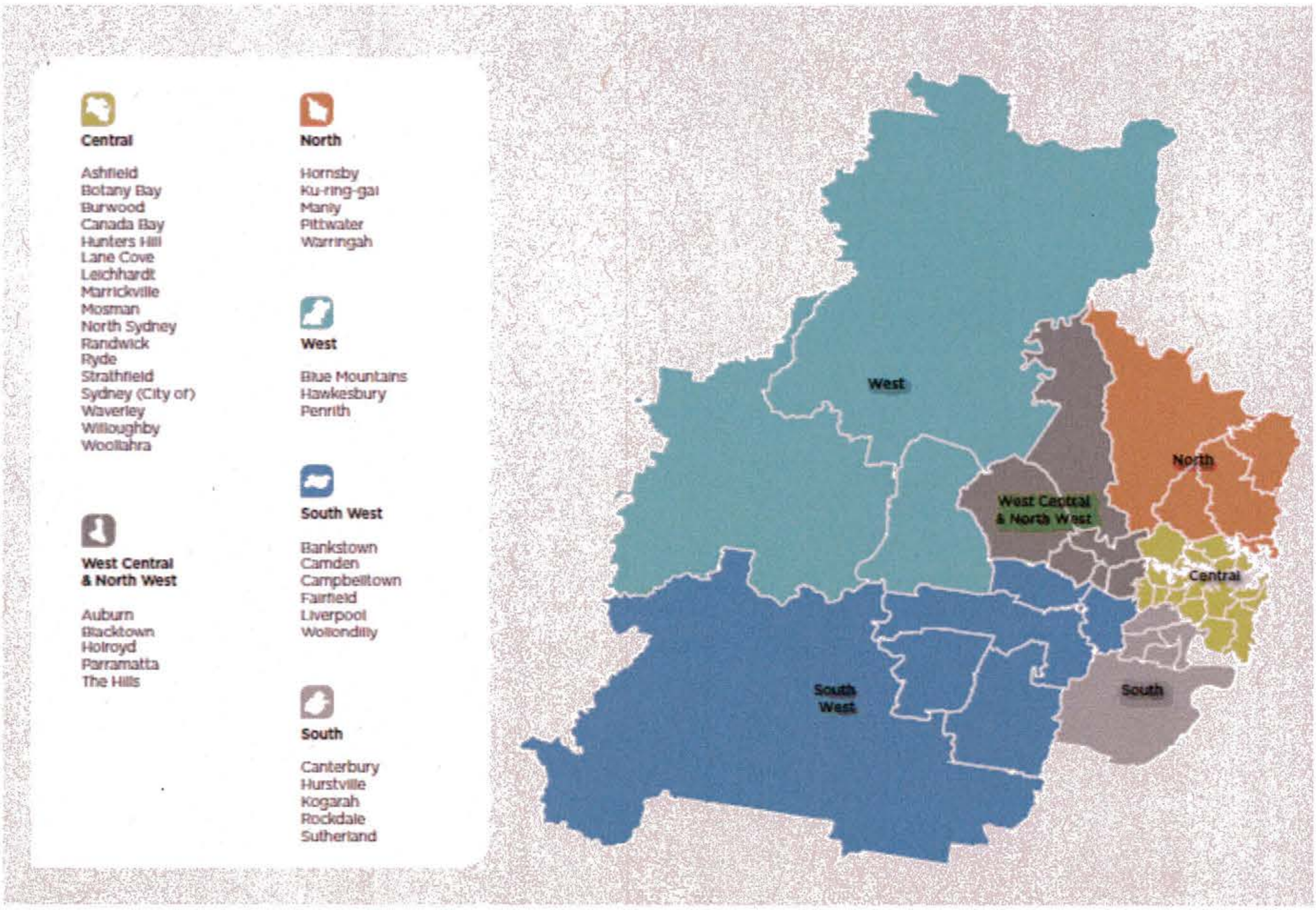
The NSW Office of Environment and Heritage (OEH), in partnership with the Climate Change Research Centre at the University of New South Wales (UNSW) has completed this pilot study to develop climate change projections for Sydney Metropolitan Area out to 2050.

The climate projections have been analysed to determine the impacts of climate change on biodiversity, coastal systems, water and soils, fire and heat and air quality. The outputs from the assessments provide an example to the attendees at the Sydney Integrated Regional Vulnerability Assessment workshop of a localised "snapshot" of one potential climate change scenario by 2050.

THE STUDY AREA: SYDNEY METROPOLITAN AREA

The Sydney Metropolitan Area (referred to as 'Sydney') consists of 6 State Planning regions: Central, West Central and North West, North, West, South West, South.

MAP 1 | Sydney Metropolitan Area (Draft Metropolitan Strategy for Sydney)



Cover photo Sourced from Draft Metropolitan Strategy for Sydney.

THE SYDNEY CLIMATE STORYLINE

How were the projections and impact assessments developed?

The Sydney climate projections used in these studies have been developed by the Climate Change Research Centre at University of New South Wales (UNSW) as a pilot study using global and regional climate models.

The Sydney climate change projections have been modelled using the Global Climate Model (GCM) CSIRO Mk 3.5. This model is just one of a suite of GCMs available for the Sydney Region and was chosen because it performed best in replicating observed climate. All the global climate models project a warming of the climate but differ in their rainfall projections. CSIRO Mk 3.5 is considered a 'wetter' model, projecting higher rainfall compared with the other GCMs.

CSIRO Mk 3.5 was then dynamically downscaled to 2km using the Weather Research and Forecasting Model (WRF). A single emissions scenario – the A2 scenario - has been used.

The model has included the land release sites for urban growth areas in Sydney, to determine the impact of changes in land use on our future climate of the urban environment.

OEH undertook research on the potential biophysical impacts of climate change in Sydney including impacts on: hydrology; coastal erosion and inundation; heat; fire weather; native vegetation; and soil properties.

What are climate models?

Climate models are mathematical representations of the key processes of the Earth's climate system. They can be used to estimate how our climate might respond to more volcanic eruptions, less sunlight, different greenhouse gas levels or other potential changes in the climate system. Using these models allows us to move beyond the assumption that our climate will always stay the same, or that it will move unpredictably within the bounds of natural variability.

How much certainty do you have around the Sydney projections?

No model can perfectly represent the Earth's climate – some regions of the modelled climate may be slightly hotter or dryer, for example, than the climate actually observed in reality. To minimise the impact of any given model's imperfections, it is helpful to use multiple different models.

Using several models gives us a better understanding of the uncertainty in the projected future climate, as we can see where models agree and where they differ, and temper our interpretations accordingly. Performing multiple model runs also captures more reliable information on important but rare extreme weather events such as heatwaves, heavy rain and drought.

The pilot study uses projections from a single global climate model and a single regional climate model. The results presented here are only one projection of a possible future simulated by a single global climate model (GCM). The results therefore possess a large band of uncertainty, in particular regarding the magnitude of projected changes.

In this scenario Sydney is projected to become wetter by 2050. Other scenarios could potentially project a drier scenario.

THE SYDNEY CLIMATE STORYLINE

The model was tested by UNSW and it performed well for temperature but it is complex for precipitation. It is notoriously difficult to model precipitation and it was found that the very high precipitation values in the model were due to large extreme rainfall events. These events have occurred in Sydney and therefore not outside the realm of possibilities but the information should only be used to identify potential impacts for sectors.

How much will Sydney be impacted by sea level rise?

The principal components contributing to global average sea level rise are the melting of land based snow and ice reserves and the thermal expansion of the ocean water mass.

Regional differences in sea level rise around Australia are mostly associated with El Nino Southern Oscillation (ENSO) like phenomena and are significant over inter-annual and decadal time frames.

Although one of the longest sea level records in the southern hemisphere is available from Sydney Fort Denison (since 1886), sea level trends are expected to be non-linear under climate change scenarios. Therefore, future sea levels should not be derived by simple, linear, extrapolation of observed historic trends.

The Intergovernmental Panel on Climate Change (IPCC) has developed a range of sea level rise projections. Observed global average sea level rise is currently tracking the upper range of the modelled IPCC projections.

