Climate change impacts on surface runoff and recharge to groundwater

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1. Introduction

NARCliM (the NSW and ACT Regional Climate Modelling project) is an ensemble of regional climate projections for south-east Australia. Within New South Wales, the Office of Environment and Heritage (OEH) aims to provide a sound basis for local climate-change adaptation by working with the community, other agencies and local stakeholders to identify and understand regional vulnerabilities and prepare for the impacts of climate change. A range of scientific impact assessments has been undertaken with a view to protect ecosystems, maintain natural resources and manage water resources.

Assessing the impacts of climate change on the water balance and hydrology is important because changes to the water cycle will influence other factors including water quality, salinity and groundwater availability. The objective of this study is to investigate changes in hydrology and landscape water balance; in particular, surface runoff and recharge to groundwater.

The impacts of climate change on the water cycle and hydrology will be investigated using soil water balance modelling and dynamically downscaled climate projections. This current study is technically different to the hydrology assessment undertaken for the NSW 2010 Impact statement (Vaze et al. 2008). The hydrological assessment for NSW 2010 was based on the SIMHYD (Chiew et al. 2002) and Sacramento (Burnash et al. 1973) daily rainfall-runoff models applied to 5 km grid cells. Surface runoff from each grid cell was routed to the catchment outlet using a Muskingum routing algorithm. Each model was calibrated against measured streamflow for 219 catchments across south-east Australia to maximise the Nash-Sutcliffe efficiency (Nash & Sutcliffe 1970) of daily runoff prediction while ensuring that total modelled streamflow was within 5% of total measured streamflow. This methodology was similar to that used for the CSIRO Murray–Darling Basin Sustainable Yields Project (CSIRO 2008).

Instead of using a conceptually lumped rainfall-runoff model, this current impact assessment applies a one-dimensional water balance model for each grid cell. Using rainfall and actual evapotranspiration (ET) as inputs, non-transpired water has been partitioned into surface flows and groundwater recharge. This partitioning is driven by soil properties, land use and topography. The major benefit of this type of modelling is that the impacts of climate change on surface flows and recharge can be obtained for individual parts of the landscape at a scale much finer that the 5 km grid cells used in NSW 2010. Results are not constrained to catchment boundaries. However, a change in surface runoff does not directly correlate to a similar change in streamflow at the catchment outlet. Not all surface runoff will get into the river itself, flowing instead into farm dams, wetlands and other water bodies. While the type of modelling is different from that employed in the 2010 work, the modelling used in this study is consistent with other modelling activities across NSW including:

- coastal estuarine Monitoring Evaluation and Reporting modelling (Littleboy et al. 2009; Roper et al. 2011)
- future salinity-trend modelling for the 2009 Salinity Audit Update (DECC 2009)
- salinity tools used in the Native Vegetation Assessment Tool or NVAT (DECCW 2011) and enhancements proposed under the Environmental Outcomes Assessment Methodology (OEH 2012).

2. Simulation analysis

2.1 NARCliM projections

All climate projections come from the NARCliM simulations (Evans et al. 2014) which comprise output from four Global Climate Models (GCM) dynamically downscaled using three Regional Climate Models (RCM). The four GCMs are MIROC-medres 3.2 (Centre for Climate System Research, National Institute for Environmental and Frontier Research Centre for Global Change, Japan), ECHAM5 (Max Planck Institute for Meteorology, Germany), CCCMA3.1 (Canadian Centre for Climate Modelling and Analysis) and CSIRO MK3.0 (CSIRO Australia).

The Weather and Regional Forecasting (WRF) regional climate-modelling system (Skamarock et al. 2008) was used to downscale projections from the four GCMs. Three different configurations of WRF were used with each of the four GCMs, giving a total of 12 combinations of model simulations. A single emissions scenario (IPCC high emissions scenario A2) is used for all simulations. For each combination of GCM and RCM, three time periods have been used: current climate (1990–2009), near future (2020–2039) and far future (2060–2079).

WRF is a dynamic regional climate model designed to simulate weather variables at high spatial resolution. It has been previously shown to be suitable in modelling the influence of topography and coastal processes on temperature and rainfall across NSW (Evans & McCabe 2010).

Data from the NARCliM projections are provided as spatially located points with given latitude and longitude and in projection WGS84. These points represent a resolution of 10 km and reference the centre of the climate cell. For consistency with GCMs, the points are on a rotated pole. This means that the points do not align with either north/south longitudinal or east/west latitudinal lines. As such, the points will not directly convert to a GIS-based grid, which is always assumed to be on an unrotated pole. Therefore, conversion of the NARCliM 10 km points to a regular GIS grid requires mathematical interpolation. Rather than interpolating large volumes of data, ArcGIS analysis using Thiessen polygons was undertaken to construct polygons around each NARCliM point to produce a shapefile or a 10 km quasi-grid on a rotated pole. Thiessen polygons are polygons whose boundaries define the area that is closest to each point relative to all other points (Thiessen 1911). Figure 1 shows the 10 km resolution NARCliM points along with the 10 km quasi-grid derived from Thiessen polygons. In this study, all inputs and model output are generated using this quasi-grid.

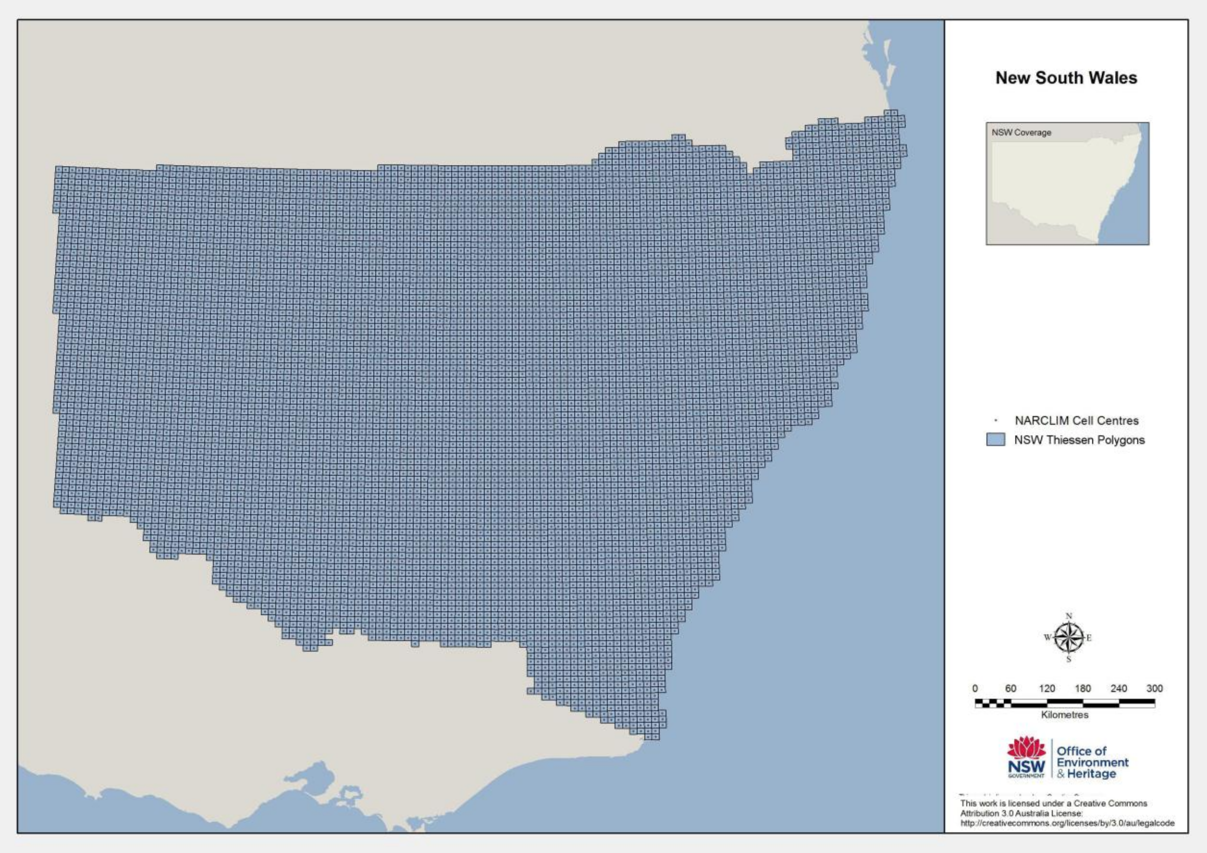


Figure 1. Thiessen polygons for each NARCliM spatial point

2.2 Modelling approaches

The objective of this study is to assess the impacts of climate change on hydrology and landscape water balance; in particular, changes to surface runoff and recharge to groundwater. In general terms, there are three broad categories of different modelling options that can be used to undertake such an analysis:

1. Catchment hydrology models estimate streamflow exiting an entire catchment at its outlet. The smallest spatial unit is the whole catchment. These types of models often use catchment averaged rainfall and potential ET as inputs. They are set up to estimate streamflow at gauging stations so that model calibration and validation can occur. There are issues in applying these models for non-gauged catchments, often resulting in the use of regionalised parameters.

2. Catchment modelling can be applied at a finer resolution to capture spatial variability in rainfall across a catchment. This methodology was used for the hydrological assessment under NSW 2010 (Vaze et al. 2008) and the CSIRO Murray–Darling Basin Sustainable Yields Project (CSIRO 2008). Catchment hydrology models were applied to 5 km grid cells with surface runoff routed to the catchment outlet using a Muskingum routing algorithm. Each model could then be calibrated against measured streamflow. These models are typically applied at the scale of the climate projections grid.

3. One-dimensional water balance modelling can be used to simulate the runoff, infiltration, soil moisture and recharge for individual landscape elements. This type of modelling can estimate the impacts of climate change on surface flows and recharge for individual parts of the landscape at a scale much finer than the grid cells used in catchment modelling.

The modelling methodology used in this study is based on landscape-scale water balance. This modelling divides a catchment into smaller hydrological response units (HRU) and applies a one-dimensional water balance model for each HRU. HRUs are based on a combination of topography, soil type and land use. The main advantages of this type of modelling are that:

- it considers water balance changes across finer landscape elements
- water quality variables can be easily estimated using land-use based event-mean-concentrations for different pollutants
- landscape scale predictions are at an appropriate scale to explore land-use change scenarios, which commonly occur at the same scale
- it is consistent with other modelling activities across NSW including modelling of stream flow, sediment and nutrient loads for coastal estuarine Monitoring Evaluation and Reporting (Littleboy et al. 2009; Roper et al. 2011), salt mobilisation processes and future salinity trend modelling for the 2009 Salinity Audit Update (DECC 2009), and salinity tools used in the Native Vegetation Assessment Tools or NVAT (DECCW 2011) and enhancements proposed under the Environmental Outcomes Assessment Methodology (OEH 2012).

The main disadvantage is that HRUs are at a finer resolution than the climate projections (10 km) which can result in spatial discontinuities when a HRU spans across 10 km cells. In addition, this type of modelling does not directly provide whole-of-catchment streamflow. Models like 2Csalt (Stenson et al. 2011), CatPlus (Future Farm Industries CRC 2011) and SourceCatchments (eWater Cooperative Research Centre 2010) can be used to aggregate one-dimensional water balance modelling to whole-of-catchment streamflow.

This impact assessment applied a one-dimensional water balance for each grid cell using rainfall and actual ET as inputs. By using actual ET, the landscape-scale water balance modelling maintains the same overall water balance of the regional climate modelling. The one-dimensional model calculates the non-transpired water and how it is partitioned into surface flows and groundwater recharge. This partitioning is based on the soil properties and topography for each HRU. This type of modelling is also consistent with the Sydney 2 km impact profile (Littleboy 2013).

2.3 Water balance modelling

The water balance model used daily time-series of rainfall and actual ET modelled by all 12 NARCliM simulations (four GCMs by three RCMs) as inputs. By using actual ET, this analysis is static in nature in that it partitions the surplus and non-transpired water from NARCliM into surface flows and recharge. By using the actual ET from NARCliM, we ensure that the RCM water balance is maintained in the impact modelling.

The partitioning between surface flow and recharge is driven by soil properties and topography for each NARCliM 10 km cell. Volumes of surface flow are governed by model parameters describing potential infiltration, antecedent soil water, surface and vegetative cover and slope. Volumes of recharge are controlled by parameters quantifying drainage rates through the soil profile, soil depth and slope. The water balance model applied in this study is the PERFECT model (Littleboy et al. 1992). PERFECT was developed as a cropping systems model in that it predicts the water balance (runoff, infiltration, soil evaporation, transpiration and recharge) for crop/fallow sequences. It has been previously applied to estimate water balance for a range of perennial pasture systems and tree water use in eastern Australia. Many examples of previous model validation in Eastern Australia are documented in Abbs and Littleboy (1998). A major strength of PERFECT is that it contains robust and well-tested algorithms, often based on proven water balance models developed by the United States Department of Agriculture.

Within PERFECT, simulation is performed on a daily time-step based on daily weather data. Runoff is calculated as a function of rainfall and modelled soil water deficit, surface roughness, surface residue and crop cover. Soil water is updated on a daily basis by any rainfall exceeding the daily runoff volume. In the case of dry profiles this infiltration may flow directly into the lower profile layer/s using an optional soil cracking algorithm. Infiltration is redistributed through the profile using a linear routing method. Redistribution from the lowest profile layer is assumed lost to the system as drainage. Transpiration is represented as a function of potential evaporation, leaf area and soil moisture. Water is removed from the profile according to the current depth and distribution of roots. Soil evaporation is based on Ritchie's two-stage evaporation algorithm (Ritchie 1972). Following rainfall, it is assumed that drying occurs at a potential rate to a user-defined limit. When this Stage 1 limit is reached, the second and slower stage of evaporation commences.

PERFECT is a one-dimensional water balance model in that it predicts the water balance in a single column of soil. It does not predict lateral subsurface movement of water. Any excess soil water is assumed to move vertically only as deep drainage to groundwater. Therefore estimates of drainage from PERFECT are actually a combination of subsurface lateral flow and vertical drainage, so are effectively the upper limit of profile drainage.

In order to partition excess soil water moving laterally and vertically, the HYDRUS 2D model (Simunek et al. 1999) was applied to develop a generic model of lateral water movement (Rassam & Littleboy 2003). The model is conceptualised in Figure 2. The slope length extends between the left uppermost side of the slope, represented by a no-flow boundary, and the right lowermost side of the slope, represented by a seepage face. The lower boundary is assumed to be freely draining. A duplex soil system with a coarse textured soil overlying a fine textured soil is assumed to promote a perched water table. The soil profile is initially saturated. The profile is allowed to drain; drainage flux comprises a lateral component F_L and a downward component that represents recharge to the water table. Therefore, this algorithm partitions drainage into lateral and vertical flow based on slope and soil hydraulic conductivity. When applied to the drainage term from the one-dimensional PERFECT model, the partitioned vertical component from this calculation is assumed to be recharge.

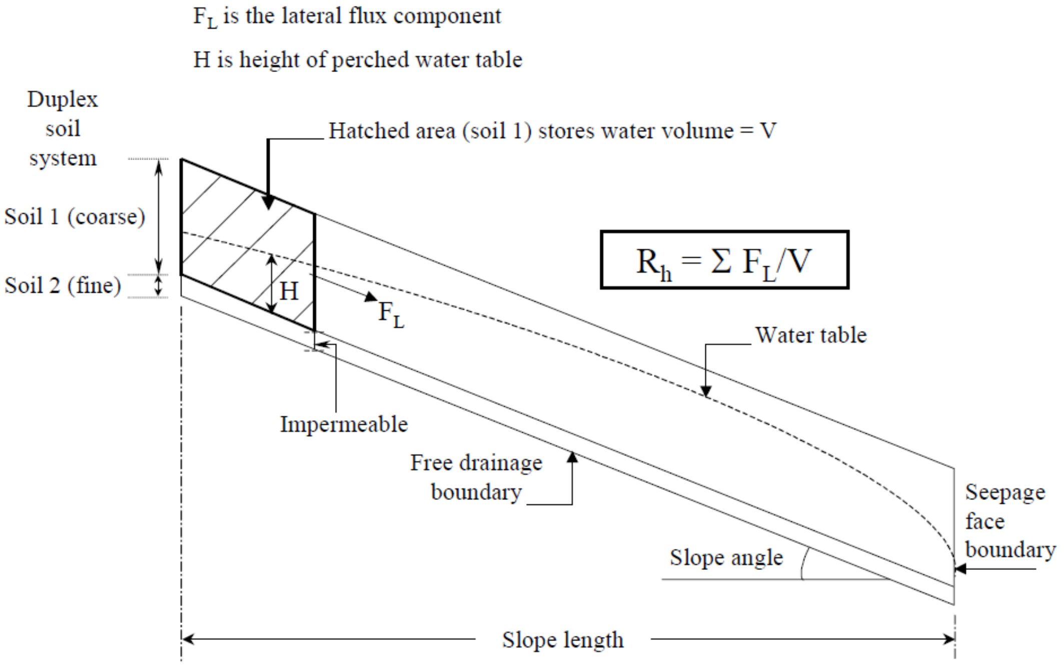


Figure 2. Conceptual model, boundary conditions, and definition of relevant terms from Rassam and Littleboy (2003)

2.4 Spatial datasets

The spatial inputs used in this study are land use, soil type and slope. For land use, we used the NARCliM 10 km land-use data as used in the RCM analyses. Since the 10 km land-use data is inherent in the pattern of actual ET modelled by RCM, it must be used for consistency in model inputs. The 10 km land-use map is shown in Figure 3.

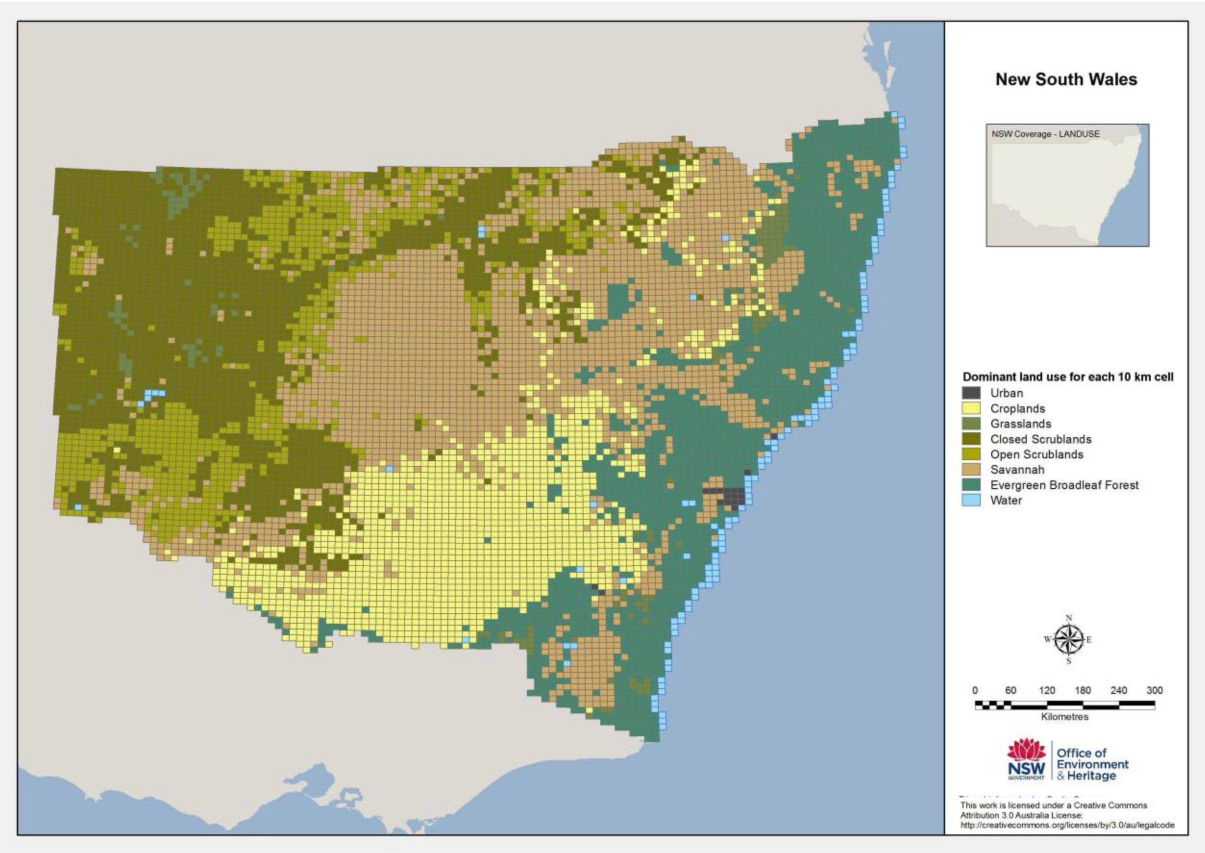


Figure 3. Dominant land use for each 10 km cell

Soils spatial data was obtained from a statewide map of Great Soil Groups produced by OEH. Lookup tables of soil hydraulic properties for each Great Soil Group as compiled by Littleboy et al. (2003; 2009) were used to assign soil hydraulic properties to each soil polygon. The dominant soil type for each 10 km cell was then determined and is shown in Figure 4.