The NSW and ACT Regional Climate Model (NARCLIM) modelling project did not provide additional or updated information on sea level rise projections although risk associated with some specific sea level rise scenarios are considered below.

IPCC AR5 Working Group 1 Report was realeased in October 2013 with updated sea level rise projections.

Can I use this climate change information in my work in Council or State Government?

The Sydney Climate Storyline is only to be used to assist participants of the Sydney Integrated Regional Vulnerability Assessment workshops to identify direct and indirect impacts on their sector and capacity to adapt to these impacts.

However, next year OEH will be publically releasing the broader (NARCliM) projections.

NARCliM is a NSW-specific climate model to deliver climate change projections at a scale relevant for use in local-scale decision-making i.e. 10km X 10km grid.

NARCliM will support development of a more comprehensive picture of the likely regional impacts of climate change in NSW. A web interface and data analysis tools are being developed to allow community, business and government to use and interpret the projections.

The Sydney assessments also demonstrate how NARCLIM data can be used to provide information on climate impacts that can assist local government, business and the community to build resilience to future changes in climate, hazards and extreme events.

THE SYDNEY CLIMATE STORYLINE

CLIMATE CHANGE IMPACTS FOR SYDNEY 2050

1 | TEMPERATURE AND RAINFALL

Sydney currently has a temperate climate with warm summers and mild winters. Sydney's weather is moderated by proximity to the ocean. The warmest month is January, with an average air temperature range at Observatory Hill of 18.6–25.9 °C (BoM, 2013). In winter, temperatures rarely drop below 5 °C in coastal areas. The coldest month is July, with an average range of 8.0–16.2 °C (BOM, 2013).

Inland, in Sydney's western suburbs, the climate is drier and summers are much hotter with temperatures around 3-4 degrees Celsius above Sydney's coastal areas and winter lows around 2 degrees cooler than the coast (BoM, 2012a). Although Sydney has high humidity and precipitation levels in summers, it does get dry heatwaves that bring hot and arid searing winds that make the temperatures soar to above 40° Celsius.

Rainfall is slightly higher during the first half of the year when easterly winds dominate (Feb-Jun). Sydney's wettest month is June, though most of its western suburbs' wettest month is February. The driest months are July through to September.

El Niño Southern Oscillation plays an important role in determining Sydney's weather patterns: drought and bushfire on the one hand, and storms and flooding on the other, associated with the opposite phases of the oscillation.

The city is prone to severe hail storms, wind storms, and flash flooding from rain caused either by East Coast Lows (during autumn-winter periods) and Ex-Tropical Cyclone remnants (during spring-summer periods). They are low pressure depressions that can bring significant damage by heavy rain, cyclonic winds and huge swells.

For more information visit Bureau of Meteorology: http://www.bom.gov.au/nsw/index.shtml

THE SYDNEY CLIMATE STORYLINE 2050

TABLE 1 | Summary of temperature and rainfall changes in the Sydney Metropolitan Area to 2050

SEASON	MINIMUM TEMPERATURES	MAXIMUM TEMPERATURES	PRECIPITATION
Summer	1-3.5°C warmer	0.5–3°C warmer	-10–60% increase
Autumn	1-3.5°C warmer	1-3.5°C warmer	-10–120% increase
Winter	1-3.5°C warmer	0.5–3°C warmer	-10–10% increase
Spring	1-3.5°C warmer	0.5–3°C warmer	-10–80% increase

1 | TEMPERATURE AND RAINFALL

TEMPERATURE (for further detail on the single scenario used refer to page 3 and 4)

- In the 2050 scenario Sydney is projected to become hotter, with higher maximum and minimum temperatures projected across the region in all seasons. The largest increases are projected during the cooler months of June, July and August.
- Increases in minimum temperatures exceed increases in maximum temperatures i.e. there is a smaller diurnal range in temperature between seasons
- Maximum temperatures are projected to rise by between 1-2 degrees Celsius across much of Sydney by 2050 with the greatest increases in the South Western region (Figure 2)
- The greatest increases in minimum temperatures are projected to occur in the west and southwest of the city, with increases of more than 2.5 degrees Celsius. (Figure 1)
- Minimum temperatures are projected to rise by between 1.5-2.5 degrees Celsius across much of Sydney by 2050 (Figure 1).

FIGURE 1 | Changes in seasonal Minimum Temperature for Sydney, 2050

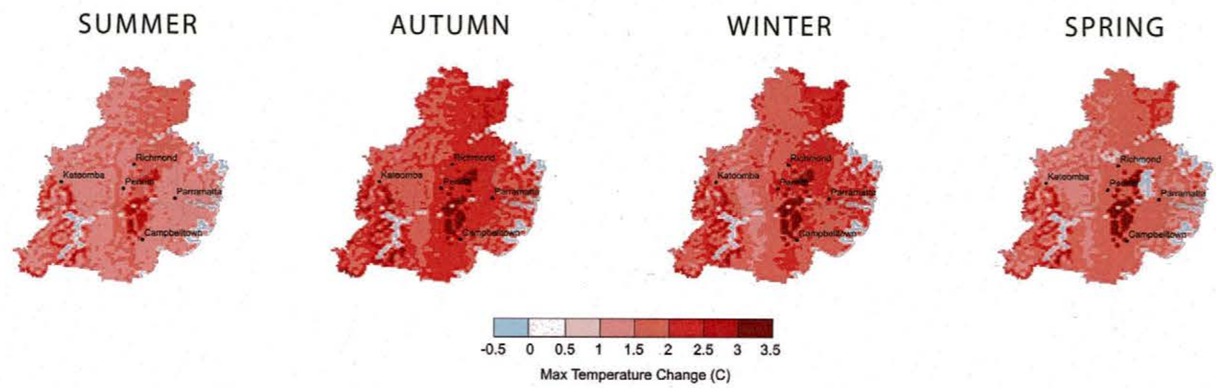
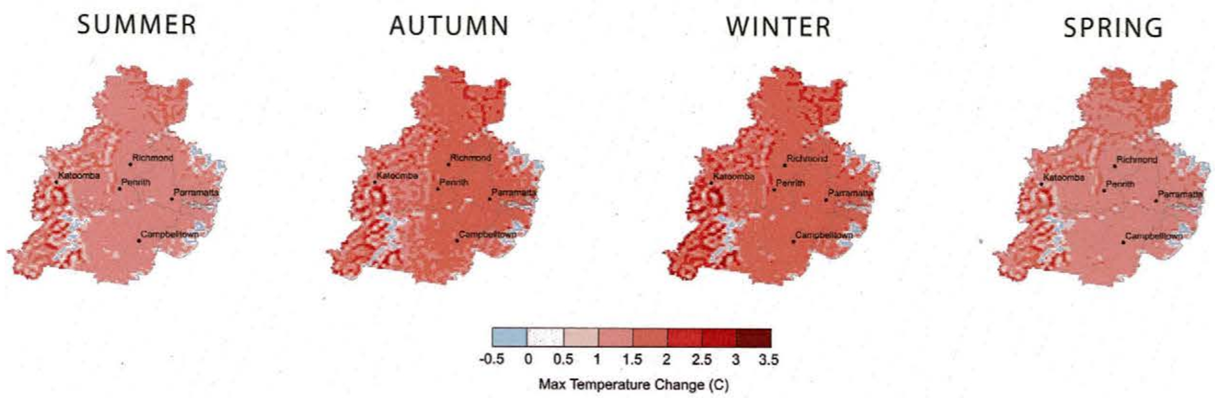


FIGURE 2 | Changes in seasonal Maximum Temperature for Sydney, 2050



1 | TEMPERATURE AND RAINFALL

RAINFALL (for further detail on the single scenario used refer to page 3 and 4)

- In the 2050 scenario Sydney is projected to become wetter, with higher annual rainfall projected to increase by 90-450mm across much of Sydney by 2050 (Figure 4).
- Annual increases in rainfall are dominated by increases in autumn (Figure 3).
- The greatest increases in rainfall are projected to occur in the Blue Mountains, and near the coast.
- The higher rainfall values are mainly due to the presence of extreme rainfall events or East Coast Low events.
- A few locations are projected to experience a decrease in rainfall (0-30%) in Summer and to a lesser extent, Spring and Winter (Figure 3)

FIGURE 3 | Changes to Precipitation for Sydney, 2050

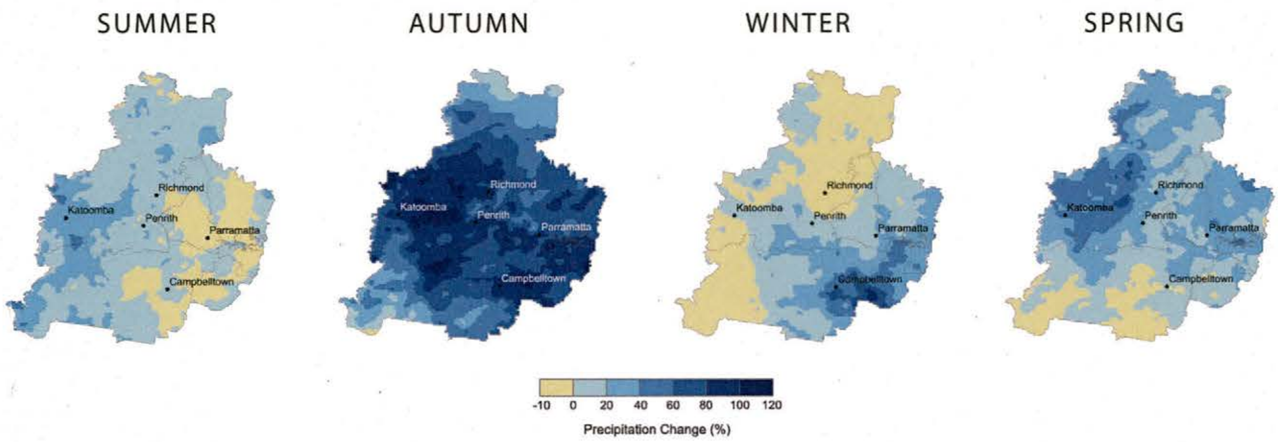
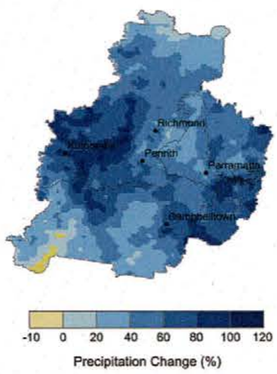


FIGURE 4 | Change to Annual Precipitation for Sydney 2050



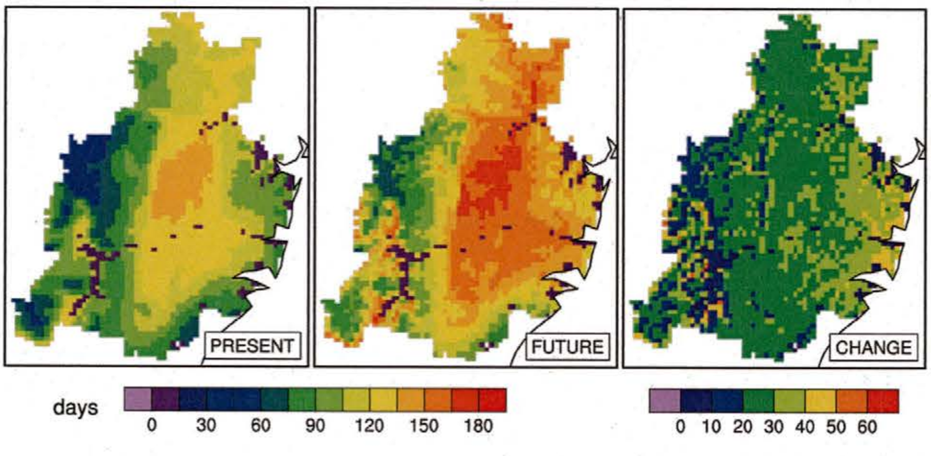
2 | HEAT AND THE URBAN LANDSCAPE

- The landscape of the Sydney metropolitan area has large areas of forested and rural lands interspersed with urban areas.
- Sydney's climate is largely dictated by its coastal position and the temperate ocean current that surrounds it. Average maximum summer temperatures in the inland suburbs are 3-4°C higher than coastal suburbs (BoM 2012a). There is also a temperature difference of 3-4°C between urban areas at sea level and mountainous areas which reach up to 600 metres above sea level.
- In comparison to surrounding natural landscapes, most urban environments experience the 'urban heat island effect', which is where buildings and hard surfaces store heat, and in turn, increase air temperatures.
- Trees and other vegetation can mitigate heat because they intercept solar radiation, shade buildings and other surfaces, and cool the air by evapotranspiration.

HEAT WAVES

- In the 2050 scenario, the number of warm days and nights (Figure 5), and the number of tropical nights (Figure 6) are projected to increase substantially in the future but the numbers will differ between locations. The number of warm days is projected to increase over all the Sydney Metropolitan Area and in the valleys. The city and new urban areas are projected to experience many more tropical nights (more than 40 nights/year over 20 °C in new urban regions).
- The changes in the number of heatwaves (3 or more consecutive days above the 90th percentile for the month) is shown in Figure 7. The largest projected changes are concentrated in the surroundings of the Sydney basin, where the number of BoM heat waves is projected to more than double to 5-6 times/year. More moderate changes are projected in the city.

FIGURE 5 | Summer Days (Tmax>25°C) per year: present, future and projected changes



2 | HEAT AND THE URBAN LANDSCAPE

FIGURE 6 | Tropical nights (Tmin>20°C) per year: present, future and projected changes

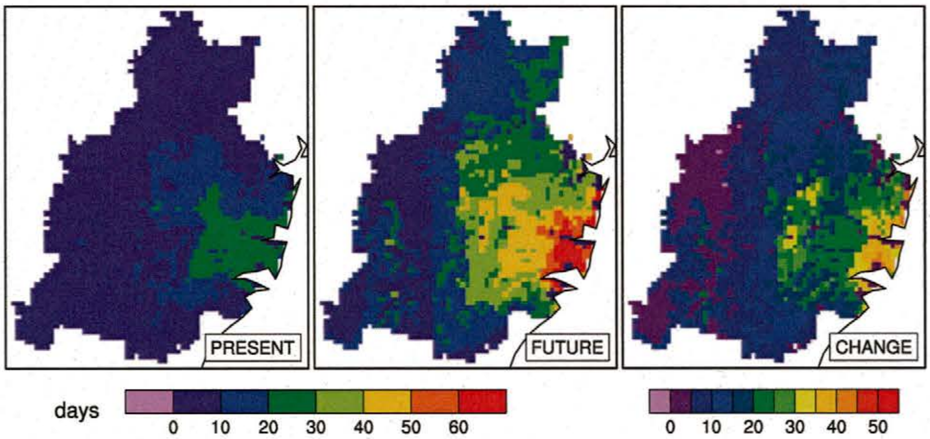
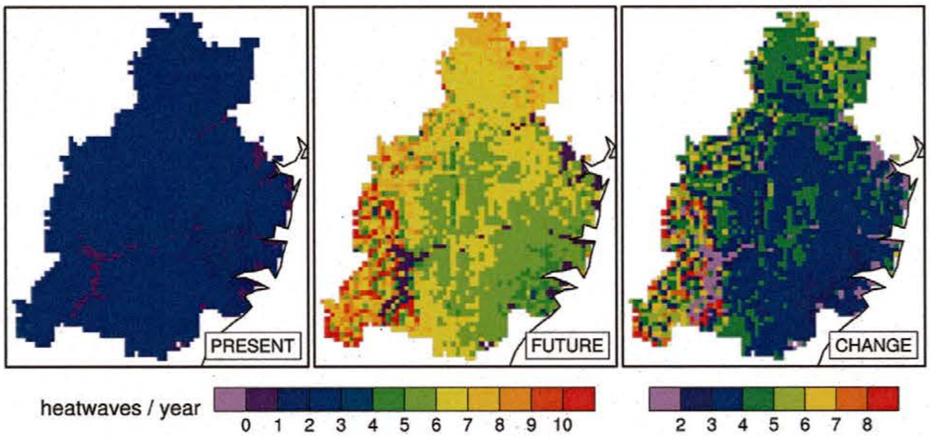


FIGURE 7 | Number of heat waves per year: present, future and projected changes



URBAN HEAT

- By 2050 it is projected that minimum temperatures will increase by between 1°C – 3.5°C (See Figure 1). In urban settings, including urban expansion areas; the temperature increase is projected to be up to 3.2°C (Argueso et al 2013). Urban structures account for 1.5°C of the increases in urban temperature.
- The relationship between vegetation and temperature in urbanised areas of Sydney was investigated. Once distance to the coast, elevation and urban structures were accounted for, a 10% increase in tree cover reduced summer land surface temperature by 1.13°C, almost completely offsetting the thermal loading effect of urban structures.
- When vegetation cover (trees, hedges, grasses) is greater than 40% of the total area, increasing the cover a further 10% reduces land surface temperature (LST) by 1.16°C. LST is not reduced when the mixed vegetation cover is less than 40% of the total area (Smith and Adam 2013).