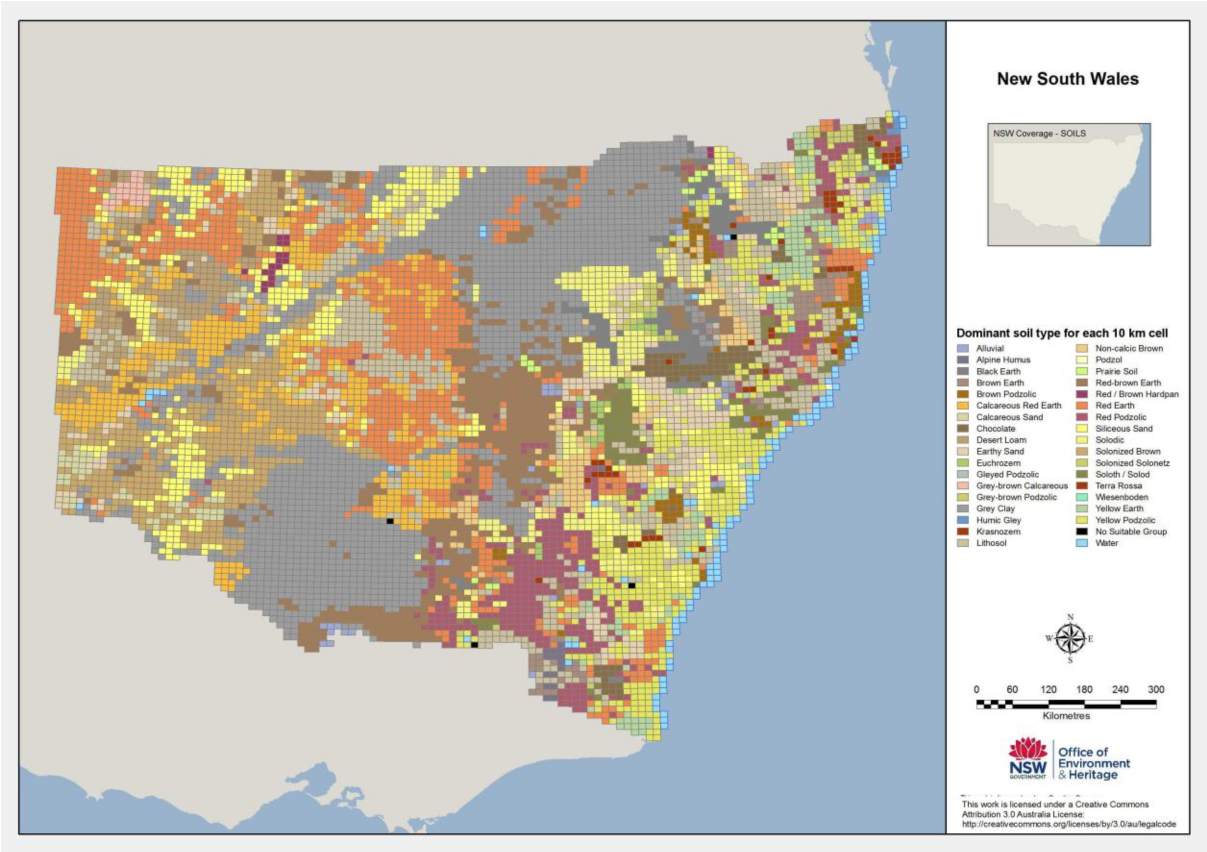


Figure 4. Dominant soil type for each 10 km cell

Mean slope for each 10 km cell was calculated from the 30 m Shuttle Digital Elevation Model and used to calculate the lateral flow partitioning coefficient. The calculated values of this lateral flow partitioning coefficient for each 10 km cell are shown in Figure 5. Higher values occur in steeper areas and assume that water is more likely to flow laterally down a slope. In flatter areas in the west, the majority of excess soil water will flow downwards to become recharge to groundwater.

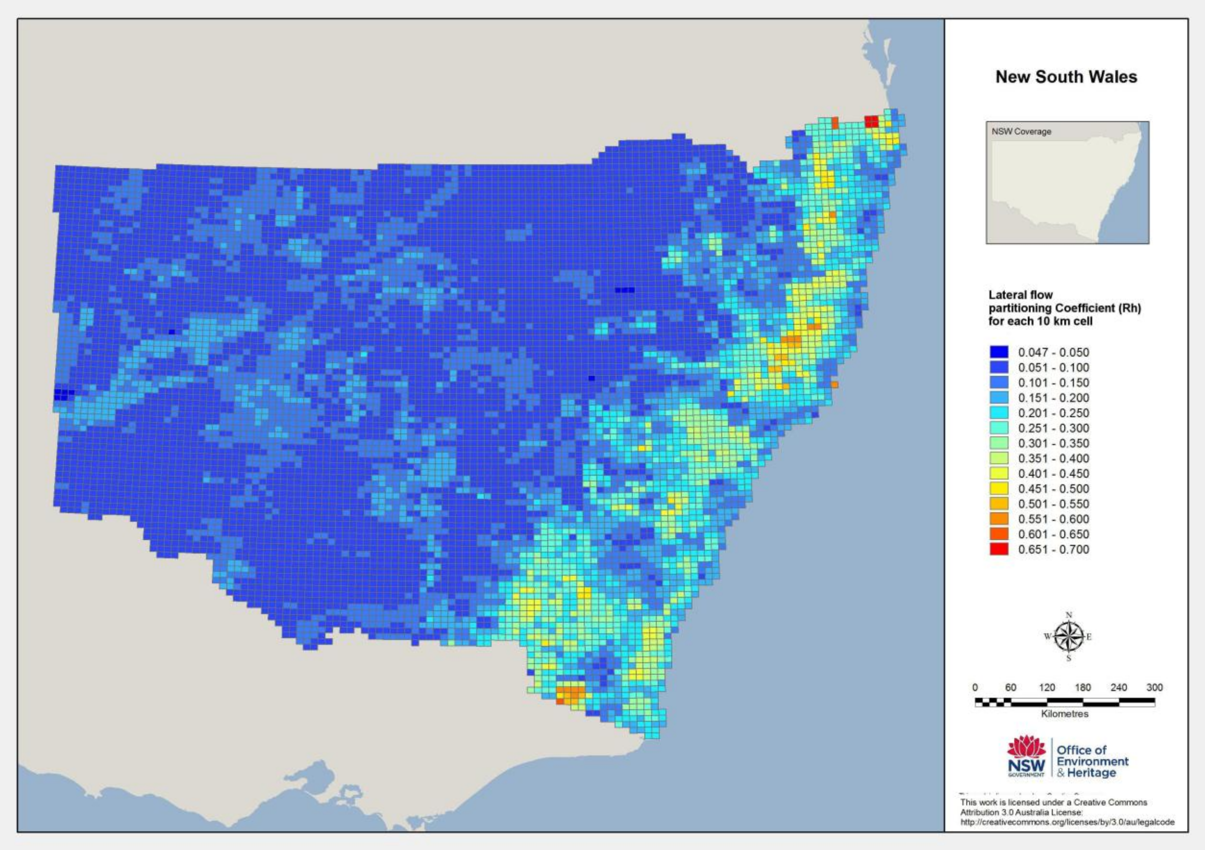


Figure 5. Lateral flow partitioning coefficient (F_L) for each 10 km cell

2.5 Model parameters

A summary of model parameters for each land-use type (Figure 3) is provided in Table 1. For most land uses, actual ET from NARCliM was used. Crop factors were set at 1.0 because actual ET was input into the model rather than potential ET.

For two land uses, urban areas and water bodies, an alternative estimate of actual ET was required. For urban areas, the RCMs in NARCliM adopt a standard set of parameters that assume all urban areas have an impervious area greater than 90% and limited vegetation cover for transpiration. This resulted in very low actual ET for all urban area cells, typically less than 10% of mean annual rainfall. Since the mapped urban areas include cells with a wide range of different hydrological responses; for example, Sydney Central Business District, rural-residential lots in western Sydney and country NSW residential areas, an alternative method to estimate ET was required. Potential ET was estimated for each cell using the method of Morton (1983). Actual ET was then calculated by multiplying the potential ET by the fractional foliage project cover for that cell. Foliage project cover data at a resolution of 25 m were obtained from woody extent mapping undertaken as part of NSW reporting on Native Vegetation (OEH 2014). From these inputs, the mean foliage projected cover for each 10 km cell was determined.

For water bodies, the estimates of actual ET from the RCMs used in NARCliM appear abnormally large, especially in winter months. Consequently, potential ET was calculated for each cell using the method of Morton (1983). The crop factor was set at 1.0 which results in actual ET equalling potential ET, a safe assumption if the supply of water from the water body is unlimited; for example, in the case of coastal estuaries and large water bodies.

Table 1. Source of actual ET data for each land-use type

Land use	Crop factor	Data source
Croplands	1.0	NARCliM actual ET
Grasslands	1.0	NARCliM actual ET
Closed scrublands	1.0	NARCliM actual ET
Open scrublands	1.0	NARCliM actual ET
Savannah	1.0	NARCliM actual ET
Evergreen broadleaf forest	1.0	NARCliM actual ET
Urban	Foliage projected cover for each cell	Potential ET calculated from Morton (1983)
Water	1.0	Potential ET calculated from Morton (1983)

The dominant Great Soil Group for each 10 km cell was previously shown in Figure 3. For each soil type, PERFECT requires a number of parameters that define its hydraulic properties. Soil hydraulic properties were previously compiled by Littleboy et al. (2003; 2009) and are summarised for each Great Soil Group in Table 2.

Table 2. Summary of hydraulic properties for each Great Soil Group

Great Soil Group	Soil Depth (m)	Lower Limit[1] range (%vol)	Upper Limit[2] range (%vol)	Sat[3] Range (%vol)	PAWC[4] (mm)	CN[5]	Ksat[6] (mm/hr)
Alluvial Soil	5	20–27	34–36	48–50	335	75	40.0
Alpine Humus Soil	4	20–22	29–35	38–42	292	80	10.0
Black Earth	5	30–32	44–50	49–56	577	75	1.0
Brown Earth	5	8–14	15–19	33–35	200	85	10.0
Brown Podzolic	4	13–17	17–24	34–41	162	80	0.5
Calcareous Red Earth	5	12–18	17–32	41–44	466	85	30.0
Calcareous Sand	4	6–7	19–20	36–39	560	75	300
Chocolate Soil	5	16–18	31–36	39–48	665	80	10.0
Desert Loam	5	25–26	36–37	37–42	400	80	1.0
Earthy Sand	5	3–8	7–22	12–28	193	70	100.0
Euchrozem	5	25–30	40–44	46–50	581	75	1.0
Gleyed Podzolic Soil	4	5–19	14–27	32–34	356	80	1.0
Grey-Brown Calcareous Soil	4	12–22	22–30	29–37	371	85	1.0
Grey-Brown Podzolic Soil	4	12–23	22–30	28–37	372	85	1.0
Grey Clay	5	28–30	41–43	46–49	556	75	1.0
Humic Gley	4	16–22	22–27	40–44	201	75	10.0
Kraznozem	5	23–29	30–46	36–51	371	80	20.0
Lithosol	4	12–15	18–27	24–33	188	85	50.0
Non-Calcic Brown Soil	4	15–18	22–32	28–39	217	85	30.0
Podzolic Soil	4	12–22	22–30	29–37	370	85	5.0
Prairie Soil	5	9–22	17–28	34–43	320	85	10.0
Red and Brown Hardpan Soil	4	25–26	35–37	37–42	400	90	1.0
Red Brown Earth	5	16–25	28–35	35–41	530	85	5.0
Red Earth	5	14–18	25–30	32–37	362	80	10.0
Red Podzolic	4	12–22	22–30	29–37	337	85	5.0
Siliceous Sand	5	3–8	7–15	12–28	187	70	100.0
Solodic Soil	4	15–22	23–30	30–37	339	85	3.0
Solonized Brown Soil	4	6–7	20–21	38–43	600	75	30.0
Solodized Solonetz	4	6–21	15–26	32–43	230	85	2.0
Soloth	4	14–22	24–31	31–38	350	85	1.0
Terra Rossa Soil	4	19–27	24–44	41–50	275	75	1.0
Wiesenboden	4	25–29	41–44	46–50	452	75	1.0
Yellow Earth	5	12–15	20–28	26–34	277	80	5.0
Yellow Podzolic	4	12–22	22–30	29–37	337	85	1.0

[1] 'Lower limit' or 'wilting point' is the minimum soil water content before a plant starts to wilt.
[2] 'Upper limit' or 'field capacity' is the soil water content after any excess soil water has drained.
[3] 'Sat' is the water content at which a soil is saturated.
[4] 'PAWC' is the total volume of water available for plant uptake (upper limit minus lower limit).
[5] 'CN' is the runoff curve number, which describes runoff potential.
[6] 'Ksat' is the saturated hydraulic conductivity or rate of water movement down a soil profile.

2.6 Python scripts

Python scripts were used to create a hydrological modelling shell. This was built to coordinate multiple runs of the PERFECT water balance model using the NARCliM climate projections. At its core, the system manages ‘scenarios’, which describe a set of PERFECT model runs based on three key information sources relating to the area of interest: climate, soils, and land-use inputs. The intersection of these three information sources identifies a spatial area to be modelled and the corresponding PERFECT model inputs and parameters required for the individual spatial unit to be modelled.

Users interact with the modelling system through a command-driven interface. While users see only these ‘top-level’ commands, the commands themselves are backed by detailed Python modules representing the spatial modelling approach, with links to the underlying PERFECT model, written in Fortran to model the water balance. This command-driven approach gives users the ability to create short scripts to automate repetitive operations.

The scripts read and write files in NetCDF (Network Common Data Form) which is an open standard multi-dimensional time-series spatial format commonly used and accepted across the scientific community. NetCDF files are machine-independent data formats designed for array-based data. Files are self-describing in that they contain header information that describes the content and structure of the file and naming attributes. To produce the simulations presented in this report, the scripts were configured to:

1. read the post-processed NARCliM NetCDF files containing daily data for rainfall, actual ET and the calculated potential ET (Morton 1983)
2. in the case of urban cells, calculate the actual ET using potential ET and foliage projected cover as a crop factor
3. in the case of water cells, set actual ET to equal potential ET (Morton 1983)
4. in the case of each 10 km cell, run PERFECT using the land-use type, great soil group and lateral flow partitioning coefficient (F_L) shown in Figure 2 for that cell
5. extract model output as NetCDF files and ASCII comma-separated files and for input to ArcGIS and Excel for further analysis.

2.7 Presentation of results

Model runs were undertaken for each combination of four GCMs, three RCMs and three epochs (1990–2009, 2020–2039 and 2060–2079), a total of 36 combinations. NetCDF files of surface runoff, lateral flow, recharge and actual ET are available as mean annual values (mm/year), monthly time-series (mm), deciles (mm) and average monthly values (mm/month). Summary spreadsheets containing mean annual and seasonal surface runoff, lateral flow, recharge and actual ET for all GCM/RCM/epoch combinations have been compiled.

For this report, maps showing the impacts of climate change on surface flows and recharge to groundwater are presented for mean annual and seasonal values of absolute change across all the 36 combinations. Absolute change (relative to 1990–2009) is calculated for both the near future (2020–2039) and far future (2060–2079) epochs. Bar graphs of changes that show the spatially averaged modelled change from each individual GCM–RCM combination are also presented to highlight the variability in future climate projections from the NARCliM ensemble of models.

Tabular output showing mean percent change in surface flows and recharge to groundwater is provided for each major catchment, state planning region, and Local Land Service area.

3. Results

In this section, **bar graphs** are used to present projections as ranges of plausible change, illustrating the projections from the 12 individual simulations as well as the central estimate. The bar graphs show future projections averaged across the entire state or entire regions. They are not representative of any particular location within the state or region. To better understand statewide changes, bar graphs and supporting tabular information are also provided for each of the 12 projections. All 12 models represent plausible futures. Presenting information for all 12 models allows the reader to better understand the variability across the projections and the uncertainty in the multimodel mean estimates. There is more confidence in the average trend of the 12 models when the majority of models agree with that trend.

For more detailed spatial information, **maps** are presented showing central estimates or the multimodel mean of future projections. These are calculated by averaging the results from the 12 climate model simulations. The central estimates provide guidance to the projections of multiple models. However, actual changes may deviate from these central estimates or multimodel means.

3.1 Statewide change in surface runoff

Changes in surface runoff can influence the availability of water resources, flows into major dams and farm dams, and the design and operation of urban stormwater drainage systems. Secondary impacts such as salinity, erosion, and changes in water quality and aquatic biodiversity can also occur as a result of changes in surface runoff.

Across much of NSW, surface runoff is projected to increase in both the near and far future (Figures 6 & 7). The largest increases are evident in the north-west plains around Moree, the western plains north of Wagga Wagga and west of Dubbo, the Riverina west of Wagga Wagga and the central coast between Port Macquarie and Wollongong. In the near future, higher average annual runoff will be in the range of 0–20 mm/yr while, in the far future, increases up to 80 mm/yr are likely for some parts of NSW: the north-west plains around Moree and the central coast north of Newcastle. Large reductions in surface runoff are projected in both the near and far future for alpine areas in the south of the state. There are also areas of reduced runoff along sections of the Great Dividing Range in northern NSW.

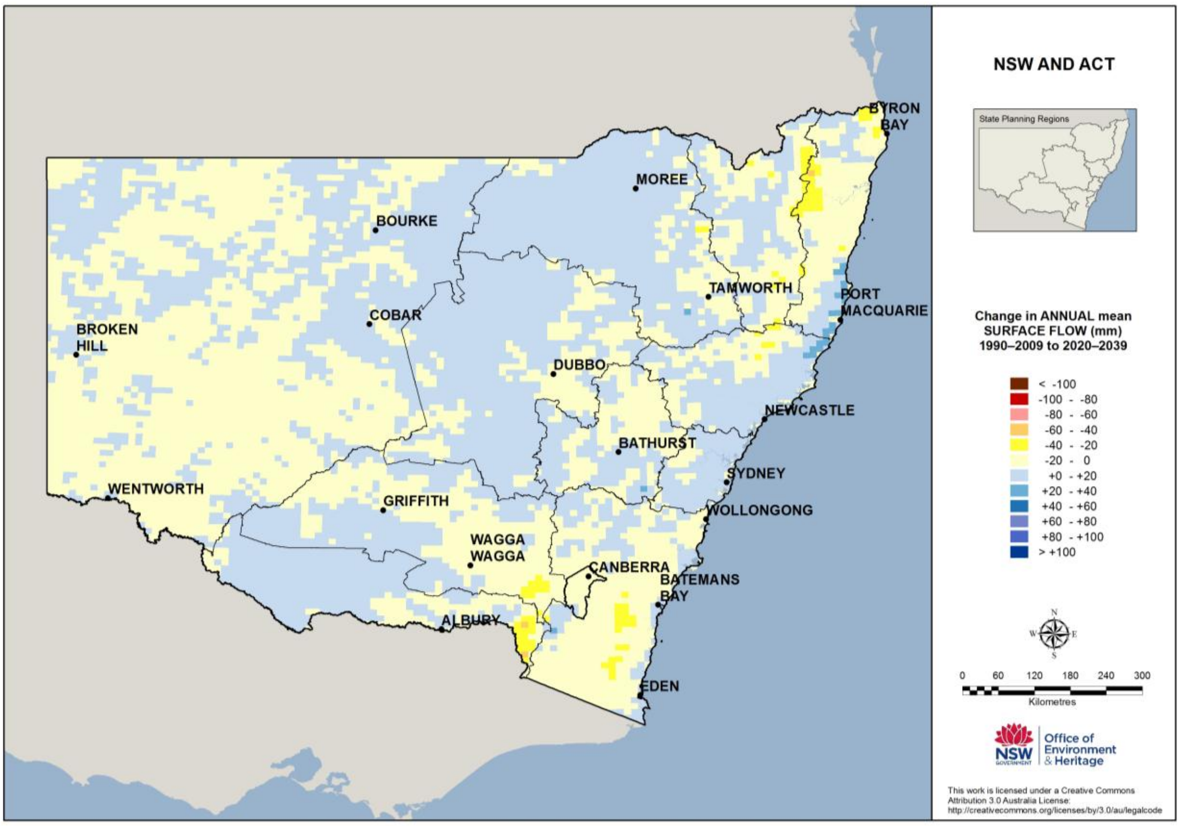


Figure 6. Near future (2020–2039) change in mean annual surface runoff (mm) compared to the baseline period (1990–2009)

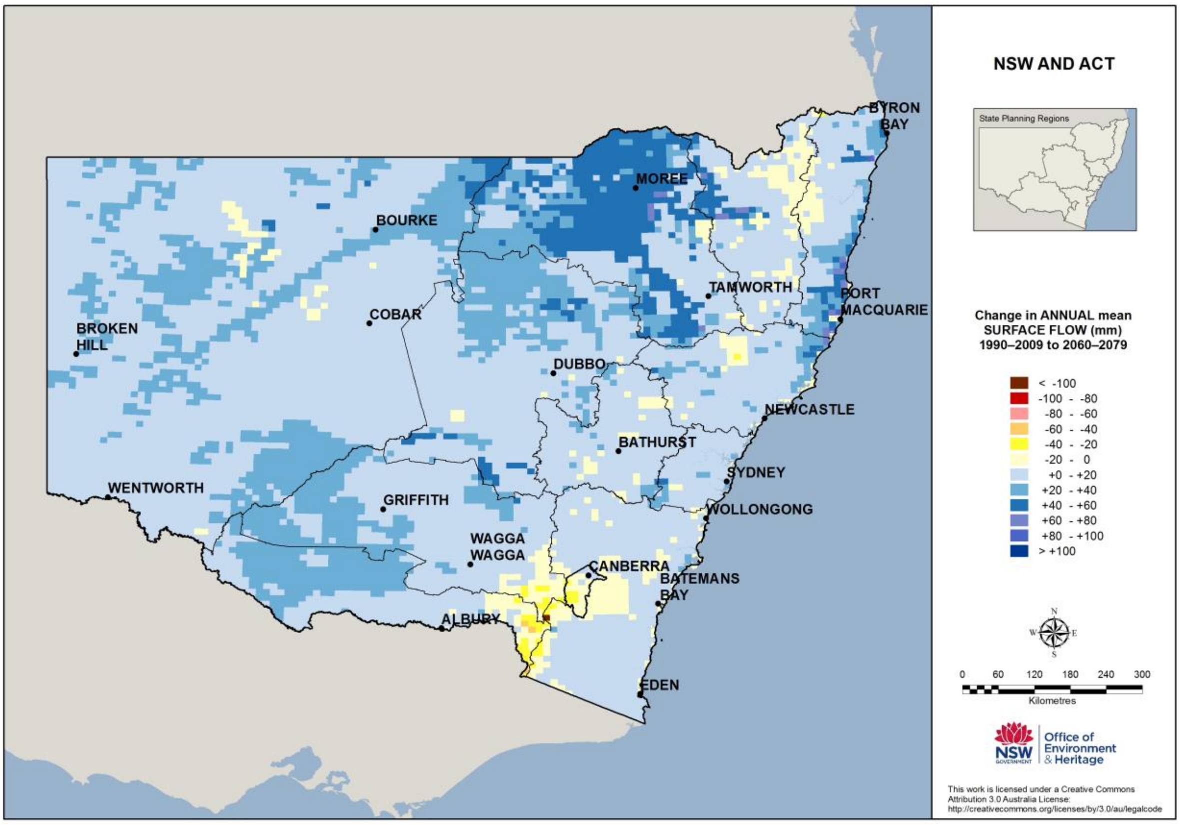


Figure 7. Far future (2060–2079) change in mean annual surface runoff (mm) compared to the baseline period (1990–2009)

Averaged across the whole of NSW, the majority of models (7 out of 12) predict more surface runoff in the near future. In the far future, 10 out of the 12 models agree that surface runoff will increase (Figures 8 & 9). Figure 9 shows the variability of trends across the 12 model ensemble. The MIROC models are wetter models, especially in the far future. In contrast, the CSIRO model predicts a drying trend in rainfall and hence runoff. Of particular interest are the predictions for the ECHAM model in the near future that show positive or negative trends depending on the RCM used. This suggests that the GCM boundary condition is less constraining than the physical scheme used in the RCM.