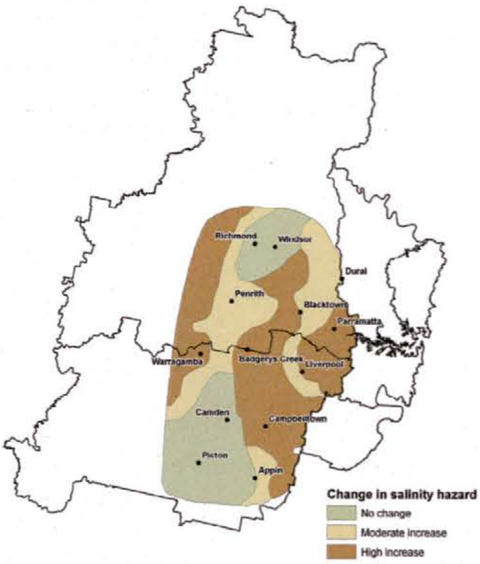
3 | SOILS

Soils support the growth of most plant life and are a crucial element of all terrestrial ecosystems. Soil influences the type of vegetation that can be supported and the agricultural potential of the land. Three soil issues were analysed for potential future impacts.

SALINITY HAZARD

- The impacts caused by increased salinity are significant in many urban areas including the Sydney metropolitan area. In Sydney, impacts include damage to urban infrastructure such as roads, buildings, underground services, parks and gardens, and can lead to a decline in water quality
- In areas of Western Sydney, there is projected to be a moderate to high increase in salinity hazard resulting from climate change. No areas which are currently impacted will have reduced salinity impacts due to climate change (Figure 8).
- Of significance is the band of 'high increase' through Campbelltown, Badgerys Creek and Blacktown (Figure 8). Major parts of Sydney's South West Growth Centre are within this zone.

FIGURE 8 | Change in Salinity Hazard in Western Sydney



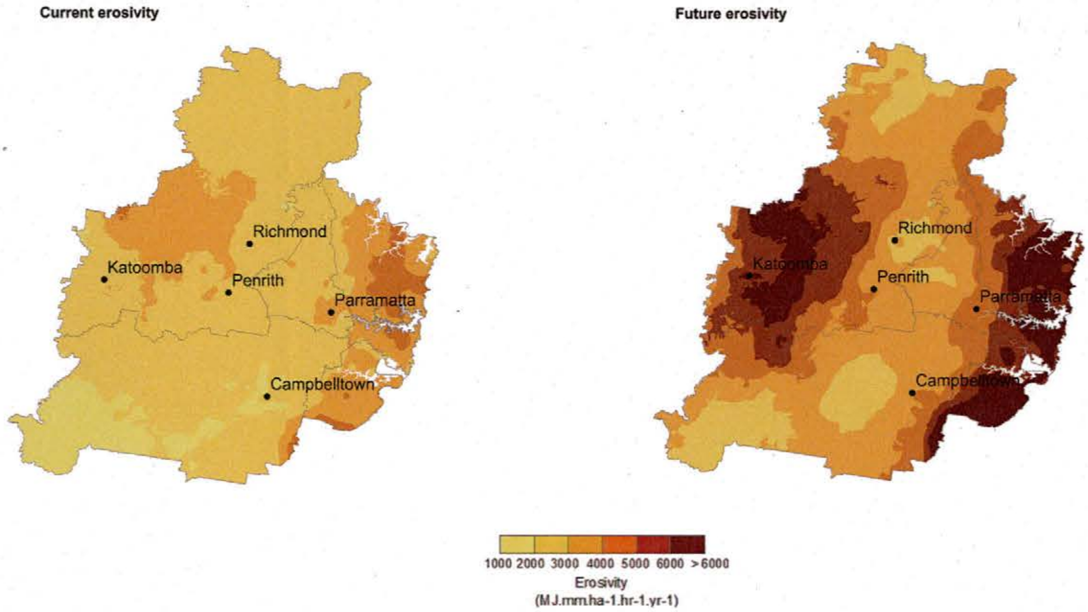
RAINFALL EROSIVITY

- Rainfall erosivity is largely a function of the amount of rainfall and its peak in intensity. It is one of the main drivers for soil erosion.
- Unchecked hill slope erosion (sheet and rill erosion) has caused profound and irreparable economic and ecological damage in Australia (Rosewell et al 2007; Russell and Isbell 1986).

3 | SOILS

- Sydney is projected to experience an increase in rainfall erosivity (Figure 9). The increase reflects a shift in rainfall seasonality – with more rainfall in late summer/autumn, coupled with more intense summer storms projected for 2050. Late summer/autumn is critical for maintaining ground cover because it is the period of greatest soil exposure.
- The regions projected to be most affected by the erosivity changes include all of the coastal regions (Northern, Northern Beaches, Eastern Inner, Southern) as well as the western half of Western Region (Figure 9).

FIGURE 9 | Present and future projected erosivity in Sydney, 2050



SOIL COMPOSITION

- Soil fertility is a function of a soil's composition, which controls its ability to support various landuses. Soil composition can be measured by assessing organic carbon (OC), pH (acidity) and base content (e.g. magnesium, potassium, calcium and sodium).
- The Coastal and Blue Mountains areas are projected to have increases in the OC (Figure 11) content of the soil but decreases in pH (Figure 10) and base content (Figure 12). Far North Western region and the South Western region are projected to have significant decreases in OC and increases in pH and base contents. In the broad central areas where significant agriculture is practised, changes in all three soil properties are generally only minor. These trends reflect the patterns of rainfall and temperature change across the region.
- Overall, the fertility of soils in Sydney is not projected to change significantly. The relatively low proportion of agricultural uses in the region suggests these slight changes will not have serious implications for the region. The change in soil character may affect the ecology of the region. It may cause changes in species composition of ecological communities in addition to those resulting from the changed climate.

3 | SOILS

FIGURE 10 | Change in pH (absolute value) in soils for Sydney, 2050

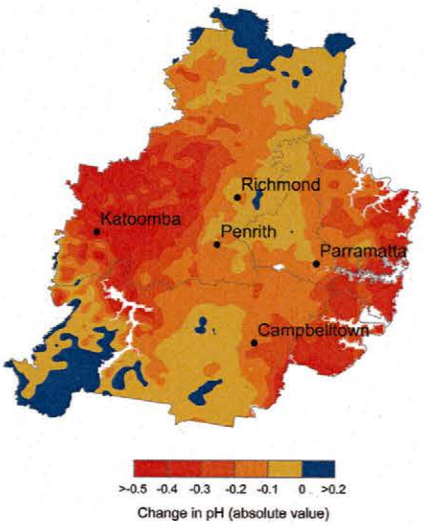


FIGURE 11 | Change (%) in organic carbon content of soils for Sydney, 2050

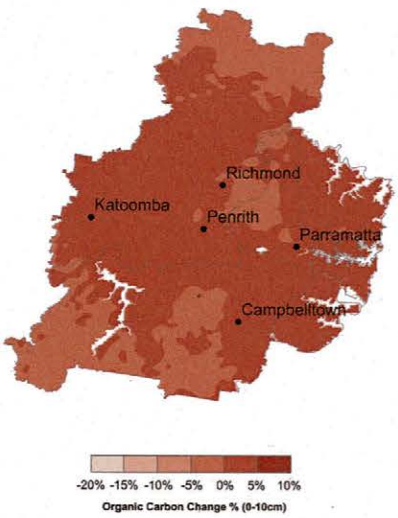
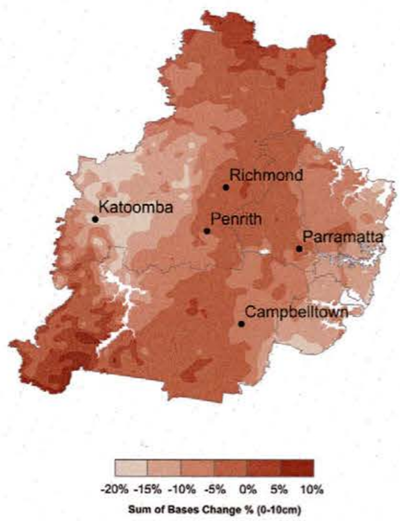