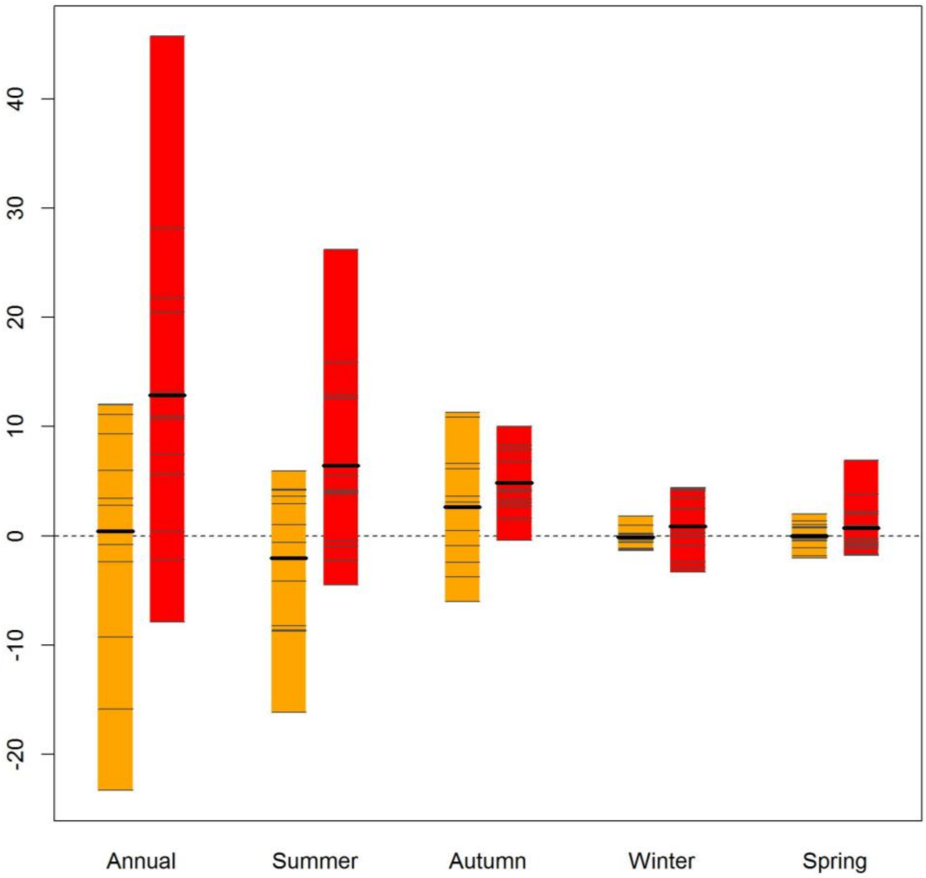
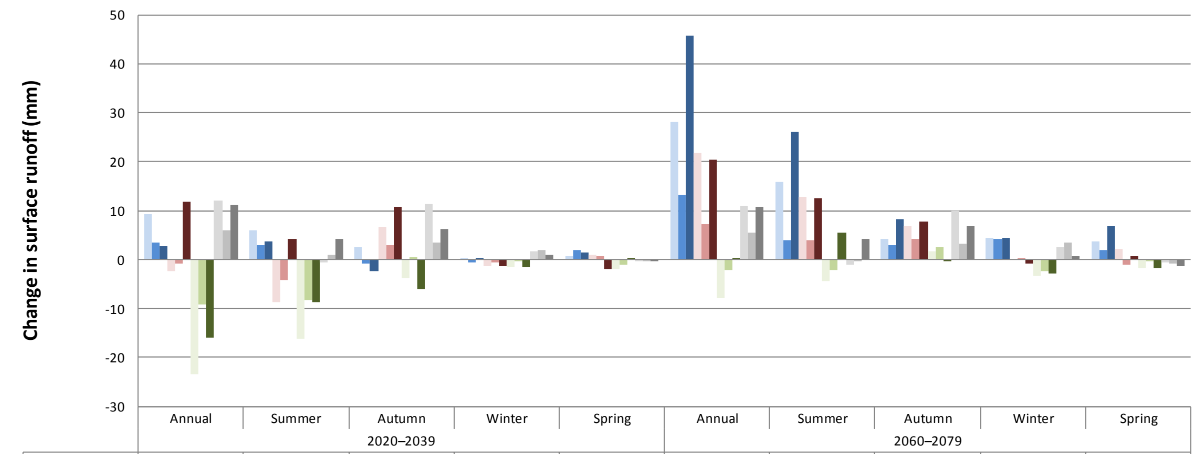


Figure 8. Projected changes in mean annual surface runoff (mm), annually and by season (2030 yellow, 2070 red)



	2020–2039 Annual	2020–2039 Summer	2020–2039 Autumn	2020–2039 Winter	2020–2039 Spring	2060–2079 Annual	2060–2079 Summer	2060–2079 Autumn	2060–2079 Winter	2060–2079 Spring
MIROC32_R1	9.4	5.9	2.6	0.1	0.7	28.2	15.9	4.1	4.4	3.8
MIROC32_R2	3.4	2.9	-0.9	-0.6	2.0	13.2	4.0	3.0	4.1	2.0
MIROC32_R3	2.8	3.6	-2.5	0.2	1.4	45.7	26.2	8.3	4.3	6.9
ECHAM5_R1	-2.4	-8.7	6.6	-1.3	1.0	21.8	12.8	6.8	-0.1	2.2
ECHAM5_R2	-0.8	-4.1	3.1	-0.6	0.8	7.4	3.9	4.2	0.3	-0.9
ECHAM5_R3	12.0	4.1	10.8	-1.1	-1.9	20.5	12.6	7.9	-0.8	0.9
CSIROMK30_R1	-23.3	-16.2	-3.8	-1.4	-2.0	-7.9	-4.5	1.6	-3.3	-1.7
CSIROMK30_R2	-9.3	-8.3	0.5	-0.4	-1.1	-2.2	-2.3	2.7	-2.4	-0.3
CSIROMK30_R3	-15.9	-8.6	-6.0	-1.4	0.1	0.4	5.5	-0.4	-2.9	-1.8
CCCMA31_R1	12.1	-0.6	11.3	1.8	-0.4	11.0	-0.9	10.0	2.5	-0.6
CCCMA31_R2	6.0	1.0	3.6	1.8	-0.5	5.6	-0.4	3.3	3.5	-0.8
CCCMA31_R3	11.1	4.2	6.1	1.0	-0.3	10.7	4.2	6.8	0.9	-1.2

Figure 9. Projected changes in mean annual surface runoff (mm), annually and by season for all 12 members of the NARCliM ensemble

The models predict considerable variation in the magnitude and spatial patterns of changes across the four seasons. In the near future, the majority of models (8 out of 12) predict that autumn runoff will increase as a result of higher autumn rainfall, summer runoff will decrease slightly, and runoff in winter and spring is likely to remain unchanged (Figures 8 & 9).

In the far future, higher surface runoff in autumn is strongly supported by 11 of the 12 models (Figures 8 & 9). Higher runoff in summer and winter is supported by 8 and 7 of the 12 models respectively. Less surface runoff during spring is supported by the majority of models (7 out of 12 models).

The variability of future changes across the 12 models is highest in the summer months and lowest in winter and spring. This indicates more certainty and confidence in the predictions for winter and spring.

In the near future, summer runoff is likely to increase in parts of central and southern NSW but decrease across much of the state, especially in north-eastern areas on the lower slopes of the Great Dividing Range (Figure 10). In contrast, autumn runoff is projected to increase across large areas of NSW (Figure 11). Winter runoff is predicted to increase slightly across southern NSW and along the Central Coast (Figure 12) but decrease in other areas, especially northern inland catchments and south-coast catchments. The largest reductions in surface runoff are predicted to occur across the southern and western parts of NSW during spring (Figure 13) when less rainfall is likely to occur.

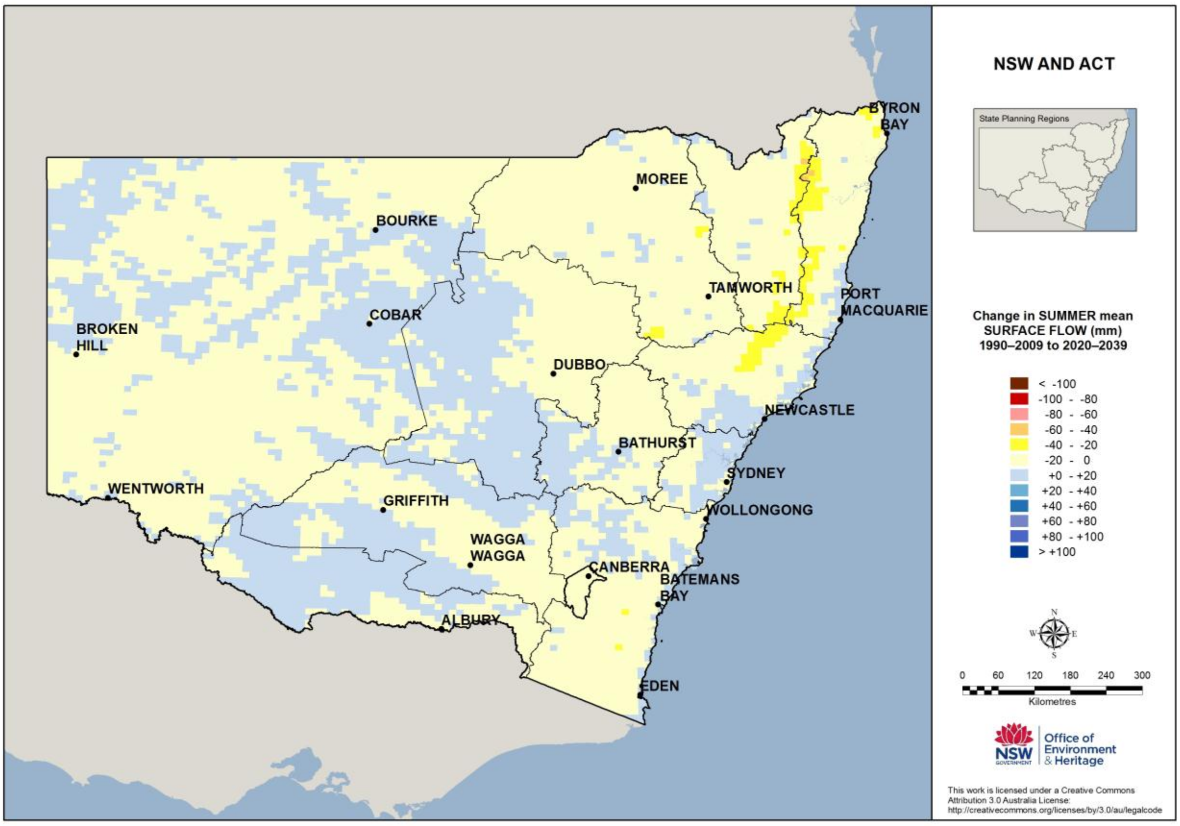


Figure 10. Near future (2020–2039) change in mean summer surface runoff (mm) compared to the baseline period (1990–2009)

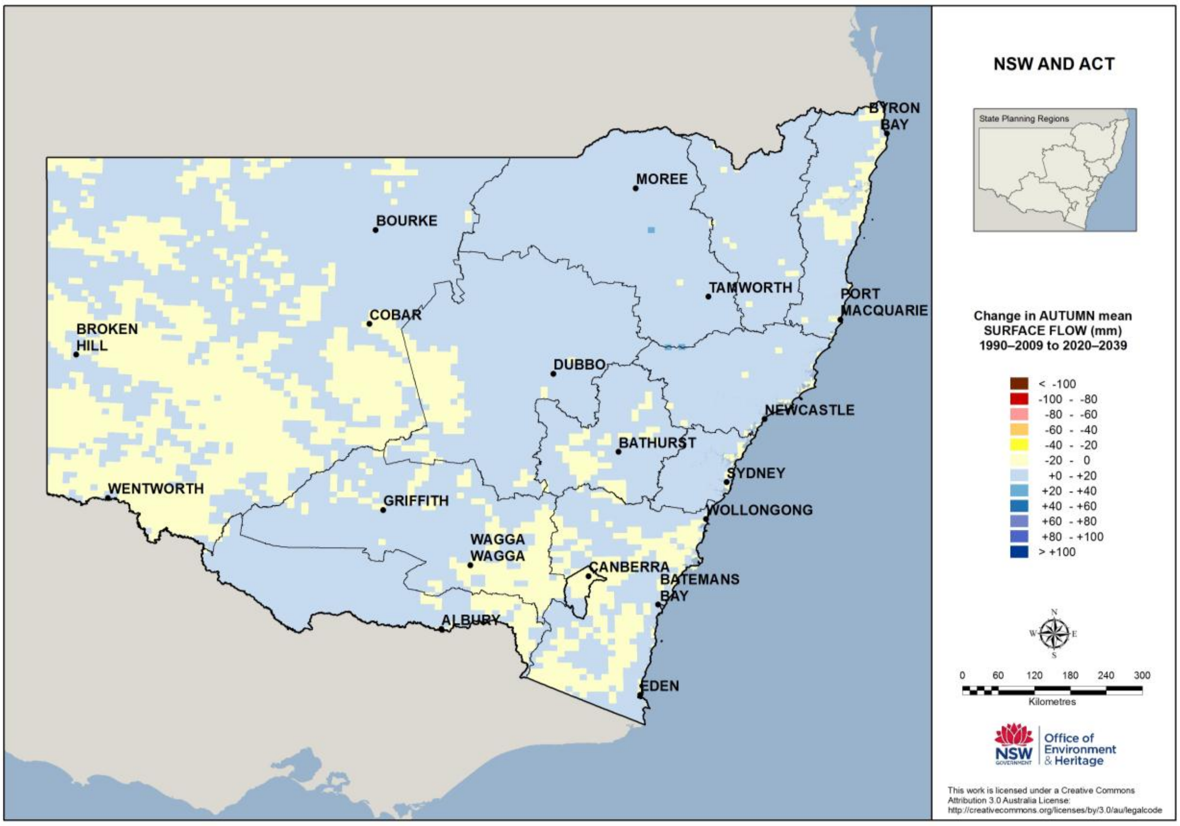


Figure 11. Near future (2020–2039) change in mean autumn surface runoff (mm) compared to the baseline period (1990–2009)

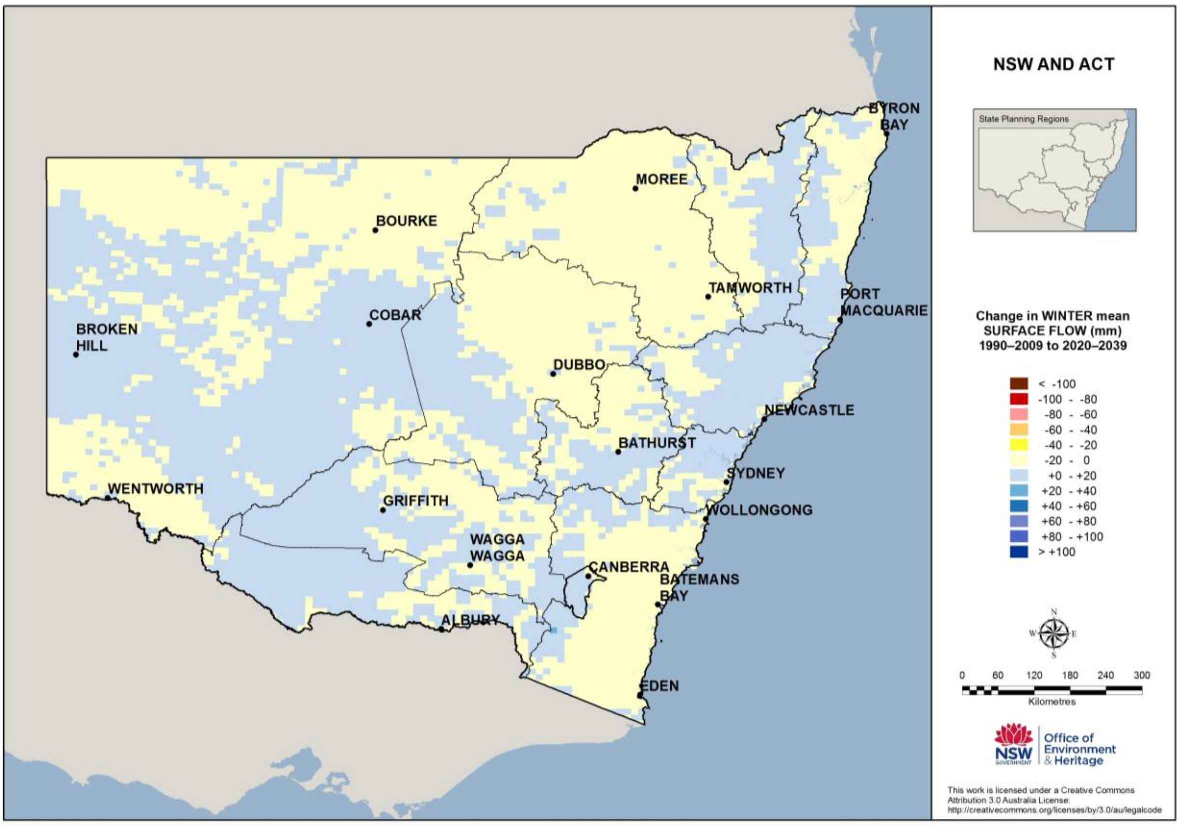


Figure 12. Near future (2020–2039) change in mean winter surface runoff (mm) compared to the baseline period (1990–2009)

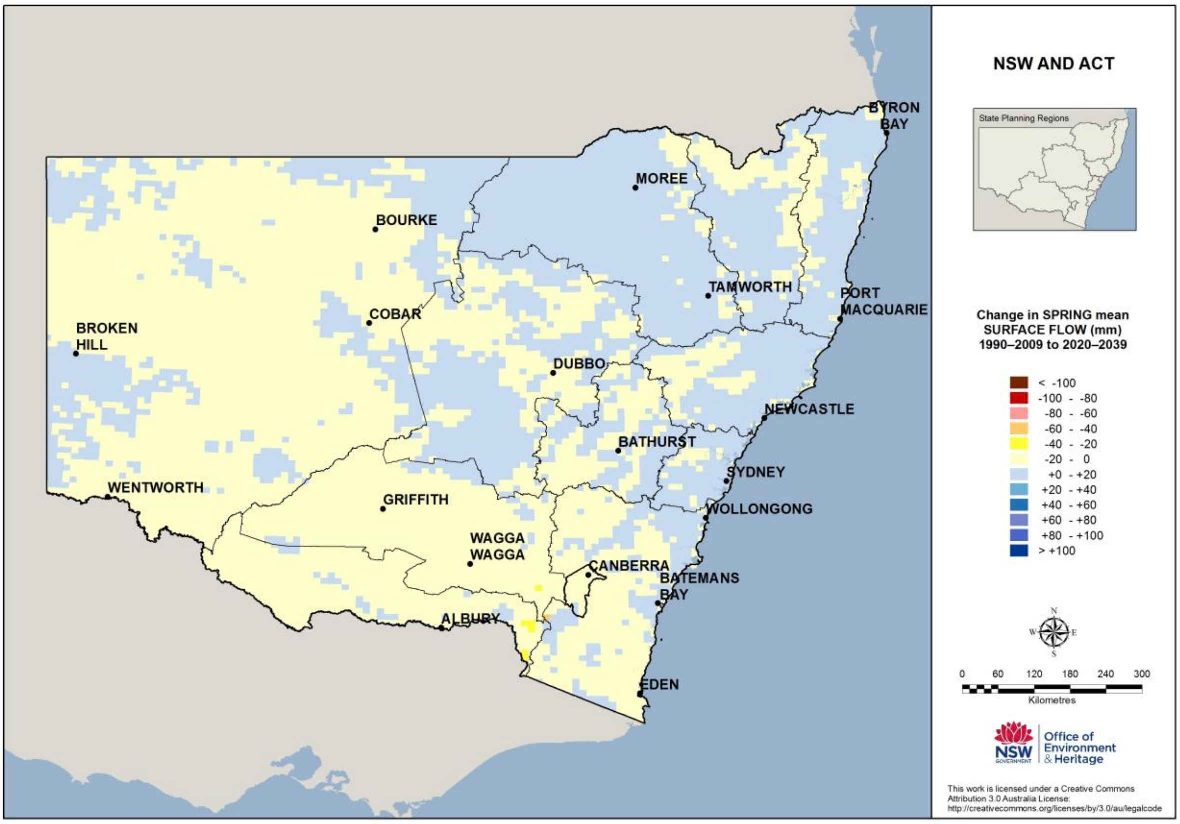


Figure 13. Near future (2020–2039) change in mean spring surface runoff (mm) compared to the baseline period (1990–2009)

In the far future, the patterns of changes in summer and autumn are for more surface runoff, with the largest increases in the northern parts of the state, especially the north-west plains around Moree and the north coast (Figures 14 & 15). Winter runoff is expected to be lower in coastal areas with small increases elsewhere in NSW (Figure 16). Larger reductions in spring runoff are likely in the south-east, with much lower runoff in the alpine areas of southern NSW (Figure 17).