FIGURE 12 | Change (%) in sum of bases in soils for Sydney, 2050



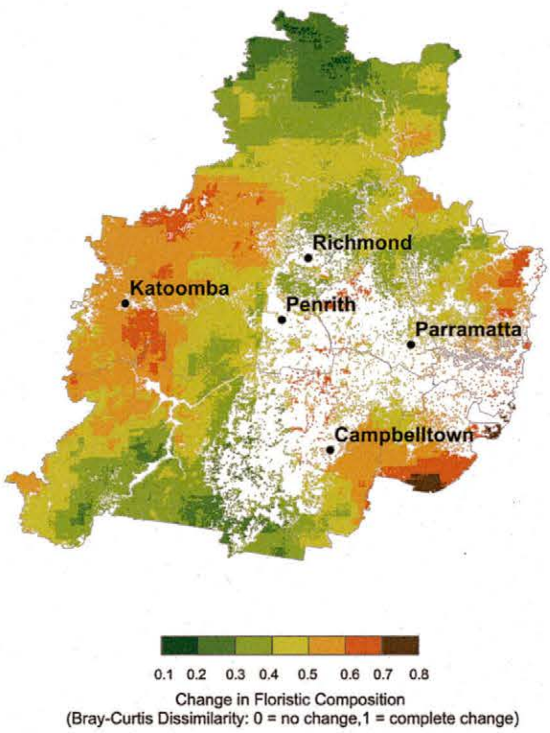
4 | BIODIVERSITY

Sydney comprises a tapestry of national parks, geological features, harbour, coastal plains and bushlands. These natural assets are important to maintain our agriculture, fishing and recreational spaces in Sydney, and for maintaining ecosystem function. Climate change is expected to impact biodiversity and ecosystems in a complex way. Three elements of our biodiversity were analysed: fauna, saltmarsh and mangroves, and changes to floristic composition.

CHANGES TO FLORISTIC COMPOSITION

- Native vegetation covers 67% of Sydney. The 2010 NSW Climate Impact Profile assessments concluded that the structure, function and composition of all ecosystems in NSW is 'expected to alter' with adverse consequences for many existing ecosystems and species. In the Sydney/Central Coast region, coastal and estuarine communities are likely to be affected by rising water tables and saltwater intrusion as sea level rises. High altitude species are likely to contract in their lower range.
- There is likely to be additional pressure on highly fragmented ecosystems with ecosystems and their components stressed by factors other than climate change.
- In the 2050 scenario changes in climate are predicted to create significant pressure for all vegetation classes across Sydney (Figure 13). The greatest pressure is projected to be on Coastal Dune Dry Sclerophyll, Wallum Sand Heaths and Maritime Grasslands. The greatest change is projected in Sydney Coastal Dry Sclerophyll forests and North Coast Wet Sclerophyll forests.

FIGURE 13 | Change in floristic composition for Sydney, 2050



4 | BIODIVERSITY

FAUNA

- Projected changes in the region's climate can affect species in a variety of ways: by altering the extent to which weather conditions are suited to the species or beyond its physiological tolerance; by shifting cues for events in the species' life cycle; by changing the timing, frequency and intensity with which the species is impacted by extreme events such as wildfire, drought and flooding; and by modifying the species' food supply, predators and competitors. These processes are likely to be complex and difficult to forecast, and their net effect may be beneficial or detrimental depending on the physiology, behaviours and ecology of the species.
- In the 2050 scenario bioclimatic modelling indicated potential for both beneficial and adverse impacts of projected climate change on threatened fauna species in Sydney.

SALTMARSH AND MANGROVES

- Saltmarshes and mangroves are an important component of estuarine foreshores in Sydney. Detailed studies at Towra Point and Botany Bay found these wetlands provide habitat for a range of fish species (Mazumder et al 2006), as well as additional ecosystem goods and services.
- Increased atmospheric carbon dioxide, temperature and sea-level rise will promote the growth of mangrove over saltmarsh in the Sydney region. These add to other non-climatic drivers of mangrove dominance, including enhanced nutrient conditions and sediment delivery to estuaries.
- Increased mean minimum temperature is likely to change the diversity of mangrove and saltmarsh in Sydney, potentially increasing mangrove diversity and decreasing saltmarsh diversity (Saintilan and Rogers 2013). The shift in floristic composition of coastal wetlands in the region may have flow-on effects for biota occupying these wetlands.

5 | FIRE

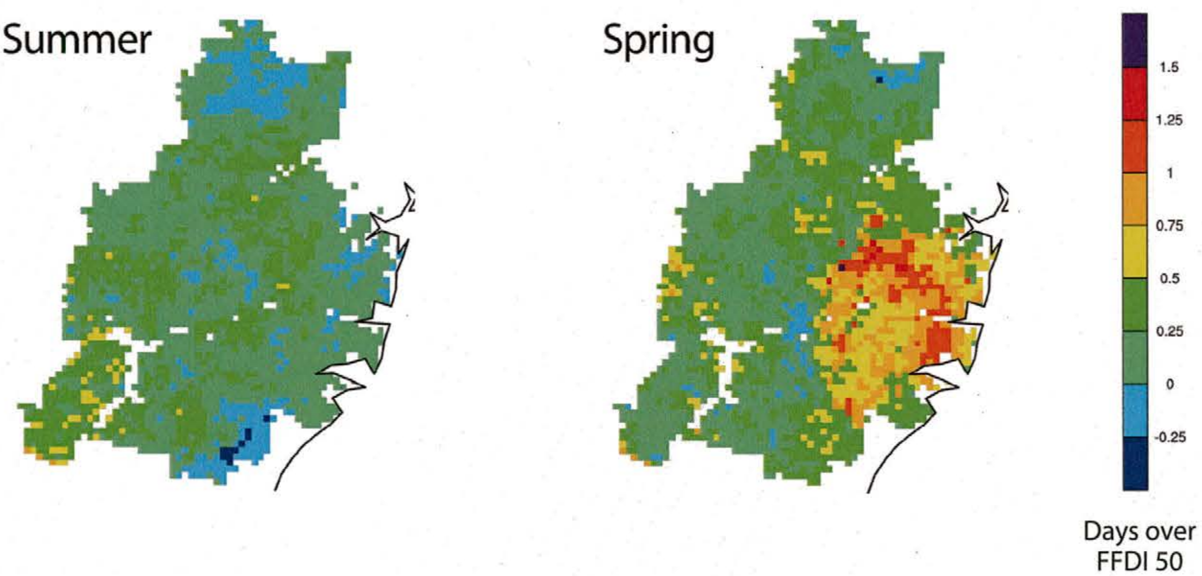
Sydney experiences major episodes of fire once or twice a decade which burn large areas and destroy property (Cunningham 1984; Conroy 1996; Gill and Moore 1996; Bradstock et al 2009).

Sydney's natural vegetation forms an arc around the bulk of metropolitan areas and the outlying ribbons of coastal development. Significant areas of urban development abut or are intermingled with bushland. Fragments of bushland of varying size are also embedded in the urban matrix. Exposure of urban development to major bushfires is exacerbated by the prevailing north and westerly winds that are typically associated with periods of severe fire danger (Gill and Moore 1996; Bradstock et al 1998; Hennessey et al 2006; Bradstock et al 2009).