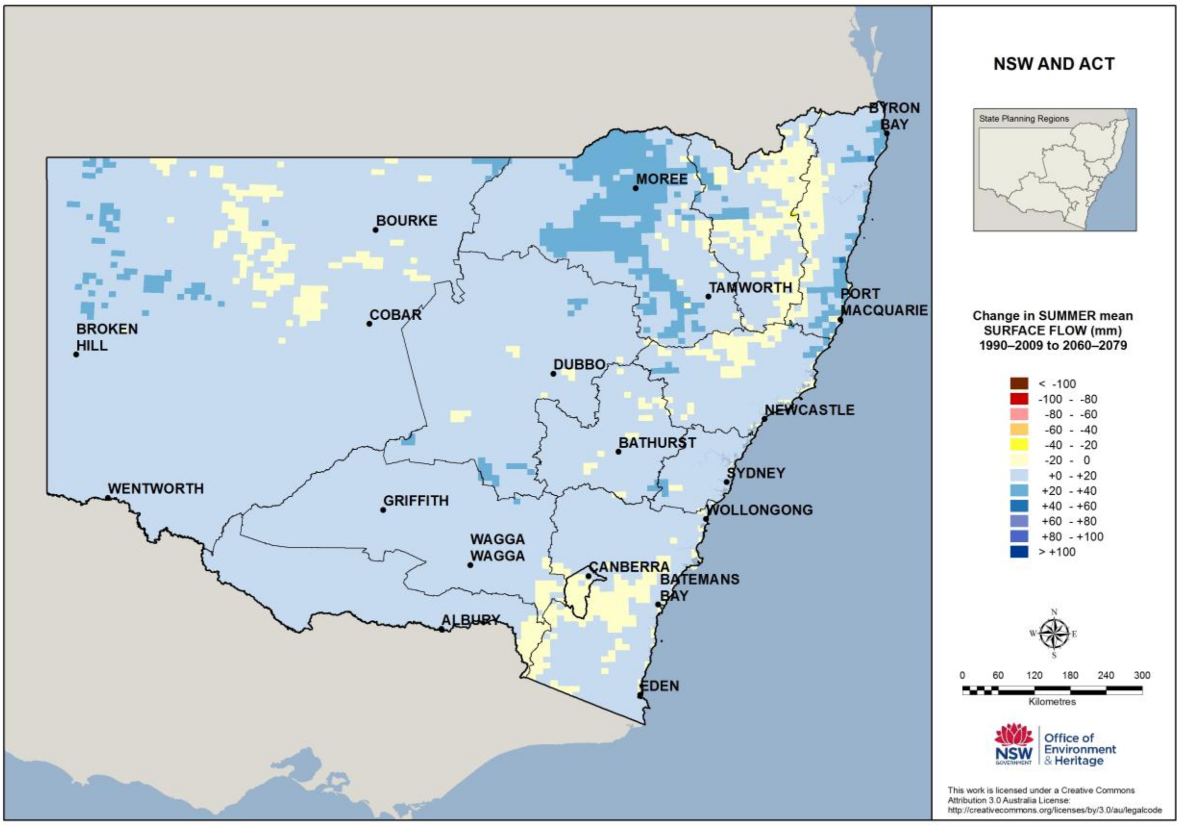


Figure 14. Far future (2060–2079) change in mean summer surface runoff (mm) compared to the baseline period (1990–2009)

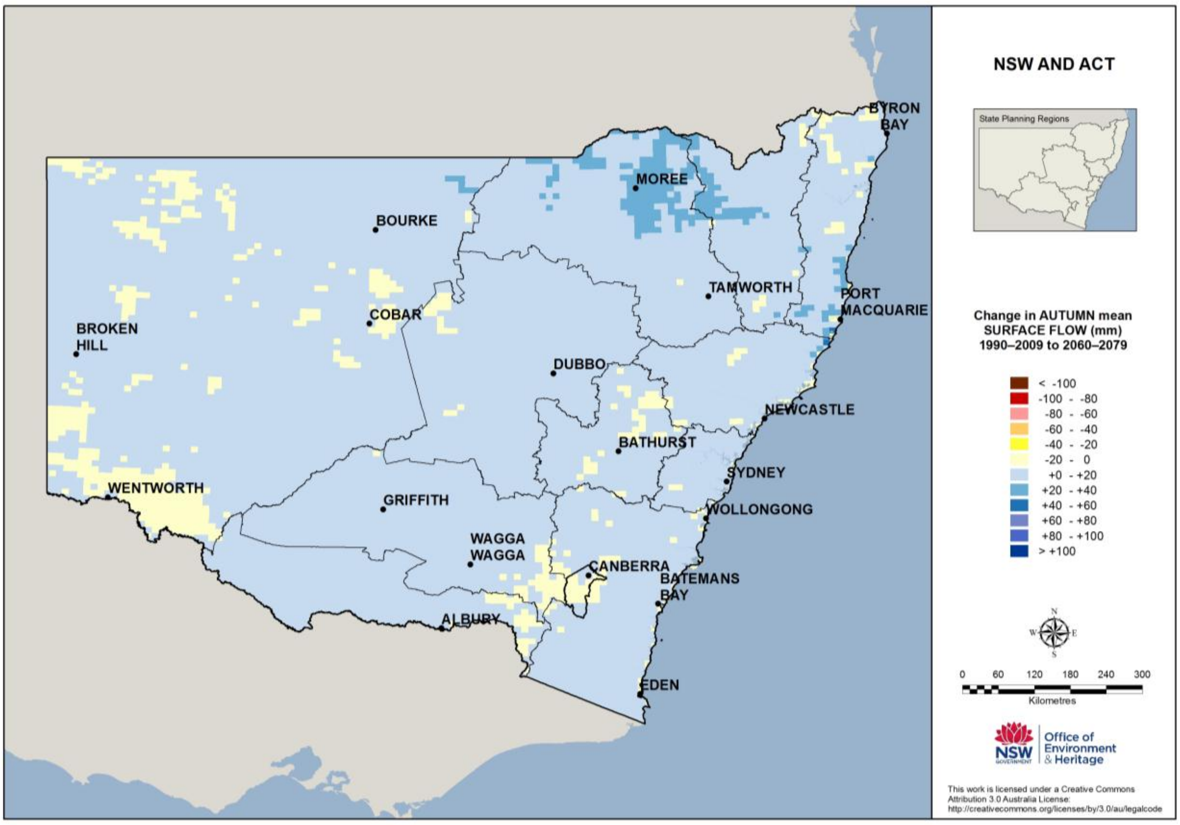


Figure 15. Far future (2060–2079) change in mean autumn surface runoff (mm) compared to the baseline period (1990–2009)

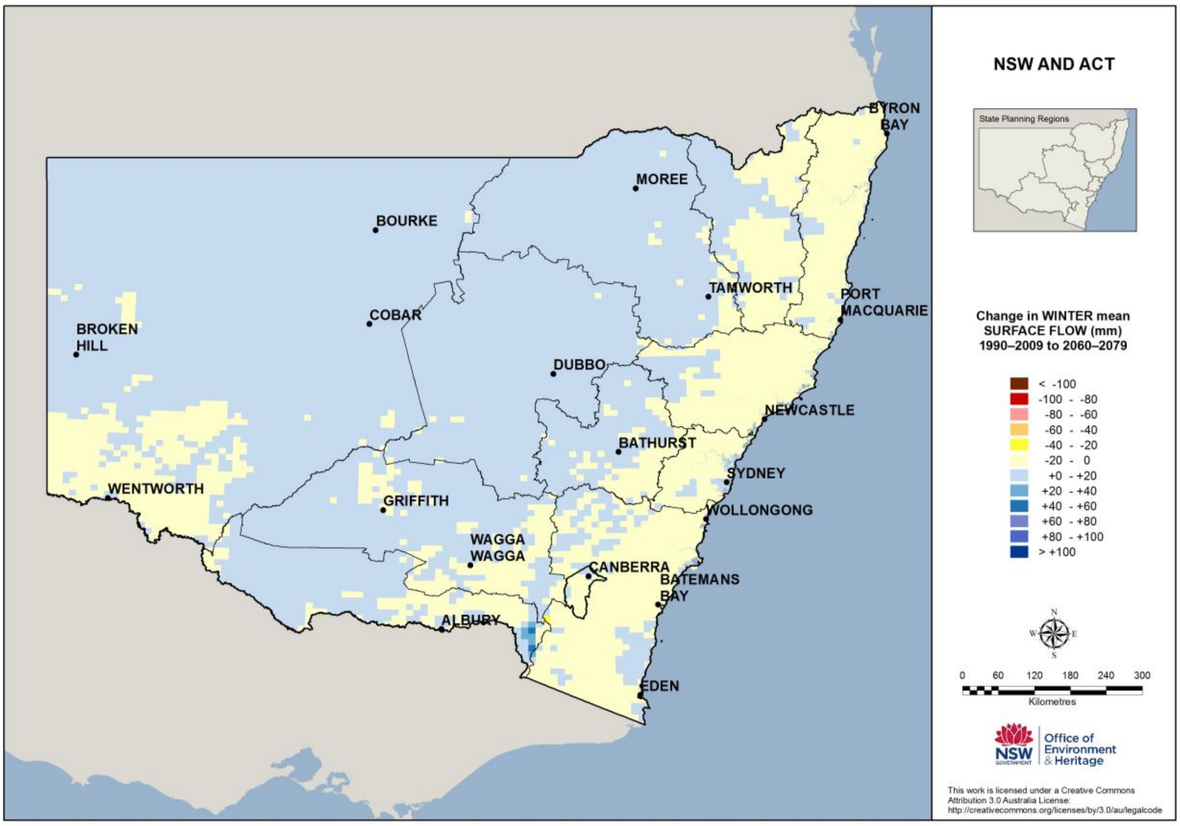


Figure 16. Far future (2060–2079) change in mean winter surface runoff (mm) compared to the baseline period (1990–2009)

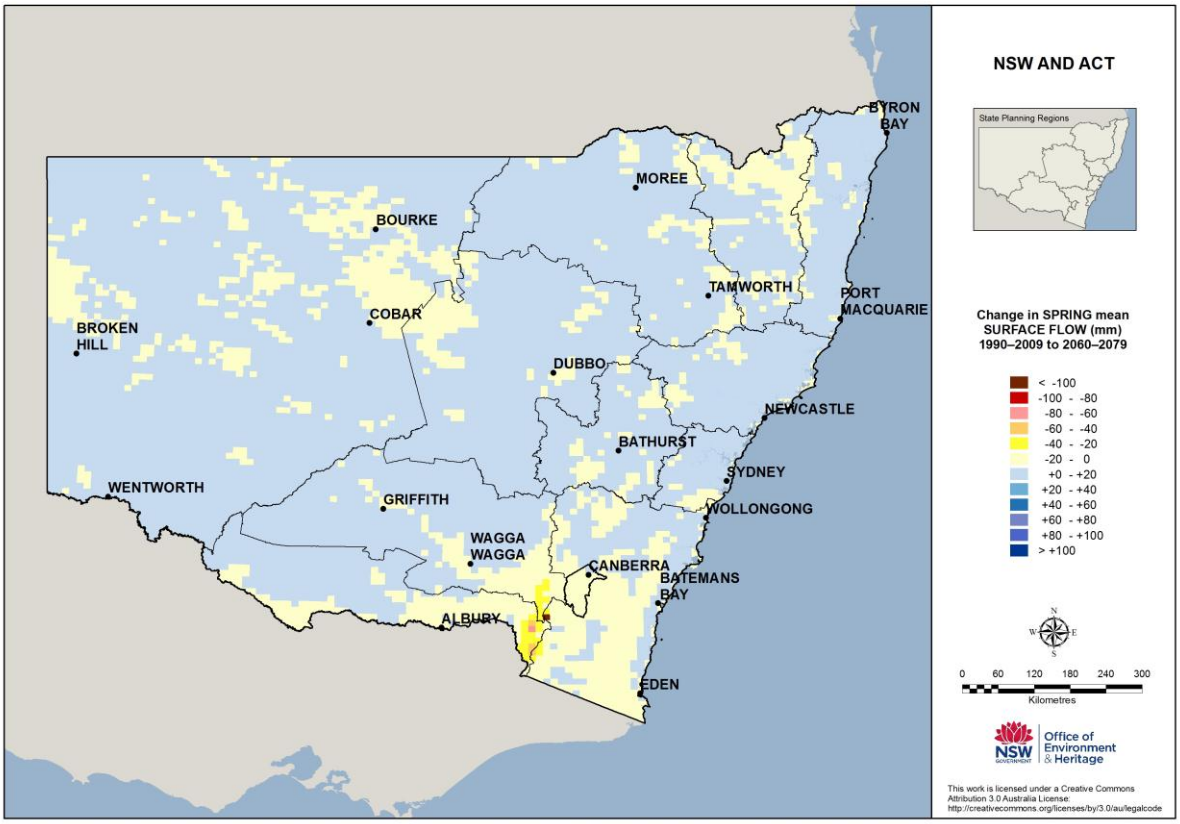


Figure 17. Far future (2060–2079) change in mean spring surface runoff (mm) compared to the baseline period (1990–2009)

3.2 Statewide change in recharge to groundwater

Changes in recharge can influence the availability of groundwater resources and the volumes of base flow in streams. Secondary impacts on salinity and water quality with subsequent impacts on aquatic biodiversity can also occur.

In the near future, less recharge is predicted across much of NSW, especially in the south-east of the state (Figure 18). Considerably less recharge is likely in alpine areas, with reductions ranging from 20 to 80 mm/yr. Some areas of western NSW do show a slight increase in recharge but these increases are relatively small. In the far future, recharge is expected to increase across many parts of NSW. Between 20 and 80 mm/yr more recharge is likely across areas of the north coast. The largest change in any water-balance component in this study is the dramatic reduction in recharge (more than 100 mm/yr in some areas) across alpine areas south of the ACT (Figure 19). The magnitude of these changes is possibly outside any historical variation expected due to natural climate variability.

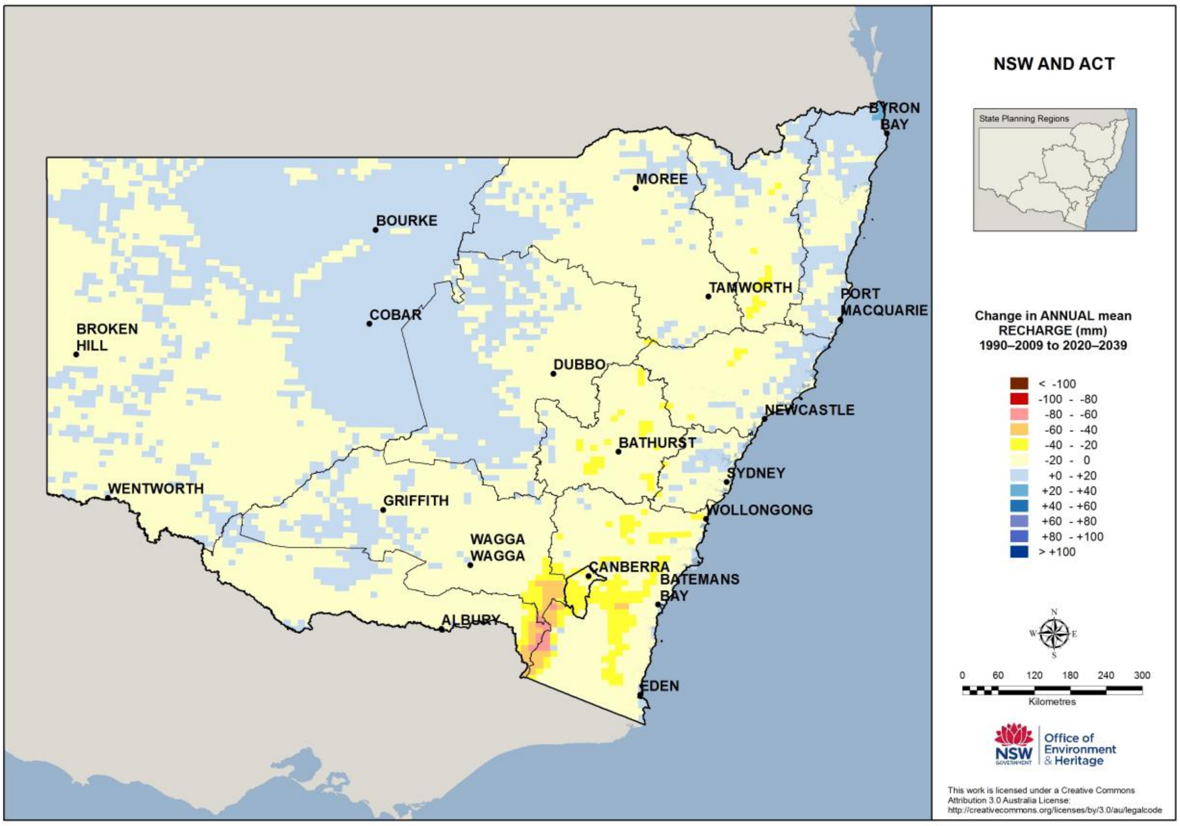


Figure 18. Near future (2020–2039) change in annual recharge (mm) compared to the baseline period (1990–2009)

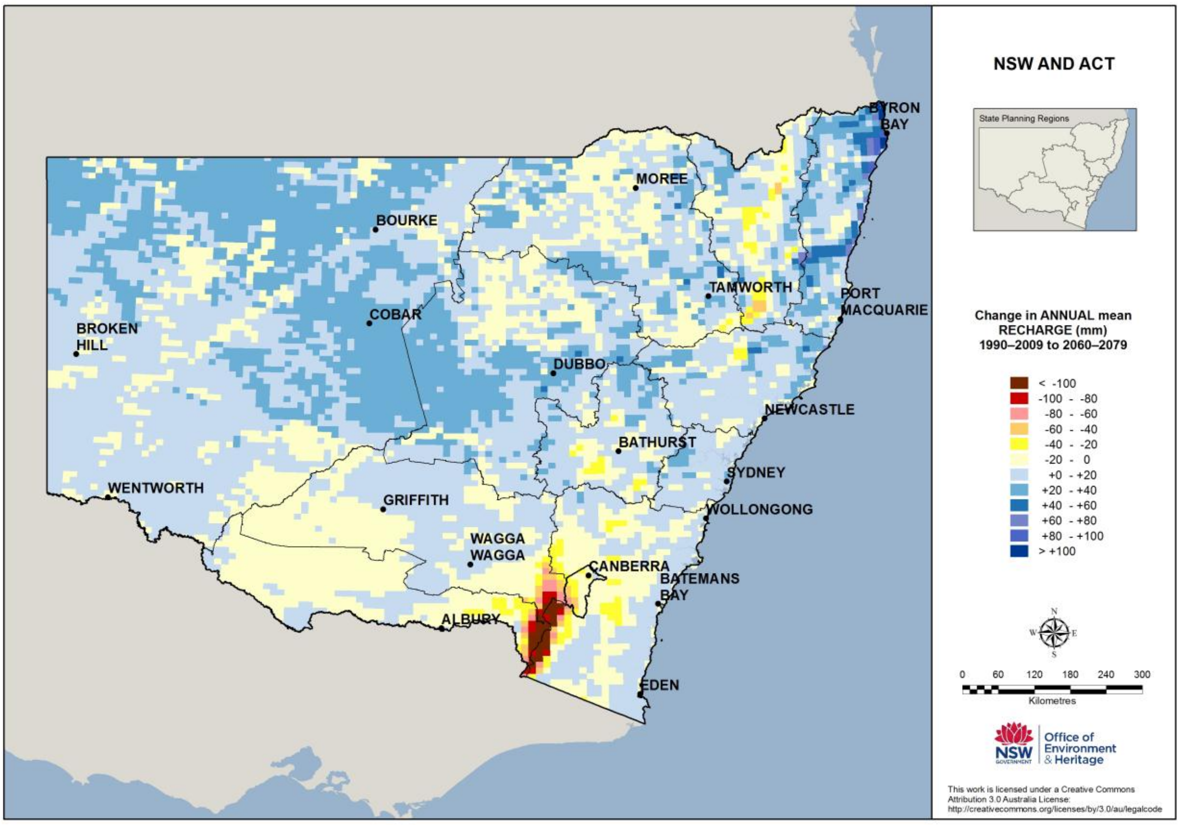


Figure 19. Far future (2060–2079) change in annual recharge (mm) compared to the baseline period (1990–2009)

The majority of models (7 out of 12) predict more recharge in the near future. In the far future, 9 of the 12 models agree that recharge will increase (Figures 20 & 21).