CHANGES IN FIRE WEATHER

- In the 2050 scenario widespread increases in mean daily Forest Fire Danger Index (FFDI) are projected during Spring particularly east of the Blue Mountains. The largest Spring increases (20% or more) are in the Western region.
- Widespread increases in Spring are also projected for days with FFDI over 50 (indicating extreme fire weather conditions). The largest increases (an additional day every year) can be seen from the northwest to the southwest of the region (Figure 14). Increases are also projected throughout much of the region in Summer but are of much lower magnitude than in Spring.

FIGURE 14 | Change in days for Spring and Summer with FFDI above 50



5 | FIRE

CHANGES IN IGNITION

- Currently there is variation in the location and cause (human versus lightning) of ignitions in the Sydney Basin (Penman et al 2013).

- The likelihood of lightning and human-caused ignitions increases with FFDI, which suggests that under projections of elevated FFDI in response to climate change, ignition rates could increase. Changes to human populations and associated development patterns could change the rate and location of ignitions because the highest rates of human ignitions have occurred near infrastructure and developments.

CHANGES IN PLANT FUNCTIONAL TYPES AND FUEL

- The principal fuel in dry forests and woodlands dominating Sydney is fine surface litter composed of dead leaves and twigs derived mainly from trees and shrubs. Live foliage of shrubs and grasses plus suspended dead material also contributes significantly to the fuel array.

- Changes in the composition and structure of vegetation will directly and indirectly affect fuel loads. Hammil and Bradstock (2006) demonstrated that tree and shrub cover may decline with increasing temperature and lower rainfall, although grassy cover may increase. Such changes could make vegetation more ignitable.

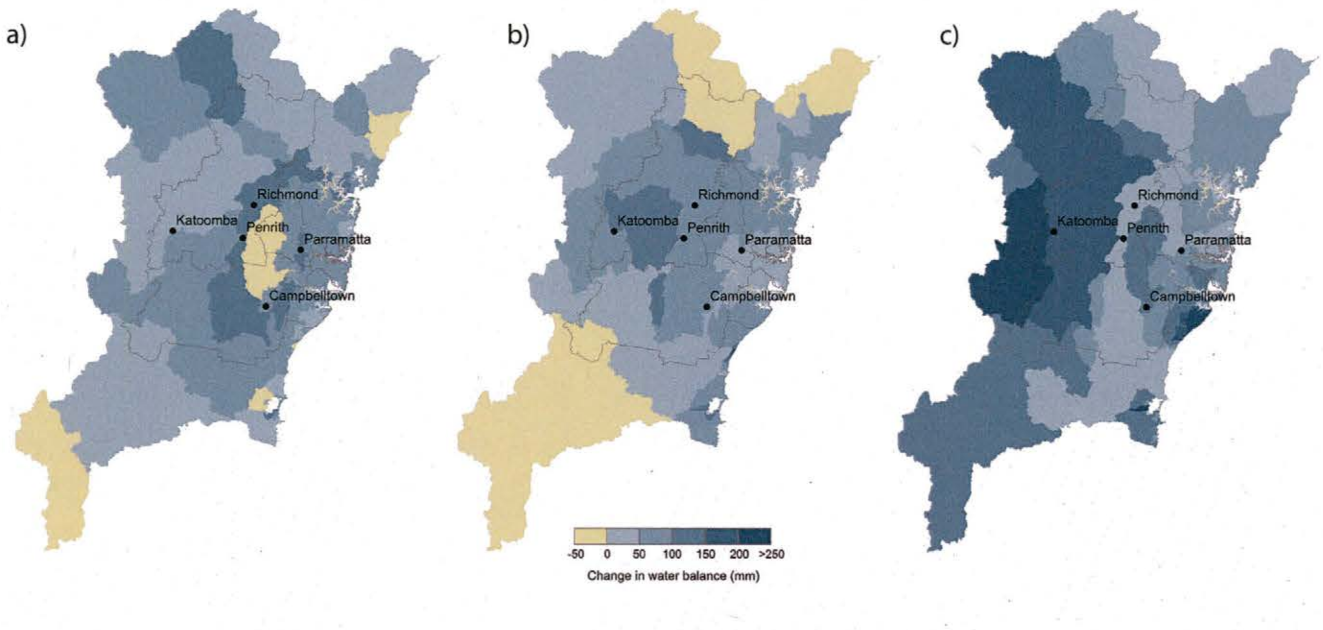
6 | RECHARGE, RUN-OFF & FLOODING

The hydrological system is the movement of water from the atmosphere, through the earth and back again – also known as the water cycle. Rainwater infiltrates the soil and is then absorbed by plants, evaporates, percolates to the groundwater or runs into surface waters. Changes to the hydrological system can influence water quality, salinity and the availability of groundwater.

CHANGES TO HYDROLOGY

- In the 2050 scenario the hydrological cycle of Sydney is projected to change significantly – with the most significant impacts in seasonality of rainfall. These detailed analyses show the largest increases in surface flows and recharge are forecast to occur during Autumn months (large increases in autumnal rainfall see Figure 3 Autumn rainfall). However, these increases are not evident south and west of the Sydney region where a drying trend is projected in terms of surface flow and recharge.
- In some areas of western Sydney, there is a projected decrease in evapotranspiration which reflects the changes in urban growth areas that were included in the modelling. Increased impervious urban areas are known to cause a decrease in evapotranspiration.
- Changes in surface flow are projected to be larger than changes in recharge. The greatest changes to surface flow occur near coastal areas and extend west through Richmond to Lithgow (Figure 15).

FIGURE 15 | Change in (mm) for a) annual evapotranspiration, b) annual recharge, c) annual surface water levels, for Sydney catchments, 2050.



6 | RECHARGE, RUN-OFF & FLOODING

FLOODING

- Climate change is predicted to result in higher ocean levels and more severe storms with more intense rainfall which is likely to increase the prevalence and severity of flooding and the associated damage and danger to local communities.
- The Sydney Metropolitan Area is likely to be particularly sensitive to increasing rainfall intensity during flood-producing rainfall events.
- The historic location of settlements near fertile riverine land, means urban areas in the vicinity of the Georges and Hawkesbury Rivers and tributaries are prone to riverine flooding. These include areas such as Liverpool, Fairfield, Bankstown, Sutherland, Blacktown, Penrith, Windsor Hawkesbury and Hills Shires.
- Historic riverine floods have had major impacts in the Sydney region, including the:
  - Hawkesbury – Nepean Valley in 1867, 1956, 1961, 1964, 1978 and 1990
  - Georges River floodplain in 1949, 1950, 1956, 1989 and 1988.
- Over the last 30 years, the largest floods on the Georges River occurred in April 1988 and August 1986. In 1988, more than 1000 properties along the Georges River, Prospect Creek and Cabramatta Creek were inundated with a damage bill of $18M (1988 value). This was estimated as a 1 in 20 year ARI (Average reassurance interval) flood.

PHOTO 1 | *1986 flood, on the lower reaches of Prospect Creek (Georges River Floodplain Risk Management Study & Plan, Volume 1 – Main Report. May 2004. Bewsher Consulting Pty Ltd. Prepared for the Georges River Floodplain Management Committee).*

- Most councils within the Sydney Metropolitan Area will have some local overland flooding issues. This can be due to the geography and the historic development patterns and standards of an area. Some areas where problems have been identified include areas within Fairfield, Penrith, Liverpool, Bankstown, Holroyd, Pittwater and the eastern suburbs.
- **Coastal areas,** particularly areas around coastal creeks and estuaries can be vulnerable to the impacts of sea level rise on tidal water levels and on flood behaviour. The scale of the impacts will vary depending upon the scale of existing development and the scale of change likely at the location.
- The exposure of the community to flood risk varies significantly as do potential increases in the risk

6 | RECHARGE, RUN-OFF & FLOODING

CHANGES TO WATER QUALITY (estuarine pressures and ecological condition)

- In the 2050 scenario climate change is projected to affect catchment exports (nitrogen, phosphorus, suspended solids) which will, in turn, affect the water quality and ecological condition of the receiving estuaries. In most areas, catchment exports are predicted to increase by at least 1.8 times.
- There is also a projected increase in total nitrogen and phytoplankton concentrations in receiving estuaries, with reductions in water clarity and seagrass cover. The magnitude of change depends on local stressors such as land use change. Climate related changes in the ecological condition of lakes and lagoons are projected to be relatively large compared with rivers.
- The surface flows from coastal catchments in Sydney are projected to increase most in Autumn and decrease in Summer. Together with extreme weather events, the changes in timing of the hydrological cycle will affect the ecological condition of estuaries (e.g. Lehman, 2004; Currie and Small, 2005; Cardoso et al., 2008; Cozzi et al., 2012)
- The interaction of other climate stressors, such as temperature and sea level rise, will significantly impact the functioning of estuary ecosystems. Sea level rise will cause loss of important habitats, including saltmarsh and seagrass; alter tidal range; change species distribution; and alter opening and closing regimes of estuaries

GROUND WATER VULNERABILITY

- In the 2050 scenario a long term increase in rainfall is projected under climate change, which will increase aquifer recharge and water tables/levels.
- Botany sands, Richmond, Blue Mountains and the Southern Region are predicted to have the greatest recharge change.
- The rise in water tables/levels and steeper hydraulic gradient will increase groundwater discharge. Several outcomes are predicted including:

  - Potential changes in vegetation communities based on root depths
  - Soluble salts within the rock may be activated and flushed from the system - altering aquifer chemistry
  - Mine pit or quarry voids designed to be permanent evaporative sinks may overflow particularly during extended long wet periods.

7 | AIR QUALITY

The frequency of hot days and high fire risk days are projected to increase in Sydney under climate change. This has important ramifications for air pollution.

OZONE

- Ozone is an air pollutant. It exacerbates respiratory problems and stings the eyes.
- An increase in ozone concentrations is linked to the frequency of hot, sunny days.
- Increased drought leads to more severe dust storms, which, in turn enhance ozone concentrations.
- A predicted increase in daily maximum temperatures increases ozone concentrations which, in turn, increases hospital emissions (CSIRO, 2008).
- Increasing vegetation cover in urban areas can have a cooling effect on air temperatures. However, it can also impact air quality by releasing volatile organic compounds (VOCs) which are a catalyst in the production of ozone. In Sydney there is already a relatively high proportion of greenspace. Therefore, increasing vegetation cover is unlikely to have a significant impact on ozone concentrations.

BUSHFIRES

- Bushfires are a large contributor to ozone concentrations. It is likely that with the projected increase of bushfires in Sydney, the ozone concentration standard (NEPM – National Environmental Protection Measures) is likely to be exceeded more often.
- High particle pollution concentrations are linked to the presence of bushfire plumes in the Sydney airshed.

8 | COASTAL SYSTEMS

The Sydney Metropolitan Area features some of Australia's most valuable beaches for tourism and recreation. It also boasts the spectacular drowned river valley estuaries of the Hawkesbury River, Sydney Harbour, Botany Bay and Port Hacking.

However, settlements and infrastructure occupying low lying foreshores around beaches and estuaries are particularly vulnerable to coastal hazards and the impacts of climate change.

The level of exposure to coastal hazards varies throughout Sydney based on coastal geomorphology and proximity to dynamic coastal environments. Hazards such as beach erosion, shoreline recession and oceanic inundation have the potential to cause significant and widespread damage to properties, transport infrastructure and public recreation spaces.

Exposure to coastal hazards is expected to increase under future climate change scenarios, due to the increased landward reach of beach erosion and oceanic inundation associated with a projected rise in mean sea levels. This has the potential to cause significant impacts in Sydney due to the concentration of population, buildings and infrastructure in close proximity to dynamic coastal environments.

Global mean sea level projections for the coming century vary between steadily rising and accelerating scenarios (Meehl et al., 2007). Existing/recent observations indicate global mean sea level has followed the upper range of previous projections (Church and White, 2011; Rahmstorf et al., 2007).

Whilst not assessed together here, the combination of mean sea level rise and catchment driven flooding is likely to increase flood frequency, height and extent in the lower portions of coastal floodplains.

Future sea level scenarios including 0.4 m and 0.9 m mean sea level rises were examined here by combining existing oceanic inundation modelling (McInnes et al., 2012) and hazard assessments with databases of properties and infrastructure.

OCEANIC INUNDATION

- Under present conditions, 6,500-7,000 properties across Sydney may be exposed to oceanic inundation due to extreme storms. However, more than 80% of the total properties exposed would experience less than 10% lot-area inundation. In fact, for 1-year and 100-year Average Reassurance Interval (ARI) design storm events, only 200 and 400 properties were predicted to experience greater than 50% lot-area inundation respectively.
- Whilst the total number of properties subject to minor level (i.e. < 10%) inundation remained relatively constant (6-7,000) with the addition of the sea level rise scenarios, the proportion of properties subject to more severe inundation increased. For example, in the case of a 100-year ARI storm and 0.9m sea level rise:

  - Approximately 5,000 properties were subject to 10-50% lot-area inundation
  - Approximately 1,800 properties were subject to 50-90% lot-area inundation
  - Approximately 3,300 properties were subject to 90-100% lot-area inundation.

8 | COASTAL SYSTEMS

FIGURE 16 | Extent of predicted impacts of coastal hazards at North Narrabeen for the immediate future and under 0.4 m and 0.9 m sea level rise scenarios. Modelled oceanic inundation due to 1-year (left) and 100-year (right) storms is shown for each scenario (McInnes et al., 2012), with predicted extents of beach erosion and shoreline recession indicated by coastal hazard lines (WorleyParsons, 2009).

- Variation in exposure to oceanic inundation and property vulnerability between the Sydney regions reflects differences in their distribution and coastal topography. For example, the Northern Beaches and Southern Sydney regions are characterised by expanses of low-lying foreshores surrounding the lower reaches of estuaries. The influence of sea level rise on inundation is likely to be acute in these regions (for example Figure 16).
- Both the Eastern/Inner Sydney and Northern Sydney regions flank Sydney Harbour estuary and the Parramatta River. However, the Northern Sydney region is characterised by steeper terrain along its Sydney Harbour and Hawkesbury foreshores, and is comparatively less exposed to significant inundation from sea level rise. In contrast, the Eastern/Inner Sydney region features low-lying foreshores surrounding both Sydney Harbour and Botany Bay, and therefore a much higher proportion of properties were predicted to be significantly or completely inundated.
- Property exposure in the Western Sydney region was limited to foreshore areas surrounding the Parramatta River.
- In summary, property exposure to oceanic inundation was predicted to be most extensive in the Southern Sydney region, followed by Eastern and Inner Sydney, the Northern Beaches, Northern Sydney and finally Western Sydney.

8 | COASTAL SYSTEMS

BEACH EROSION AND SHORELINE RECESSION

- Exposure to beach erosion and shoreline recession is greatest where development has occurred within or close to active beach systems, and where existing natural or engineered coastal protections are insufficient to mitigate expected increases in shoreline variability due to climate change.
- The Northern Beaches region is particularly exposed to beach erosion and shoreline recession hazards due to the relatively high concentration of development near exposed beach systems (Photo 2).
- Surf Life Saving Clubs and public amenities are the most vulnerable properties in terms of beach erosion and shoreline recession, with club buildings in the Northern Beaches, East/Inner Sydney and Southern Sydney regions identified as particularly exposed.

PHOTO 2 | Examples of property damage and loss of beach resulting from beach erosion at Collaroy-Narrabeen Beach during the extreme storms of 1967 (left) and 2003 (right).