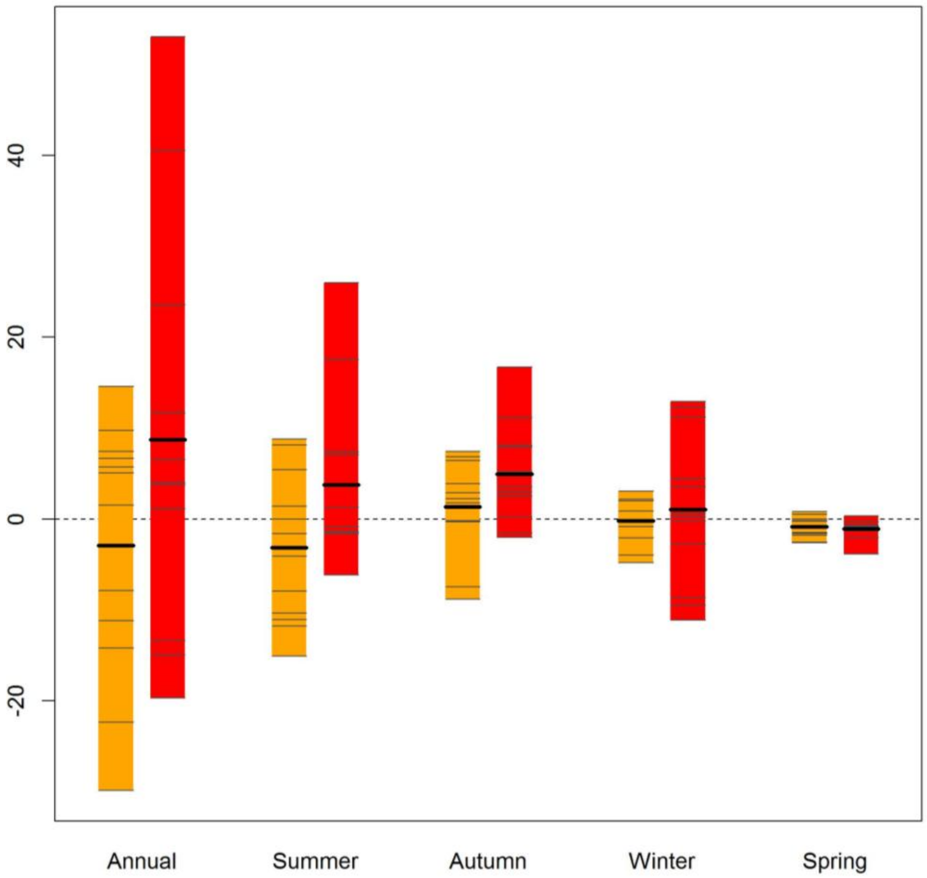
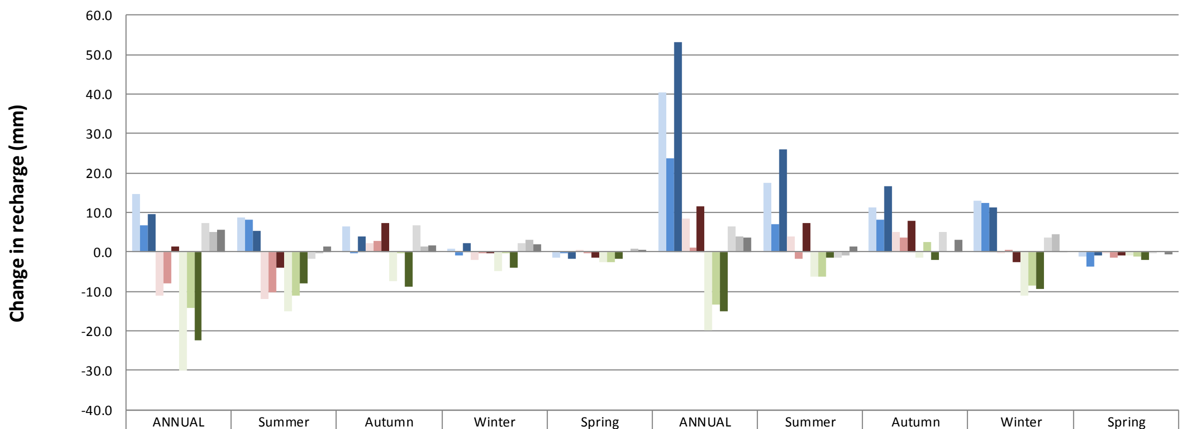


Figure 20. Projected changes in mean annual recharge (mm), annually and by season (2030 yellow, 2070 red)



	2020–2039					2060–2079				
	ANNUAL	Summer	Autumn	Winter	Spring	ANNUAL	Summer	Autumn	Winter	Spring
MIROC32_R1	14.6	8.8	6.4	0.9	-1.5	40.6	17.6	11.2	12.9	-1.1
MIROC32_R2	6.7	8.1	-0.3	-0.8	-0.3	23.6	7.1	8.1	12.3	-3.8
MIROC32_R3	9.7	5.4	3.9	2.2	-1.8	53.1	26.0	16.7	11.2	-0.8
ECHAM5_R1	-11.2	-11.8	2.2	-2.1	0.5	8.5	3.9	5.2	-0.2	-0.3
ECHAM5_R2	-7.9	-10.4	2.9	-0.2	-0.2	1.1	-1.6	3.5	0.5	-1.3
ECHAM5_R3	1.5	-4.1	7.4	-0.3	-1.5	11.6	7.4	7.9	-2.7	-0.9
CSIROMK30_R1	-29.9	-15.1	-7.5	-4.8	-2.5	-19.7	-6.2	-1.6	-11.1	-0.9
CSIROMK30_R2	-14.2	-11.1	-0.2	-0.3	-2.6	-13.4	-6.2	2.5	-8.6	-1.1
CSIROMK30_R3	-22.4	-7.9	-8.8	-4.0	-1.6	-15.0	-1.4	-2.1	-9.5	-2.0
CCCMA31_R1	7.4	-1.6	6.9	2.2	0.0	6.6	-1.6	4.9	3.5	-0.3
CCCMA31_R2	5.1	0.0	1.2	3.1	0.8	4.0	-0.9	0.2	4.4	0.3
CCCMA31_R3	5.7	1.4	1.8	2.0	0.5	3.8	1.3	3.0	0.2	-0.7

Figure 21. Projected changes in mean annual recharge (mm), annually and by season, for all 12 members of the NARCliM ensemble

The models predict considerable variation across the four seasons. There is less change in recharge in the near future compared to the far future (Figure 21). The majority of models (7 out of 12) agree that summer recharge will be lower, with reductions of up to 15 mm/yr. The majority of models (8 out of 12) also agree that autumn recharge will increase by up to 7 mm/yr.

In the far future, the majority of models predict increases in recharge during autumn, with 10 out of 12 agreeing that recharge will be higher by up to 17 mm/yr (Figure 21). Almost all (11 out of 12) also agree that recharge during spring will be less, but the reductions will be small (up to 4 mm/yr). The range of predictions across all models is broader in the far future, indicating more uncertainty in these estimates (Figures 20 & 21). For example, predictions of changes in average annual recharge for the far future range from a decrease of 19.7 mm to an increase of 53.1 mm, a range of 72.8 mm. This is a much larger range than 44.5 mm, which is the range of the models' predictions for the near future (from -29.9 to 14.6).

In the near future, recharge during summer is likely to be lower in many parts of NSW (Figure 22), especially along parts of the Great Dividing Range. In autumn months there is a general trend towards a small increase in recharge, while in winter months the models predict a small decrease in recharge (Figures 23 & 24). The largest changes occur during spring, with considerably less recharge in alpine areas (Figure 25). There is a general trend towards drying, with less recharge in spring across much of NSW with the exception of the north-east.

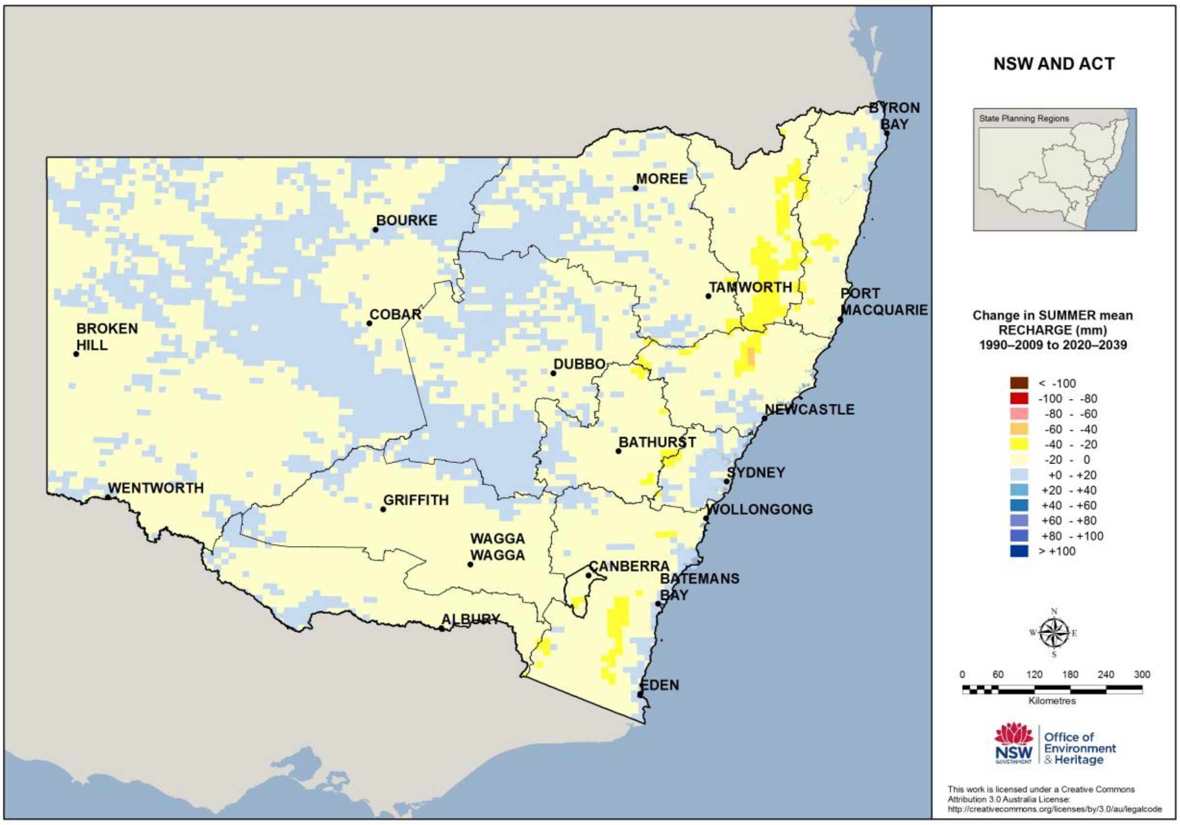


Figure 22. Near future (2020–2039) change in summer recharge (mm) compared to the baseline period (1990–2009)

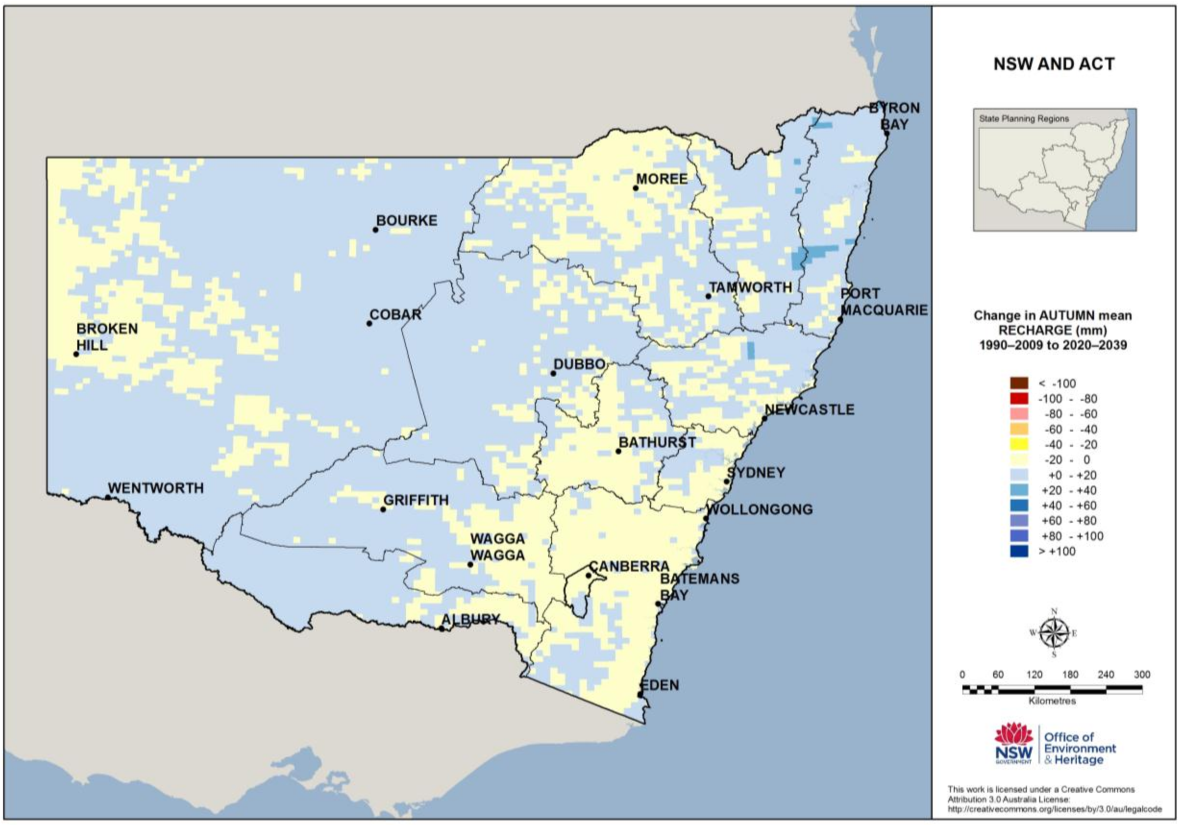


Figure 23. Near future (2020–2039) change in autumn recharge (mm) compared to the baseline period (1990–2009)

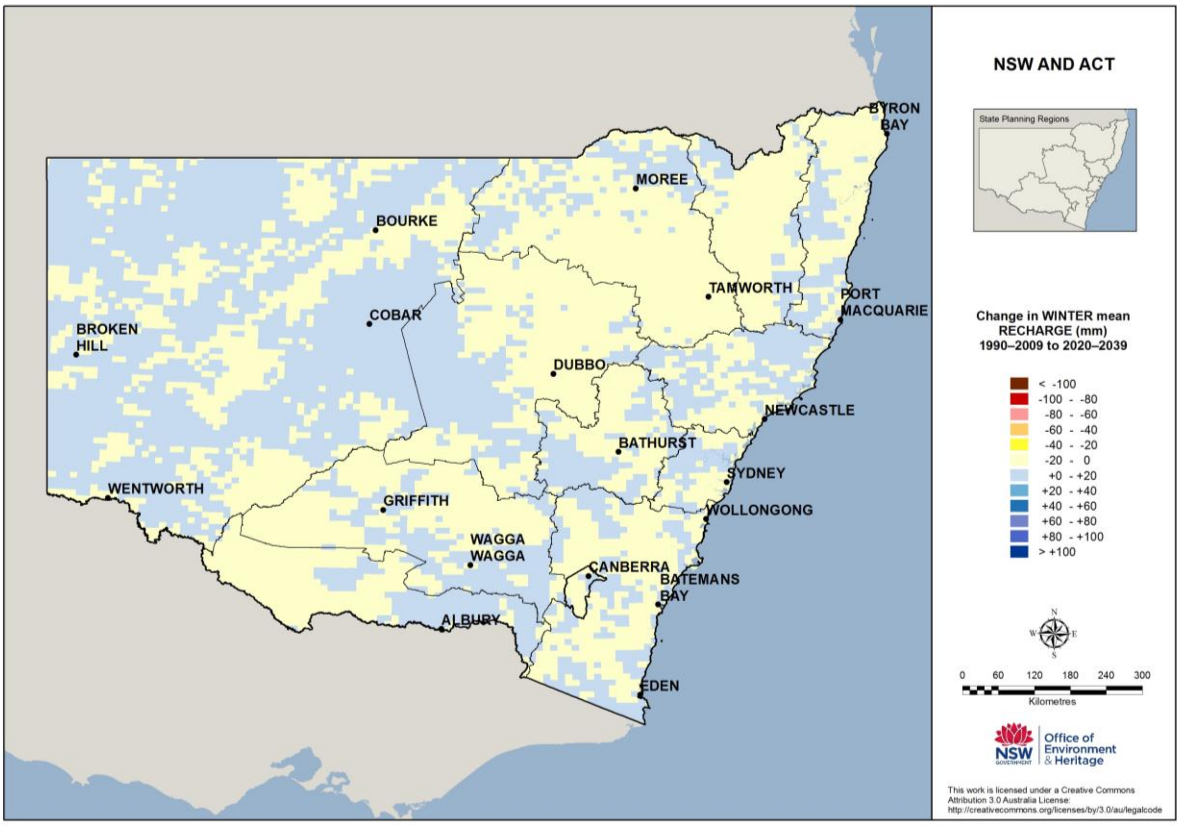


Figure 24. Near future (2020–2039) change in winter recharge (mm) compared to the baseline period (1990–2009)

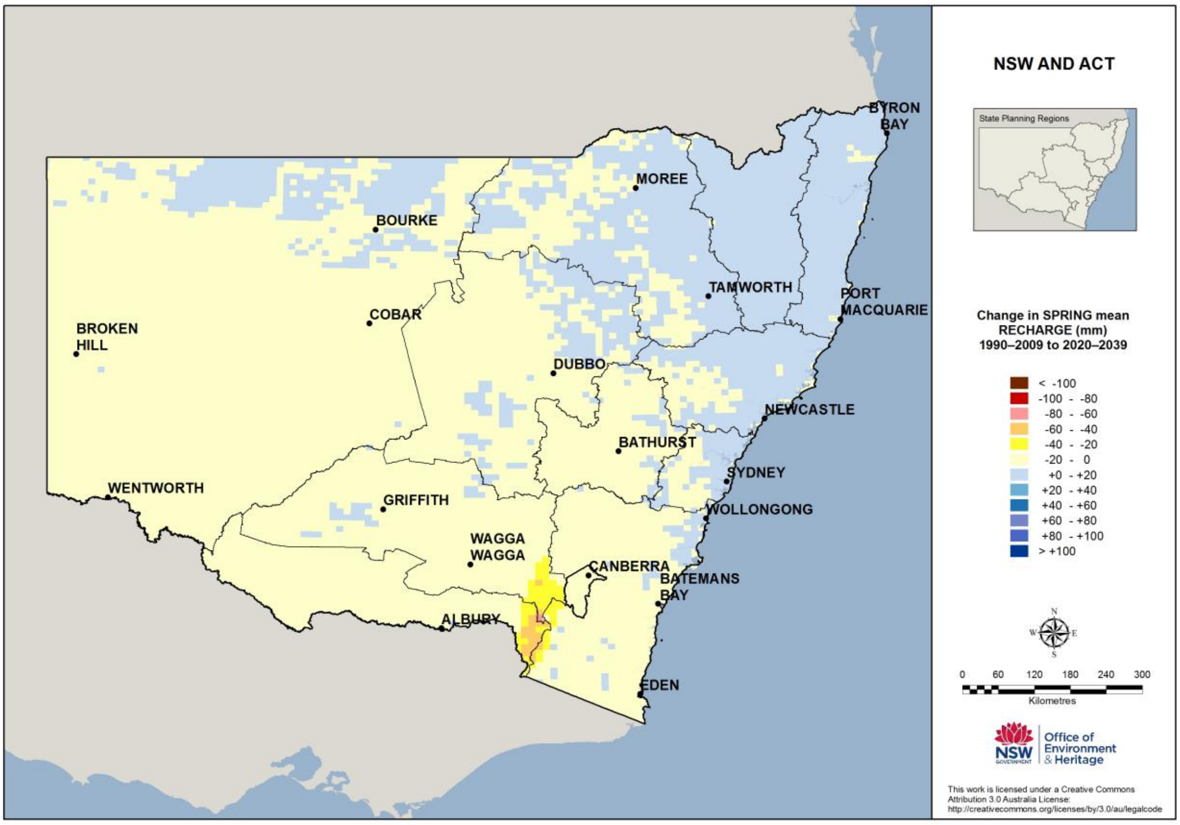


Figure 25. Near future (2020–2039) change in spring recharge (mm) compared to the baseline period (1990–2009)

In the far future, more recharge is expected across much of NSW during summer and autumn (Figures 26 & 27). In particular, higher volumes of recharge are likely in many parts of coastal catchments north of Newcastle. During winter, recharge is likely to be lower in coastal areas and southern NSW (Figure 28). Drier spring months with considerably less recharge are likely in southern NSW, and large reductions in recharge (> 80 mm/yr) are predicted in alpine areas (Figure 29). These trends reflect seasonal changes in rainfall from the NARCliM projections.

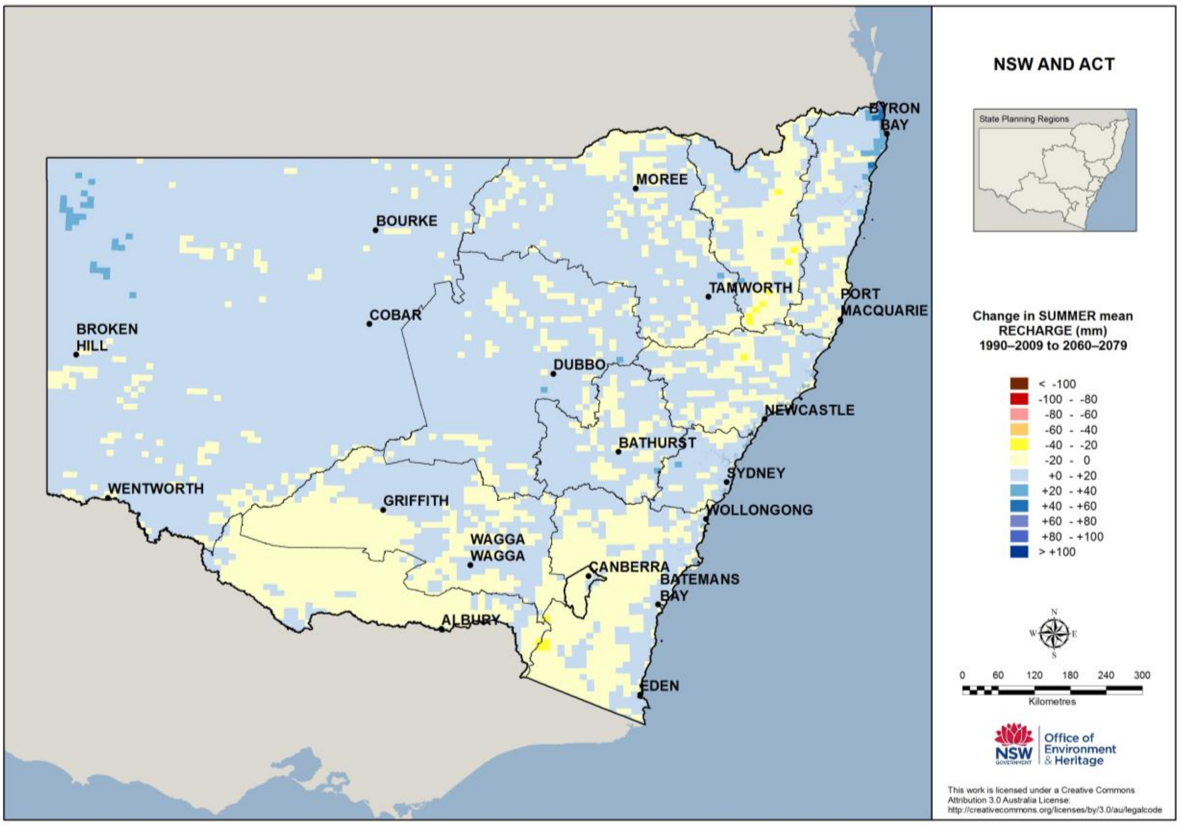


Figure 26. Far future (2060–2079) change in summer recharge (mm) compared to the baseline period (1990–2009)

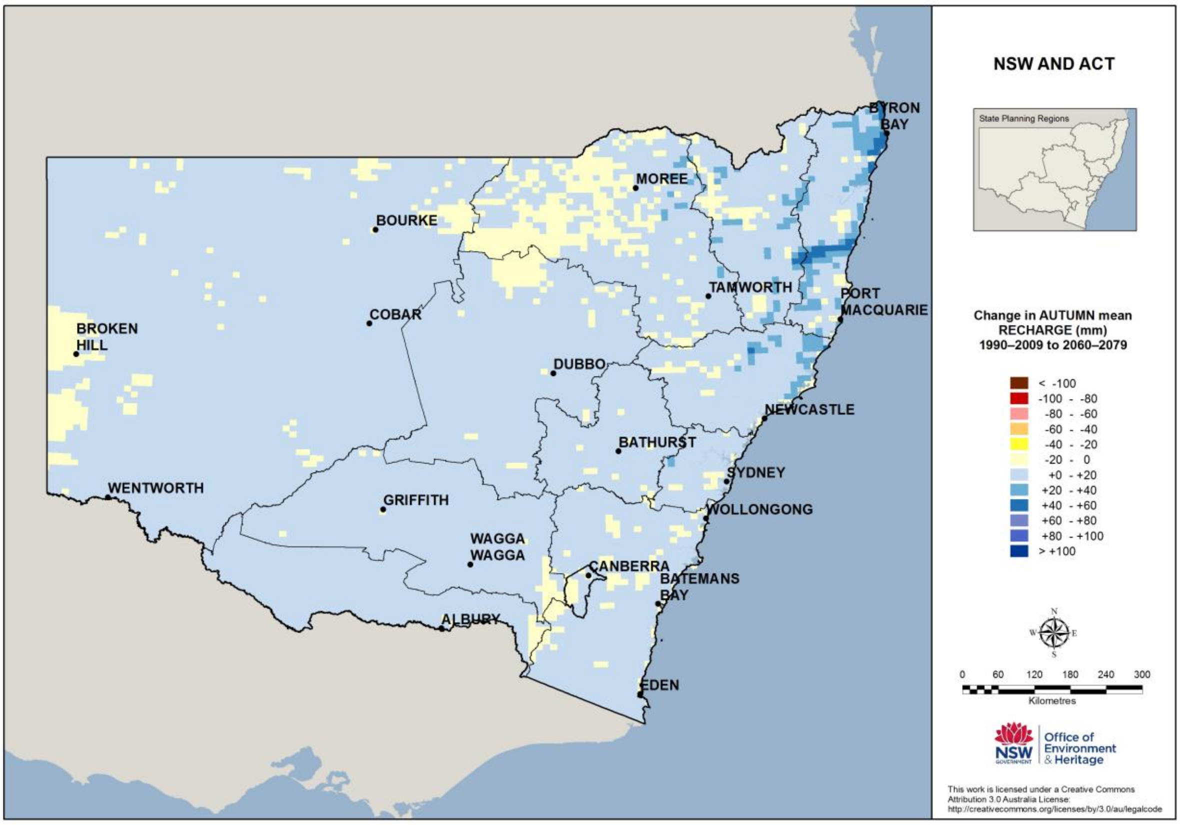


Figure 27. Far future (2060–2079) change in autumn recharge (mm) compared to the baseline period (1990–2009)

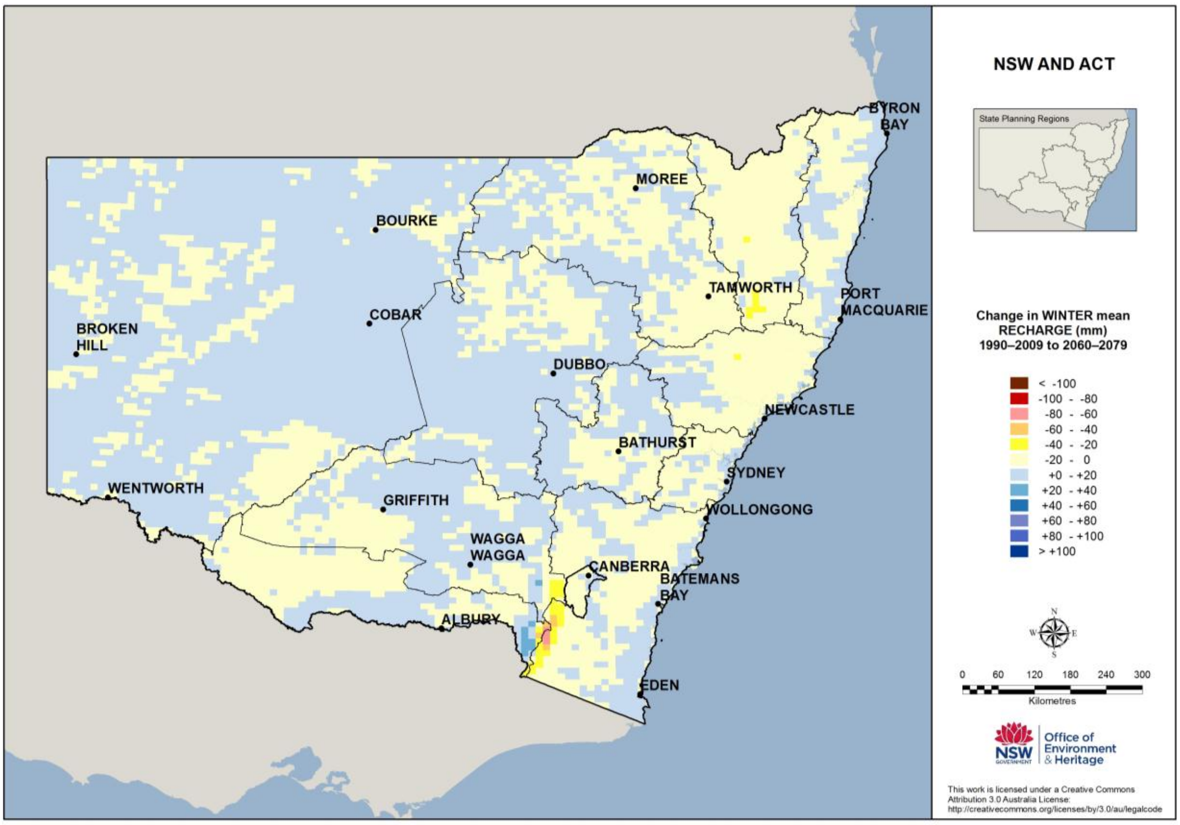


Figure 28. Far future (2060–2079) change in winter recharge (mm) compared to the baseline period (1990–2009)

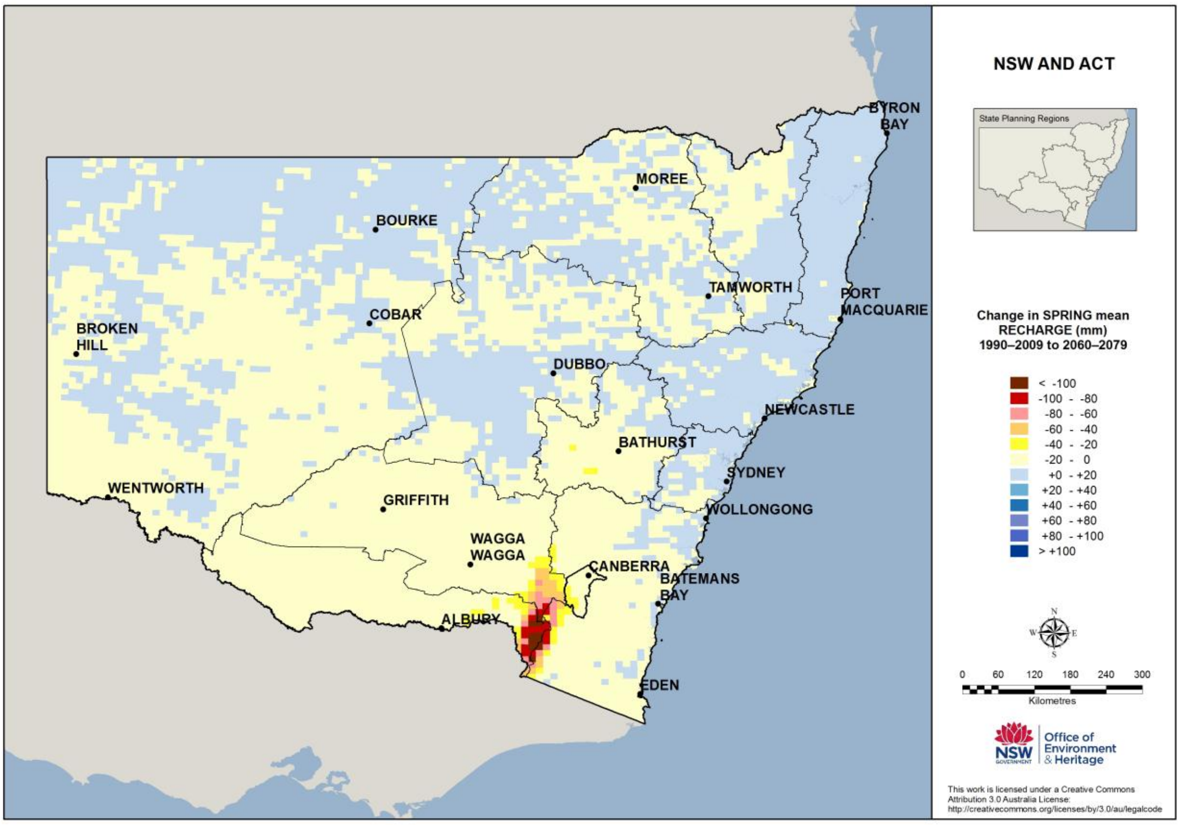


Figure 29. Far future (2060–2079) change in spring recharge (mm) compared to the baseline period (1990–2009)

3.3 Summary of change by major catchment

The major catchments in NSW are shown in Figure 30. The predicted impacts of climate change for each catchment will be presented by comparing mean annual surface runoff and recharge for the baseline period (1990–2009), near future (2020–2039) and far future (2060–2079). Percent changes in runoff and recharge will be presented, as well as changes in runoff ratios. Changes in surface runoff are also presented as megalitre volumes per catchment. An increase in surface runoff does not directly correlate to a similar increase in streamflow at the catchment outlet. All the surface runoff occurring in a catchment may not make its way into the river itself, as some will flow into farm dams, wetlands and other water bodies. In the river itself, the modelling does not include channel losses, whether natural or anthropogenic.

Results are presented for the three major drainage divisions of NSW: coastal catchments, the Murray–Darling Basin and the far north-west. Coastal catchments in NSW have their headwaters in the Great Dividing Range and drain to the coast. Many flow into estuaries, which provide spawning grounds for aquatic creatures and vital habitat for migratory birds. They are areas valued for tourism, recreation, commercial use and cultural activities. These competing economic and environmental values offer many challenges for natural-resource managers. Coastal regions are under the most pressure from population growth and changes in land use. Growing populations and developments put increasing pressure on surface and groundwater resources. Pressures on groundwater are also higher given a predicted drier climate and increasing scarcity of surface water. Agriculture is a major user of water, along with town water supplies and domestic, commercial and industrial users.

The hydrology of our coastal catchments shifts from north to south. North-coast catchments have the highest and most variable rainfall and stream flows. These catchments are located in the subtropics, which are hotter, more humid and wetter, with higher and more intense rainfall in summer and drier winters. The presence of the Great Dividing Range results in an orographic rainfall process, which produces higher rainfall along the entire coast.

Southern catchments are less developed than other coastal catchments and are largely uncleared. They sit within the temperate rainfall zone, experiencing rainfall that is more uniform and reliable but less intense. Southern catchments do not produce the same volume of runoff as northern catchments, and recharge can be high in southern areas due to the soaking nature of the rainfall, especially during winter months.

NSW catchments in the Murray–Darling Basin have their headwaters in the Great Dividing Range and flow west towards the Barwon and Darling rivers. Flows in many catchments have been affected by high rates of water extraction for irrigation and mining. Some catchments discharge into wetlands and may join the Barwon–Darling system only during flood events. The Macquarie River is an example of this. Agriculture is a major user of water, along with town water supplies, stock and domestic use. These major catchments are heavily regulated, with large dams supplying irrigators and environmental flows.

Northern catchments in the NSW Murray–Darling Basin (those of the Macintyre, Gwydir and Namoi rivers) experience a subtropical climate pattern with intense summer rainfall caused by monsoonal influences. These catchments have extremely variable flows from year to year – the smallest flows during droughts can be 1% of the average flow, and flows during wet periods can be many times the average flow.

Central-west catchments (of the Castlereagh, Macquarie and Lachlan rivers) have a temperate and more uniform rainfall pattern. In some years, monsoonal summer rainfall systems can influence flows in these catchments. In other years, southern climate systems produce winter rainfall. These are areas where influences from northern and southern rainfall mechanisms overlap.

The southern Murray–Darling Basin catchments (of the Murray and Murrumbidgee rivers) have alpine areas which produce more runoff than do many other parts of the basin.

Typically these rivers never cease to flow, and peak flow very strongly aligns with the spring snow melt. Flows in the Murrumbidgee have been dramatically enhanced by the addition of water from the Snowy Mountains Hydro-electric Scheme. This scheme diverts water from the Snowy River into the Tumut River, which connects to the Murrumbidgee River and supports irrigators downstream in the Murrumbidgee Irrigation Area.

Western areas of NSW are characterised by an arid climate with irregular rainfall and high evaporative demand. Many of the high flows in these river systems emanate from flood events in Queensland that slowly flow down the Barwon–Darling river system. These flood events can cause substantial amounts of recharge to groundwater. Catchments in the far north-west of NSW lie outside the Murray–Darling Basin and either flow into Lake Eyre or are dispersed across the flat western landscapes.

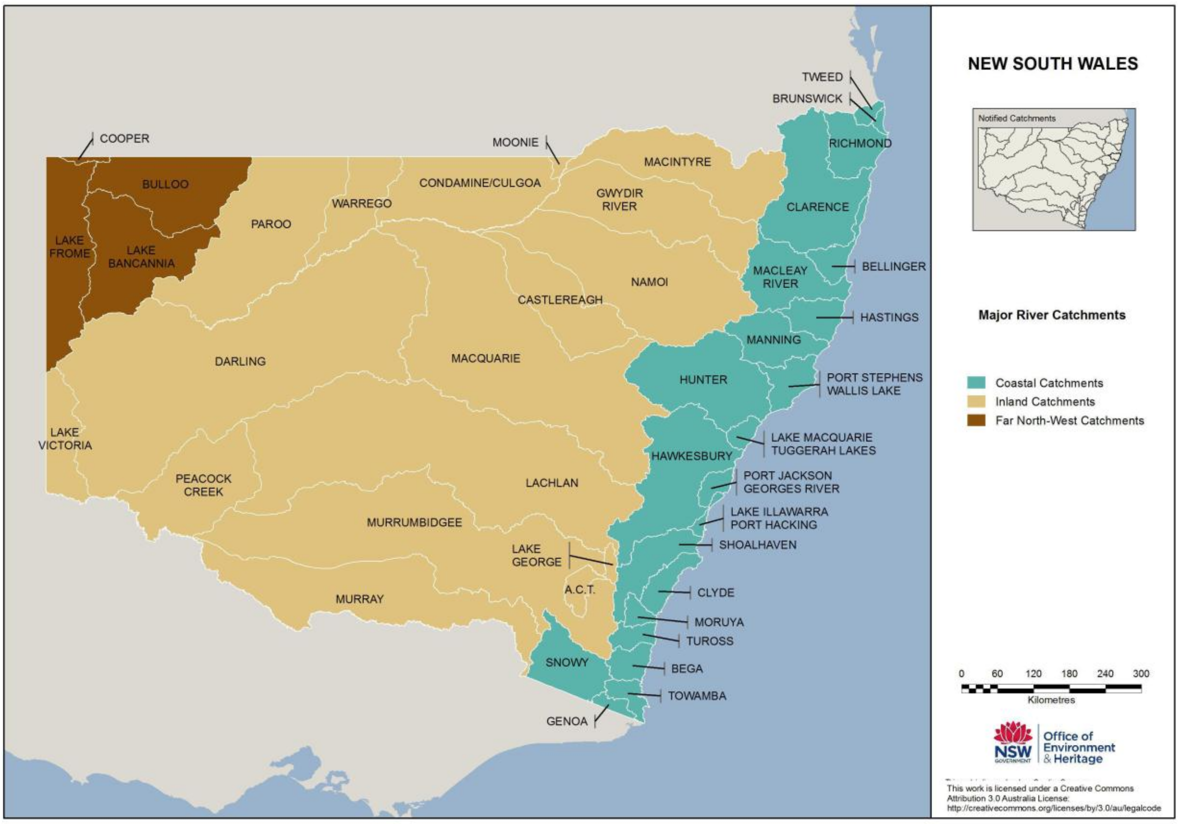


Figure 30. Map of major catchments

Changes in mean annual surface runoff, calculated as megalitres per catchment, are presented in Table 3. The major catchments of NSW have been grouped as the coastal, NSW part of the Murray–Darling Basin and far north-west regions. Changes in the far future are much greater, with higher surface runoff predicted in all catchments with the exception of the ACT and the Snowy River. In the near future, some coastal catchments are expected to have less runoff and others more runoff. The greatest predicted increases in surface runoff tend to be for central-coast catchments, and the most pronounced decreases for many north-coast and south-coast catchments. In the far future, all coastal catchments that flow to the east coast are likely to have more surface runoff, particularly the central-coast and north-coast catchments. Slightly less runoff is likely for the Snowy River, which discharges to the Victorian coast near Orbost.

The number of models in agreement with the overall multimodel mean trends provides an indication of the level of confidence in those trends. In the case of coastal catchments, there is generally more confidence in trends relating to far-future runoff than to trends in near-future runoff. For north-coast catchments, there is less agreement across the 12 models than there is for central-coast and south-coast catchments. There is more confidence in trends for inland catchments, especially when it comes to higher surface runoff in the far future. In the case of many inland catchments, 10 or 11 of the 12 models agree that surface runoff will increase in the far future.