8 | COASTAL SYSTEMS

TRANSPORT INFRASTRUCTURE

- The Eastern/Inner Sydney region has a large extent of pathways exposed to oceanic inundation, primarily due to extensive foreshore recreation areas and public access ways surrounding Sydney Harbour and Botany Bay.
- Roadways exposed to oceanic inundation were identified throughout Sydney, and exposure was particularly high for the Southern Sydney and Eastern/Inner Sydney regions. For the 100-year ARI design storm and 0.9m sea level rise scenario, these regions featured more than twice the length of exposed roadways relative to the Northern Beaches and Northern regions. Again, roadways in the Western region were comparatively less exposed due to the limited reach of tidal inundation.
- Rail infrastructure in the Eastern/Inner Sydney and Western Central regions is comparatively more exposed to projected inundation than other parts of Sydney, particularly for model scenarios that included a sea level rise component. For example, 7.5km of railways in these two regions were identified to be exposed to inundation in the case of the 100-year ARI storm and 0.9m sea level rise model scenario. This included both heavy and light rail types in low-lying foreshore areas surrounding Sydney Harbour estuary, Parramatta River, and Cooks River and canals.
- Air transport infrastructure at Sydney (Kingsford Smith) Airport was also identified as exposed to oceanic inundation. Substantial inundation of taxiways was projected for the 100-year ARI storm and 0.4m sea level rise scenario, whilst inundation to sections of runway was projected for the 100-year ARI storm and 0.9m sea level rise scenario.

PUBLIC RECREATION

- Predicted oceanic inundation impacts were identified for public recreation spaces surrounding exposed coasts and estuaries including reserves, sports grounds and national parks.
- On exposed coasts, beach erosion and shoreline recession may impact the recreational value of Sydney's iconic beaches. In the case of a 0.4 m sea level rise for example, Bondi Beach may experience up to 20 m of shoreline recession, with significant storms predicted to erode the beach back to the sea wall (WorleyParsons, 2011). For a 0.9 m sea level rise 45 m of shoreline recession may be expected, with the potential for significant storms to threaten the structural integrity of the sea wall and promenade (WorleyParsons, 2011).

REFERENCES

BOM (2013) http://www.bom.gov.au/climate/averages/tables/cw_066062.shtml

BoM (2012a). Sydney in summer 2011-12: A cool, wet summer for Sydney Seasonal Climate Summary for Sydney - Greater Sydney - Product code IDCKGC25L0. Retrieved from - http://www.bom.gov.au/climate/current//season/nsw/archive/201202.sydney.shtml

BoM (2012b). Annual climate summary
http://www.bom.gov.au/climate/annual_sum/2012/AnClimSum2012_LR1.0.pdf

BoM NTDC (2011). The Australian Baseline Sea Level Monitoring Project. Annual Sea Level Data Summary Report July 2010-June2011, Australian Bureau of Meteorology National Tidal Data Centre, Canberra [www.bom.gov.au/ntc/IDO60202/IDO60202.2011.pdf]

Bradstock, R.A., Cohn, J.S., Gill, A.M., Bedward, M. & Lucas, C. (2009) Prediction of the probability of large fires in the Sydney region of south-eastern Australia using components of fire weather. International Journal of Wildland Fire, 18, 932–943

Bradstock RA, Gill AM, Kenny B, Scott J (1998) Bushfire risk at the urban interface derived from historical weather records: consequences for use of prescribed fire in the Sydney region of south eastern Australia. Journal of Environmental Management 52, 259–271.doi:10.1006/JEMA.1997.0177

Cardoso P.G., Raffaelli D. and Pardal M.A. (2008). The impact of extreme weather events on the seagrass *Zostera noltii and related Hydrobia ulvae population. Marine Pollution Bulletin,* 56: 483-492.

Church, J. A. and N. J. White (2011), Sea-Level Rise from the Late 19th to the Early 21st Century. Surveys in Geophysics, 32, 585-602, doi:10.1007/s10712-011-9119-1.

Conroy, R.J. To burn or not burn? A description of the history, nature and management of bushfires within Ku-Ring-Gai chase national park. Proceedings of the Linnean Society of New South Wales, 116 (1996), pp. 80–96

Cope, M., Lee, Sunhee, et al (2008), A Methodology for Determining the Impact of Climate Change on Ozone Levels in an Urban Area, Final Report, CSIRO, November 2008.

Cozzi S., Falconi C., Comici C., Cermelj B., Kovac N., Valentina T. and Giani M. (2012). Recent evolution of river discharges in the Gulf of Trieste and their potential response to climate changes and anthropogenic pressure. *Estuarine, Coastal and Shelf Science,* 115: 14-24.

Cunningham CJ (1984) Recurring natural fire hazards: a case study of the Blue Mountains, New South Wales, Australia. Applied Geography 4, 5–27. doi:10.1016/0143-6228(84)90002-X

Currie D.R. and Small K.J. (2005). Macrobenthic community responses to long-term environmental change in an east Australia sub-tropical estuary. *Estuarine, Coastal and Shelf Science,* 63: 315-331.

DECCW 2010, NSW Climate Impact Profile: the impacts of climate change on the biophysical environment of New South Wales, Department of Environment, Climate Change and Water, Sydney: http://www.environment.nsw.gov.au/resources/climatechange/10171climateimpactprof.pdf

Gill, AM, Moore, PHR (1996). Regional and historical fire weather patterns pertinent to the January 1994 Sydney bushfires. *Proceedings of the Linnean Society of New South Wales* 116, 27-35

REFERENCES

Hammill KA, Bradstock RA (2006) Remote sensing of fire severity in the Blue Mountains: influence of vegetation type and inferring fire intensity. International Journal of Wildland Fire 15:213–226

Hennessy KJ, Lucas C, Nicholls N, Bathols JM, Suppiah R, Ricketts JR (2006) Climate Change Impacts on Fire-Weather in South-East Australia Report C/1061. (CSIRO: Melbourne)

Lehman P.W. (2004). The influence of climate on mechanistic pathways that affect lower food web production in northern San Francisco Bay estuary. *Estuaries,* 27: 311-324.

Mazumder D., Saintilan N., and Williams, R. 2006. Fish assemblages in three tidal saltmarsh and mangrove flats in temperate NSW, Australia: a comparison based on species diversity and abundance. *Wetlands Ecology and Management.* 14 (3) 201-209.

Mcinnes, K., Lipkin, F., O'grady, J., Inman, M., 2012. Mapping and responding to Coastal Inundation – Technical Report on the Modelling and Mapping of Coastal inundation Under Future Sea Level Rise. Sydney Coastal Councils Group and CSIRO, 54p.

Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye A, Gregory J, Kitoh A, Knutti R, Murphy J, Noda A, Raper S, Watterson I, Weaver A, Zhao ZC, 2007. Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change, chap 10. Cambridge University Press, Cambridge, pp 747–845.

Penman,t.D., R. A. Bradstock, and O. Price (2012) Modelling the determinants of ignition in the Sydney Basin, Australia: implications for future management. International Journal of Wildland Fire 22(4) 469-478 http://dx.doi.org/10.1071/WF12027

Rosewell CJ, Crouch RJ, Morse RJ, Leys JF, Hicks RW and Stanley RJ, 2007, 'Forms of Erosion' in Charman PEV & Murphy BW (eds.), Soils – Their Properties and Management, 3rd edn, Oxford University Press in association with Department of Natural Resources, pp. 16–26.

Russell JS and Isbell RF (eds) (1986) Australian Soils: The Human Impact Australian Society of Soil Science University of Queensland Press St Lucia, Australia.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker and R.C.J. Somerville (2007), Recent Climate Observations Compared to Projections. Science, 316, 709, doi:10.1126/science.1136843.

Saintilan N and Rogers K (2013) The significance and vulnerabiliyt of Australian saltmarshes: implications for management in a changing climate. *Marine and Freshwater Research* 64, 66-79.

Smith PL and Adams MP (2013 in press) A systematic approach to model the influence of the type and density of vegetation cover on urban heat using remote sensing.

WorleyParsons (2011). Waverly Coastal Risks and Hazards Vulnerability Study, 111p.

WorleyParsons (2009) Review of Coastal Hazard Lines for Collaroy-Narrabeen Beach and Fishermans Beach. 156p.

Zhang, X. B. and J. A. Church (2012), Sea level trends, interannual and decadal variability in the Pacific Ocean. Geophysical Research Letters, 39, L21701, doi:10.1029/2012GL053240.

FIGURES AND IMAGES