In the central and northern catchments of the Murray–Darling Basin (e.g. those of the Macintyre, Gwydir, Namoi, Macquarie and Lachlan rivers), increases in surface runoff are predicted in the near future. In its southern catchments (e.g. of the Murrumbidgee and Peacock Creek) less surface runoff is expected. In the far future, all catchments are predicted to have much higher surface runoff, especially the Macintyre, Gwydir, Namoi, Condamine and Culgoa catchments in the north and the Macquarie and Lachlan catchments in the central west.

Table 3. Change in multimodel mean annual surface runoff volume (in megalitres) for the near future (2020–2039) and the far future (2060–2079) and number of models that agree with the trend of change

	Change in surface runoff		Number of models in agreement[1]	
	Near future	Far future	Near future	Far future
Coastal catchments				
Tweed	-2425	2222	7 of 12	7 of 12
Brunswick	-878	1376	7 of 12	7 of 12
Richmond	-1891	12871	7 of 12	7 of 12
Clarence	-21266	8129	8 of 12	7 of 12
Bellinger	-1676	12411	7 of 12	8 of 12
Macleay	-3942	12833	6 of 12	9 of 12
Hastings	3232	14340	6 of 12	9 of 12
Manning	-1902	12890	6 of 12	9 of 12
Port Stephens and Wallis Lake	3341	6071	7 of 12	9 of 12
Hunter	4064	18643	8 of 12	9 of 12
Lake Macquarie and Tuggerah Lakes	862	1628	7 of 12	7 of 12
Hawkesbury	1367	20525	6 of 12	9 of 12
Port Jackson and Georges River	638	2335	8 of 12	9 of 12
Lake Illawarra and Port Hacking	-119	589	8 of 12	8 of 12
Shoalhaven	-5234	1522	8 of 12	6 of 12
Clyde	-799	3428	5 of 12	8 of 12
Moruya	-2172	932	8 of 12	6 of 12
Tuross	-1746	1777	8 of 12	8 of 12
Towamba	-769	2512	7 of 12	10 of 12
Bega	-2383	3447	8 of 12	9 of 12
Genoa	-175	1433	6 of 12	9 of 12
Snowy	-5631	-793	7 of 12	7 of 12
NSW Murray–Darling Basin				
ACT	-2468	-2337	6 of 12	8 of 12
Castlereagh	6444	43639	9 of 12	10 of 12
Condamine and Culgoa	12132	73516	8 of 12	10 of 12
Darling	-3199	81792	6 of 12	10 of 12
Gwydir	15285	92338	7 of 12	9 of 12
Lachlan	3410	118924	7 of 12	11 of 12
Lake George	-239	190	8 of 12	7 of 12
Lake Victoria	-380	4710	7 of 12	10 of 12
Macintyre	8306	78678	6 of 12	9 of 12
Macquarie	23811	105402	9 of 12	10 of 12
Moonie	161	2527	7 of 12	11 of 12
Murray	1838	42199	7 of 12	10 of 12
Murrumbidgee	-10884	67054	7 of 12	10 of 12
Namoi	18718	117915	8 of 12	11 of 12
Paroo	1852	48223	6 of 12	9 of 12
Peacock Creek	-1114	13375	7 of 12	12 of 12
Warrego	1730	16250	7 of 12	10 of 12
Far north-west				
Bulloo	-333	18695	7 of 12	9 of 12
Cooper	-42	963	6 of 12	8 of 12
Lake Bancannia	39	34802	6 of 12	11 of 12
Lake Frome	585	19824	7 of 12	10 of 12

[1] Number of models in agreement refers to the number of model combinations that agree with the average trend, either positive or negative.

Changes in surface runoff are driven by changes in rainfall, with a non-linear response between rainfall and surface runoff. Percentage changes in mean annual rainfall and surface runoff for each catchment are shown in Table 4. The changes in mean annual runoff are generally larger than changes in rainfall.

For catchments along the central coast, small increases (0.9% to 11.0%) in surface runoff are likely in the near future (Table 4). North-coast catchments are showing small decreases in surface runoff in the near future (1.5% to 7.8%). Many south-coast catchments are likely to become drier, with up to 16% less runoff in the near future. In the far future, larger increases in surface runoff are likely for all coastal catchments with the exception of the Snowy River. Of particular interest are south-coast catchments, which show substantially less runoff in the near future but substantial percentage increases in surface runoff in the far future.

In the Murray–Darling Basin, less runoff in the near future is likely for the ACT and southern catchments, including the Murrumbidgee, Peacock Creek, Darling and Lake Victoria catchments, with reductions in runoff ranging from 1% to 6% (Table 4). In the near future, central-west and northern-inland catchments are showing increases in surface runoff of up to 5% (Macquarie). Changes in the far future are much greater, with higher surface runoff in all catchments. Of particular interest are the Macintyre, Gwydir and Namoi catchments in the north and the Macquarie and Lachlan catchments in the central west, with 20% to 29% more runoff in comparison to the 1990–2010 baseline (Table 4). Smaller percentage increases are modelled for southern catchments (Murray 14%; Murrumbidgee 10%), with the ACT being the only area with less predicted surface runoff in the far future (a reduction of 8.1%).

'Runoff ratio' is the ratio of mean annual surface runoff to mean annual surface rainfall. This is useful to explore changes in runoff response under a changing climate. Runoff ratios for each catchment in the near future and far future are shown in Table 5. An increase in runoff ratio is indicative of a change in rainfall patterns; higher runoff ratios can result from higher volumes of daily rainfall.

In the near future, runoff ratios are predicted to be similar to the baseline climate for most coastal catchments, and to be higher for inland catchments in the central and northern parts of the state (Table 5). In the far future, runoff ratios are predicted to be higher than the baseline climate for coastal catchments along the lower north coast and central coast (from Bellinger in the north to Port Jackson and Georges River in the south) and for the lower south coast south of Moruya catchment (Table 5). This is indicative of changing rainfall patterns, with higher volumes of rainfall occurring for some days. Higher runoff ratios are likely for all inland catchments in the far future (Table 5).

These trends for higher runoff ratios are in agreement with previous studies using different climate projections (e.g. Vaze & Teng 2011). Other future climate projections for this region also show that individual storm events are expected to become more extreme even if there is a decrease in average annual rainfall.

Table 4. Percent change in multimodel mean annual rainfall and surface runoff for the near future (2020–2039) and the far future (2060–2079)

	Rainfall		Surface runoff	
	Near future	Far future	Near future	Far future
Coastal catchments				
Tweed	0.7	7.3	-4.8	4.4
Brunswick	1.8	11.4	-7.8	12.2
Richmond	1.1	7.3	-1.5	9.9
Clarence	0.4	5.5	-5.3	2.0
Bellinger	1.5	10.5	-2.2	16.7
Macleay	0.6	6.1	-2.3	7.6
Hastings	2.0	9.1	3.5	15.6
Manning	1.5	7.3	-1.4	9.3
Port Stephens and Wallis Lake	1.8	8.7	11.0	20.0
Hunter	0.5	6.3	2.8	12.7
Lake Macquarie and Tuggerah Lakes	0.8	8.7	9.6	18.0
Hawkesbury	-0.1	6.1	0.9	13.4
Port Jackson and Georges River	0.5	8.7	5.5	20.0
Lake Illawarra and Port Hacking	-0.6	9.1	-2.9	14.5
Shoalhaven	-1.7	3.1	-9.7	2.8
Clyde	-0.6	7.6	-4.1	17.5
Moruya	-2.8	3.0	-16.0	6.8
Tuross	-2.1	4.8	-16.0	16.3
Towamba	-1.1	3.8	-7.9	25.9
Bega	-1.6	5.1	-13.8	19.9
Genoa	-1.5	-0.1	-3.2	25.9
Snowy	-2.1	-3.0	-5.6	-0.8
NSW Murray–Darling Basin				
ACT	-2.9	-1.3	-8.6	-8.1
Castlereagh	-0.3	7.9	3.4	23.3
Condamine and Culgoa	1.6	11.5	4.7	28.2
Darling	-0.4	7.4	-0.9	23.8
Gwydir	0.8	7.4	3.8	22.9
Lachlan	-0.3	6.1	0.8	29.2
Lake George	-2.2	0.4	-5.9	4.7
Lake Victoria	-1.8	3.0	-2.1	25.9
Macintyre	0.9	6.3	2.1	20.0
Macquarie	-0.1	7.5	5.1	22.6
Moonie	-0.4	9.7	1.8	27.6
Murray	-1.2	0.7	0.6	13.9
Murrumbidgee	-1.4	1.8	-2.1	13.0
Namoi	0.7	7.9	4.1	25.5
Paroo	1.7	10.6	0.9	23.6
Peacock Creek	-1.8	4.8	-2.4	29.4
Warrego	2.0	11.8	3.0	28.1
Far north-west				
Bulloo	1.9	10.1	-0.4	21.4
Cooper	1.0	10.0	-1.0	23.7
Lake Bancannia	-0.4	9.1	0.0	25.8
Lake Frome	-0.9	8.8	1.0	34.4

Table 5. Runoff ratios for the near future (2020–2039) and the far future (2060–2079)

	Runoff ratio		
	Baseline	Near future	Far future
Coastal catchments			
Tweed	0.16	0.15	0.16
Brunswick	0.10	0.09	0.10
Richmond	0.10	0.10	0.11
Clarence	0.10	0.10	0.10
Bellinger	0.10	0.11	0.12
Macleay	0.09	0.09	0.10
Hastings	0.13	0.13	0.14
Manning	0.11	0.11	0.11
Port Stephens and Wallis Lake	0.05	0.06	0.06
Hunter	0.06	0.07	0.07
Lake Macquarie and Tuggerah Lakes	0.04	0.05	0.05
Hawkesbury	0.06	0.06	0.07
Port Jackson and Georges River	0.06	0.07	0.07
Lake Illawarra and Port Hacking	0.03	0.03	0.03
Shoalhaven	0.07	0.06	0.07
Clyde	0.05	0.05	0.06
Moruya	0.08	0.07	0.09
Tuross	0.05	0.05	0.06
Towamba	0.04	0.04	0.05
Bega	0.05	0.05	0.07
Genoa	0.03	0.03	0.04
Snowy	0.06	0.06	0.07
NSW Murray–Darling Basin			
ACT	0.09	0.09	0.09
Castlereagh	0.14	0.15	0.16
Condamine and Culgoa	0.14	0.16	0.17
Darling	0.06	0.06	0.07
Gwydir	0.16	0.17	0.19
Lachlan	0.07	0.07	0.09
Lake George	0.05	0.05	0.05
Lake Victoria	0.05	0.04	0.05
Macintyre	0.14	0.16	0.17
Macquarie	0.08	0.09	0.10
Moonie	0.11	0.12	0.14
Murray	0.08	0.08	0.10
Murrumbidgee	0.09	0.09	0.10
Namoi	0.12	0.13	0.15
Paroo	0.10	0.10	0.11
Peacock Creek	0.05	0.04	0.05
Warrego	0.08	0.09	0.10
Far north-west			
Bulloo	0.09	0.09	0.10
Cooper	0.13	0.12	0.14
Lake Bancannia	0.13	0.13	0.15
Lake Frome	0.07	0.06	0.08

Changes in recharge to groundwater are also driven by changes in rainfall with a non-linear response between rainfall and surface runoff. Percentage changes in mean annual rainfall and recharge for each catchment are shown in Table 6. As was the case for surface runoff, the changes in mean annual recharge are larger than changes in rainfall.

In the near future, recharge is expected to be less in coastal areas, with the exception of some catchments along the far north coast. Less recharge is likely for many central-coast and south-coast catchments. In the Murray–Darling Basin, almost all catchments are likely to have less recharge in the near future. Largest reductions occur in southern catchments. In the far future, recharge is expected to be higher in most coastal areas, with the largest increases along the far north coast (in the Brunswick, Bellinger and Tweed River catchments). In the Murray–Darling Basin, almost all catchments are likely to have more recharge in the far future. The exception is in the southern catchments (Murray, Murrumbidgee, Lake George and Peacock Creek), where recharge is likely to be lower.

Table 6. Percent change in multimodel mean annual rainfall and recharge for the near future (2020–2039) and the far future (2060–2079)

	Rainfall		Recharge	
	Near future	Far future	Near future	Far future
Coastal catchments				
Tweed	0.7	7.3	4.2	18.3
Brunswick	1.8	11.4	7.0	36.2
Richmond	1.1	7.3	3.2	17.5
Clarence	0.4	5.5	-0.5	4.5
Bellinger	1.5	10.5	0.0	20.7
Macleay	0.6	6.1	-3.4	2.9
Hastings	2.0	9.1	-0.2	13.0
Manning	1.5	7.3	-3.1	6.8
Port Stephens and Wallis Lake	1.8	8.7	0.0	16.5
Hunter	0.5	6.3	-8.6	11.2
Lake Macquarie and Tuggerah Lakes	0.8	8.7	-6.6	8.7
Hawkesbury	-0.1	6.1	-9.3	5.6
Port Jackson and Georges River	0.5	8.7	-16.3	13.2
Lake Illawarra and Port Hacking	-0.6	9.1	-10.3	11.5
Shoalhaven	-1.7	3.1	-18.0	-4.8
Clyde	-0.6	7.6	-16.8	11.3
Moruya	-2.8	3.0	-23.1	-0.4
Tuross	-2.1	4.8	-17.9	8.2
Towamba	-1.1	3.8	-19.1	9.6
Bega	-1.6	5.1	-20.8	7.9
Genoa	-1.5	-0.1	-14.1	2.1
Snowy	-2.1	-3.0	-9.7	-13.8
NSW Murray–Darling Basin				
ACT	-2.9	-1.3	-13.2	-12.1
Castlereagh	-0.3	7.9	-8.0	15.0
Condamine and Culgoa	1.6	11.5	5.0	30.8
Darling	-0.4	7.4	-1.3	33.2
Gwydir	0.8	7.4	-4.0	4.4
Lachlan	-0.3	6.1	-3.4	18.4
Lake George	-2.2	0.4	-15.2	-9.9
Lake Victoria	-1.8	3.0	-2.0	19.2
Macintyre	0.9	6.3	-1.4	3.9
Macquarie	-0.1	7.5	-5.1	19.6
Moonie	-0.4	9.7	-7.0	30.0
Murray	-1.2	0.7	-4.7	-6.3
Murrumbidgee	-1.4	1.8	-8.0	-5.8
Namoi	0.7	7.9	-7.0	11.8
Paroo	1.7	10.6	5.1	31.8
Peacock Creek	-1.8	4.8	-6.8	27.4
Warrego	2.0	11.8	6.6	34.6
Far north-west				
Bulloo	1.9	10.1	1.8	27.8
Cooper	1.0	10.0	-3.1	25.4
Lake Bancannia	-0.4	9.1	-2.2	26.6
Lake Frome	-0.9	8.8	-5.7	27.8

3.4 Summary of changes by State Planning Region

Designated planning regions (shown in Figure 31) are the areas adopted by the NSW Government for regional growth plans. The impacts of climate change on each planning region are predicted by comparing mean annual surface runoff and recharge during the baseline period (1990–2009) with those expected in the near future (2020–2039) and far future (2060–2079).

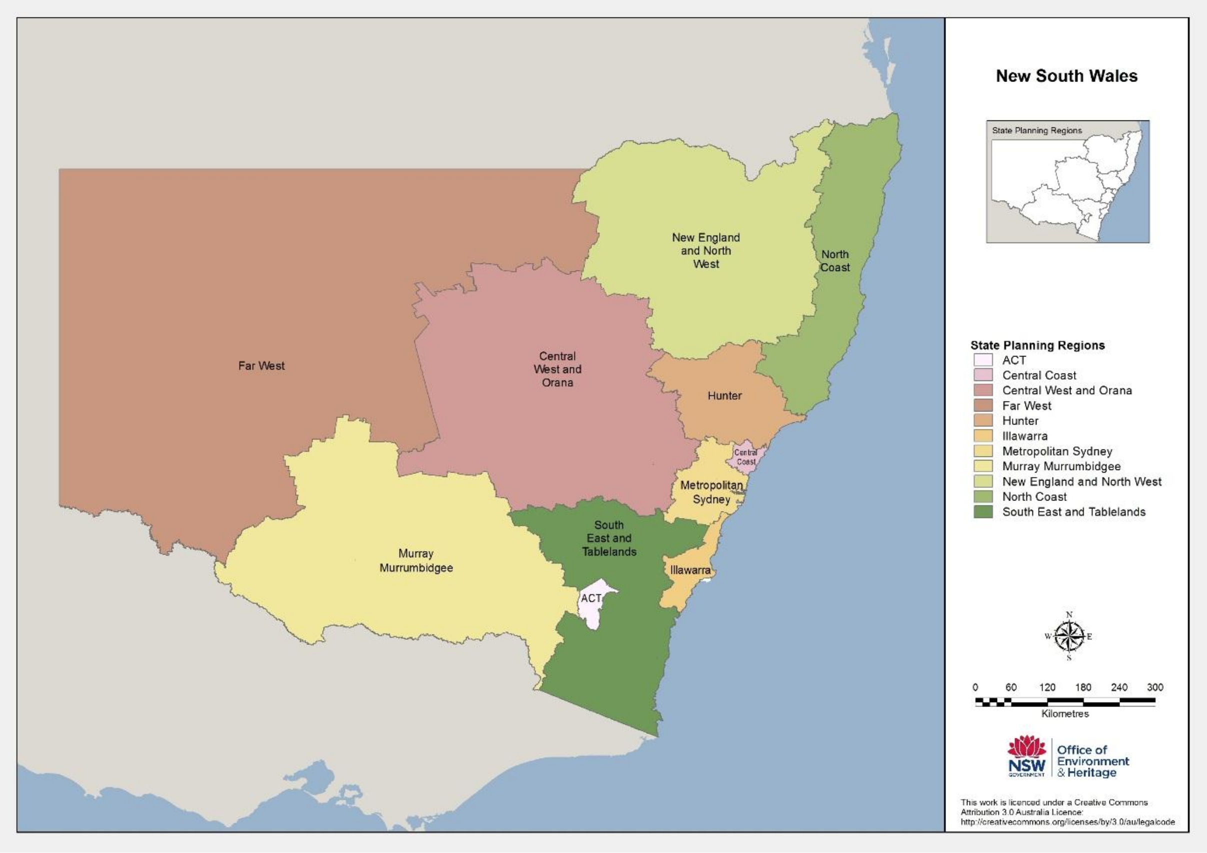


Figure 31. Map of state planning regions

Changes in surface runoff and recharge will be driven by changes in rainfall. The non-linearity of the response between rainfall and either surface runoff or recharge is demonstrated in Table 7. In all cases, the percent change in either mean annual runoff or mean annual recharge is greater than the change in rainfall, typically two to four times the change in rainfall.

In the near future, changes to mean rainfall across a planning region are less than +/- 3% (Table 7). A drying trend is likely for southern planning regions (i.e Murray Murrumbidgee, South East and Tablelands, Illawarra) and the ACT. Largest increases in surface runoff are likely for the Sydney area and the Central Coast. In contrast, recharge is expected to be lower for Sydney and the Central Coast.

In the far future, higher rainfall and surface runoff are likely across all state planning regions (Table 7) in NSW. Recharge will generally increase, except in the Murray Murrumbidgee and South East and Tablelands. Increases in surface runoff of more than 20% are likely for the Central West and Orana and the Far West. In the ACT, less surface runoff and recharge are predicted for both the near and far futures.

Table 7. Percent changes to multimodel mean annual rainfall, surface runoff and recharge for the near future (2020-2039) and the far future (2060-2079)

	Percent change in near future			Percent change in far future		
State planning region	**Rainfall**	**Runoff**	**Recharge**	**Rainfall**	**Runoff**	**Recharge**
ACT	-2.9	-8.6	-13.2	-1.3	-8.1	-12.1
Central Coast	0.4	10.6	-4.2	7.7	17.1	8.8
Central West and Orana	-0.2	3.2	-5.5	7.1	23.0	17.4
Far West	0.3	1.8	0.2	8.7	26.3	30.7
Hunter	0.7	2.8	-8.1	6.4	11.9	8.9
Illawarra	-0.9	-5.5	-13.9	7.0	12.5	6.6
Metropolitan Sydney	0.4	4.0	-5.0	8.1	17.6	12.5
Murray Murrumbidgee	-1.1	-0.4	-5.6	2.3	17.5	-3.4
New England and North West	0.7	1.7	-3.1	6.4	17.6	4.0
North Coast	1.1	-2.4	0.5	8.0	10.0	14.0
South East and Tablelands	-1.8	-6.1	-12.4	1.3	7.0	-6.7

The largest volumes of surface runoff are estimated for the North Coast and New England and North West planning regions (Figure 32), especially during summer and autumn. During autumn, surface runoff is likely to increase across all planning regions. However, during spring, less surface runoff is likely in both southern planning regions (Murray Murrumbidgee and South East and Tablelands) and the ACT.

Similar seasonal trends in changes in recharge are likely, with more recharge in autumn across all planning regions and less recharge during spring in southern NSW (Figure 33).

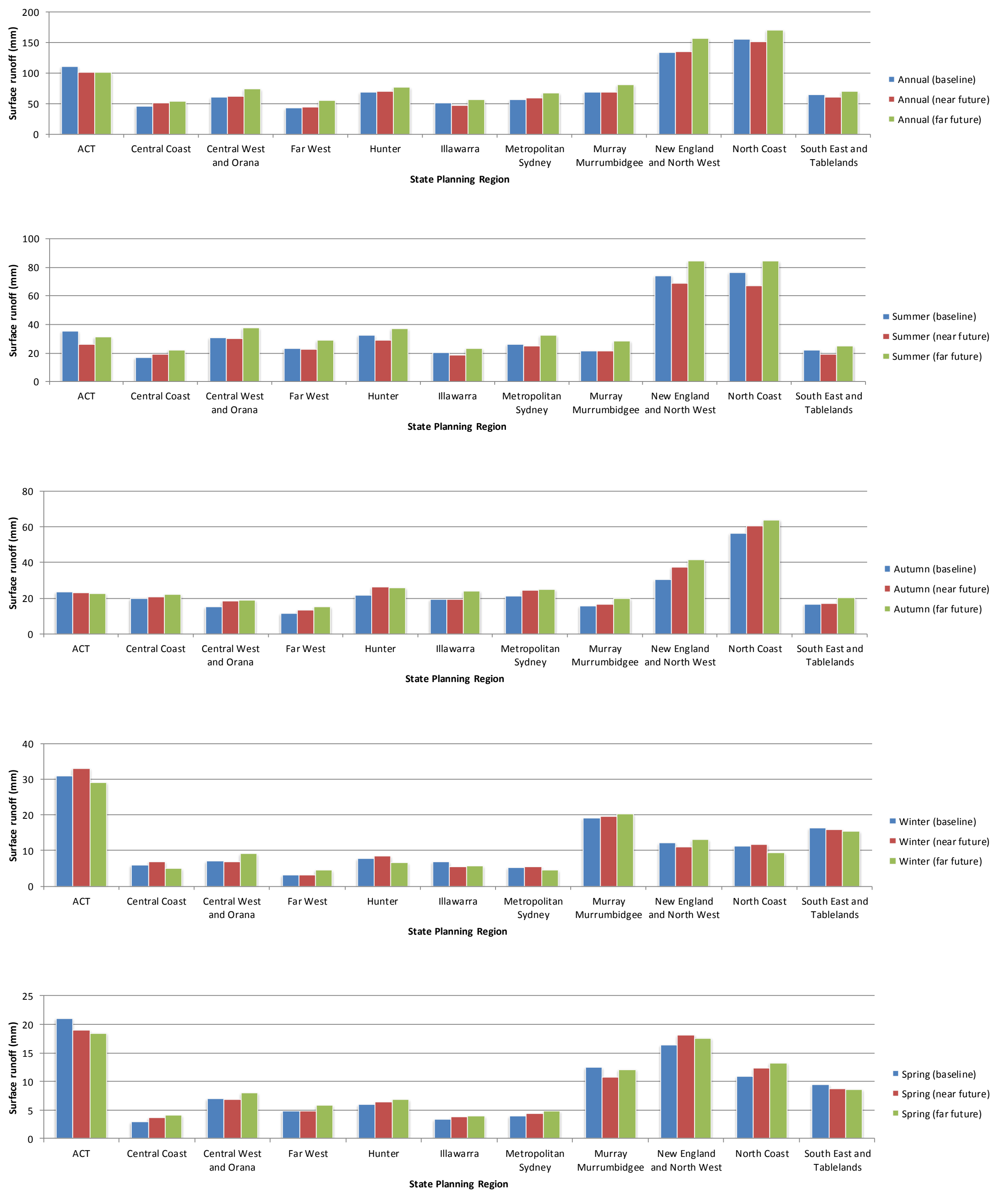


Figure 32. Annual and seasonal mean annual surface runoff for each planning region for baseline climate (1990–2009), near future (2020–2039) and far future (2060–2079)

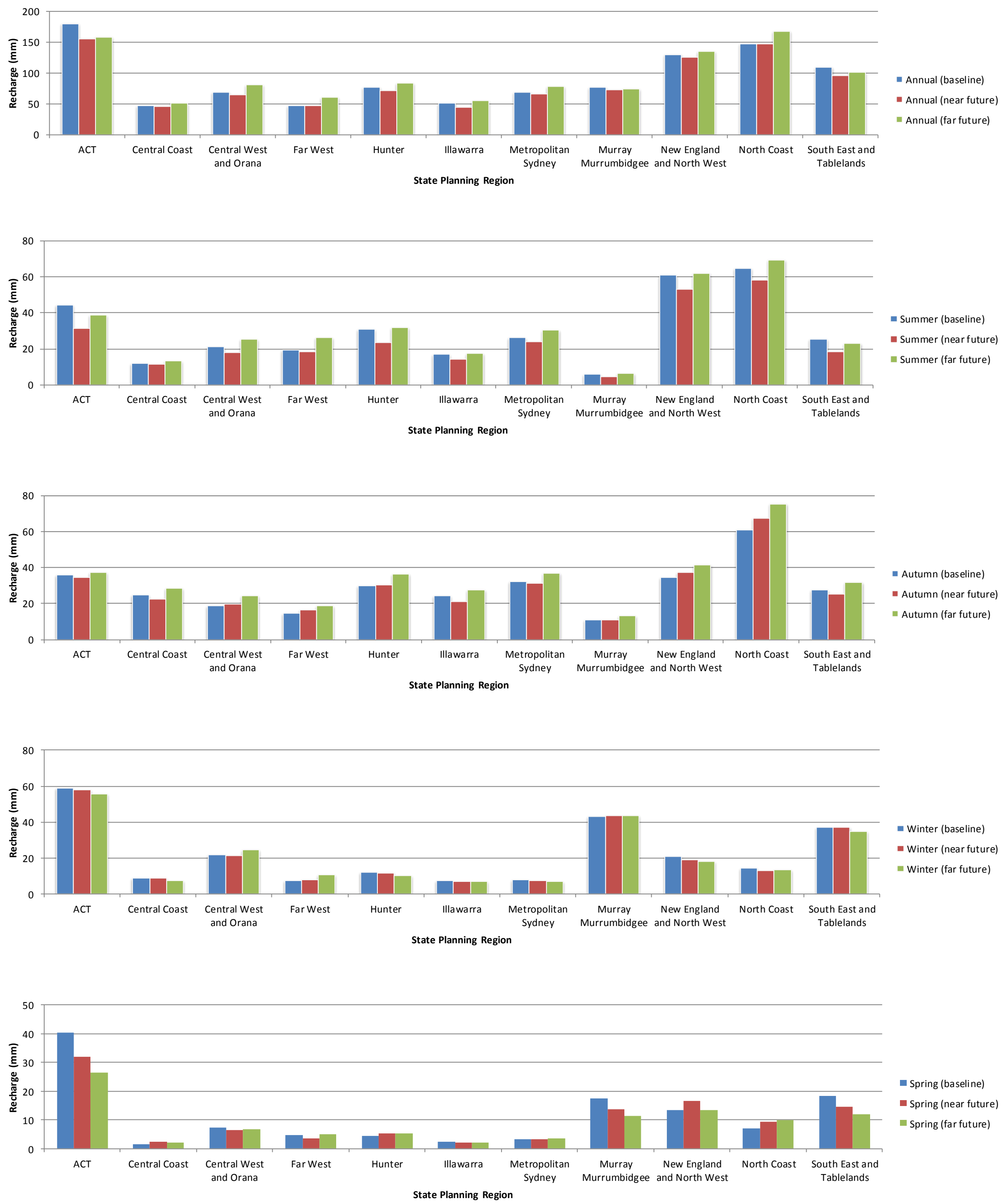


Figure 33. Annual and seasonal mean annual recharge for each planning region for baseline climate (1990–2009), near future (2020–2039) and far future (2060–2079)

3.5 Summary of change by Local Land Services area

Local Land Services (LLS) areas were created to deliver agricultural advice, enhance natural resource management, protect industries from pests and disease and help communities respond to flood, fire and drought. NSW has 11 LLS areas as shown in Figure 34.

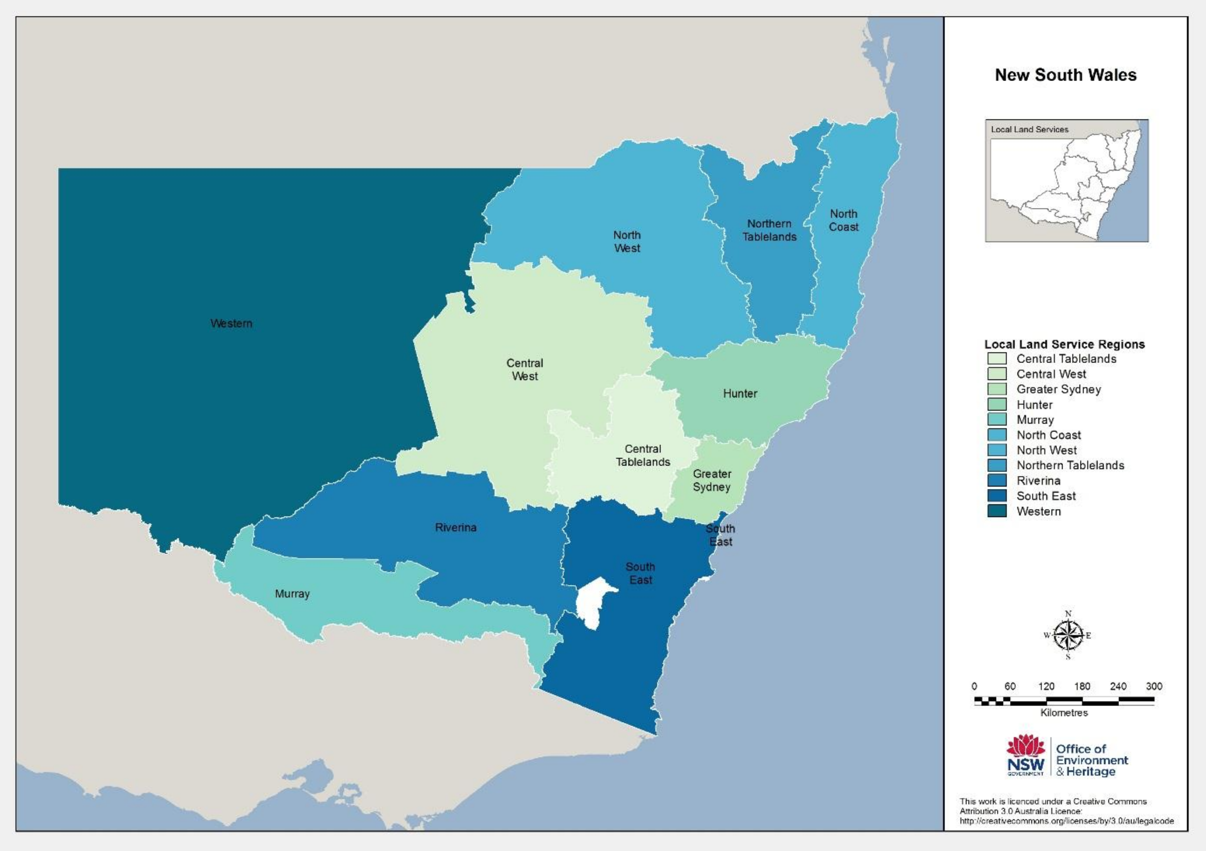


Figure 34. Map of Local Land Services areas

Percentage changes in mean annual rainfall, surface runoff and recharge for each LLS in the near future and far future are shown in Table 8. In addition, mean annual values of runoff and recharge for each LLS for the near future and far future are presented in Figures 35 and 36 and compared to the baseline.

In the near future, southern LLS areas (Riverina and South East) and northern LLS areas (Northern Tablelands and North Coast) are likely to have between 1% and 6% less surface runoff. Surface runoff is likely to increase by 1% to 5% in most other LLS areas. Recharge is likely to decrease in all LLS areas, except for the Western LLS and the North Coast LLS.

In the far future, all LLS areas are likely to have more surface runoff, with increases ranging from 6% (South East) to 26% (Western). Recharge is expected to be less for southern LLS areas (Murray, Riverina and South East) and higher for other LLS areas, by up to 31% (Western).

Table 8. Percent change in multimodel mean annual rainfall, surface runoff and recharge for each LLS area in the near future (2020–2039) and the far future (2060–2079)

	Rainfall		Runoff		Recharge	
Local Land Services area	Near future	Far future	Near future	Far future	Near future	Far future
Central Tablelands	-0.9	5.2	-1.5	16.1	-9.3	5.8
Central West	0.1	8.0	4.6	25.2	-2.8	25.6
Greater Sydney	0.4	8.0	4.8	17.5	-4.9	12.0
Hunter	1.1	7.2	2.3	12.6	-5.4	10.7
Murray	-1.2	0.7	1.1	14.1	-4.8	-7.4
North Coast	0.9	7.8	-3.3	9.3	0.8	14.1
North West	0.9	8.6	4.4	25.8	-4.6	13.0
Northern Tablelands	0.6	4.8	-1.3	7.0	-2.3	1.4
Riverina	-1.1	3.1	-1.4	18.6	-6.8	-0.6
South East	-1.7	1.7	-6.4	6.5	-12.6	-6.4
Western	0.2	8.4	0.7	25.9	0.2	30.8

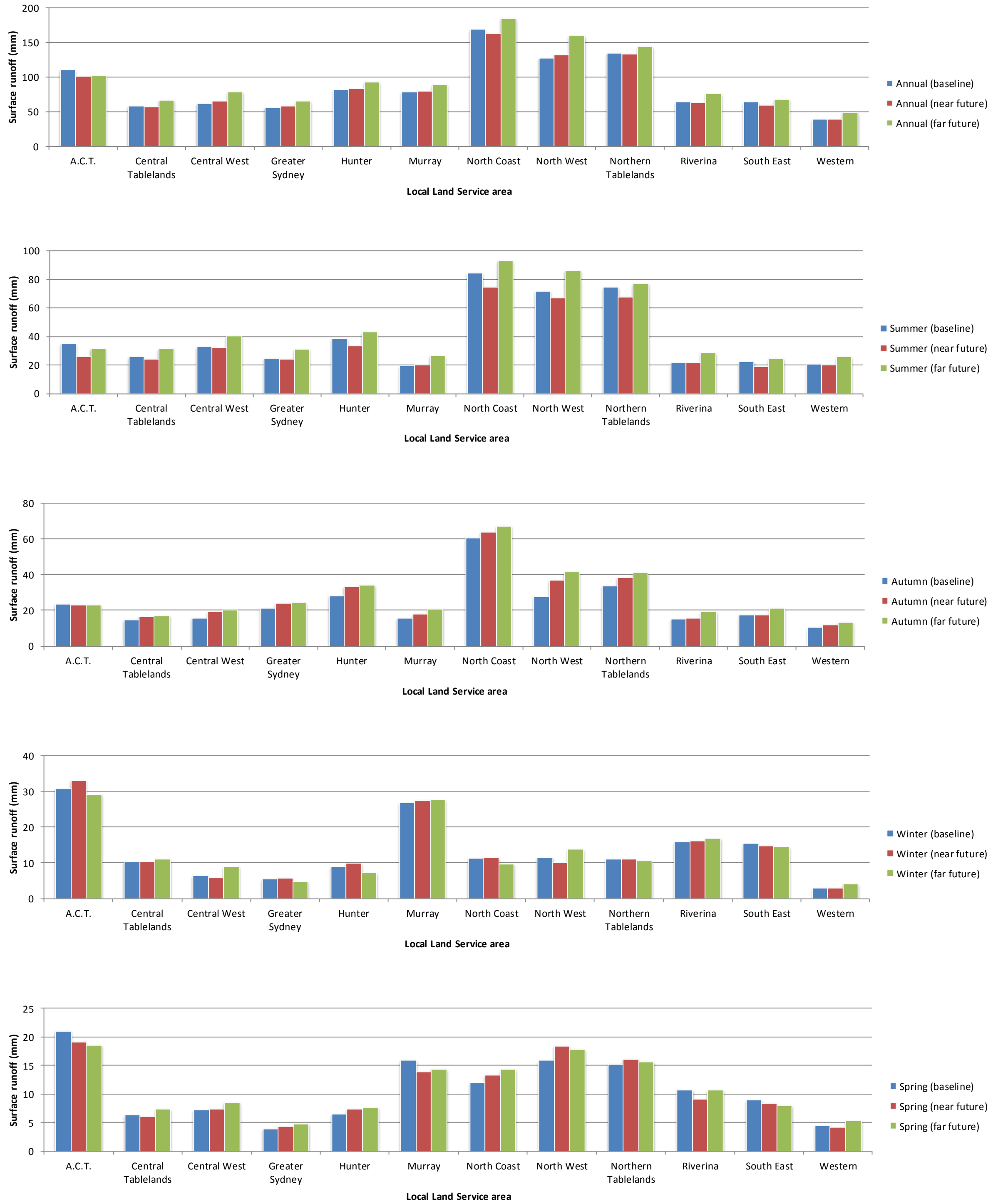


Figure 35. Annual and seasonal mean annual surface runoff for each LLS area for baseline climate (1990–2009), near future (2020–2039) and far future (2060–2079)

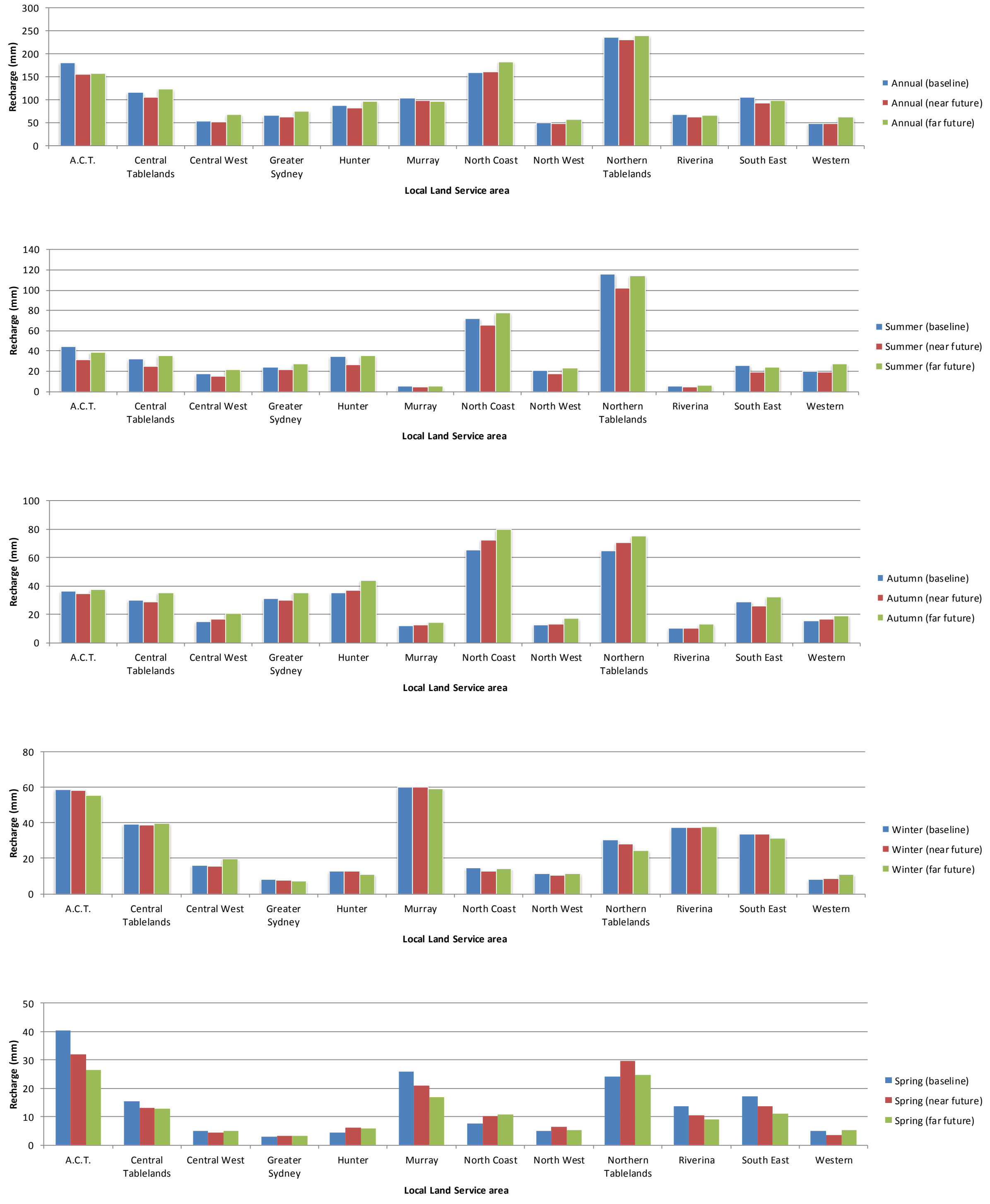


Figure 36. Annual and seasonal mean annual recharge for each LLS area for baseline climate (1990–2009), near future (2020–2039) and far future (2060–2079)

4. Summary of key impacts

There are a number of major impacts identified in this study. The impacts related to surface runoff include the following:

- Changes in surface runoff in the near future are likely to be small compared to changes in the far future.
- In the near future, southern areas of NSW are likely to have small reductions in runoff, while the central and northern areas of the state have small increases.
- In the far future, more surface runoff is likely across much of the state with the exception of the southern areas of NSW, which are likely to have less runoff.
- Large reductions in surface runoff are likely in the alpine areas of southern NSW; these reductions are predicted to be highest in the far future.
- Across most of NSW, higher surface runoff in autumn months is expected due to higher autumn rainfall.
- In southern parts of NSW, significant drying during spring months is expected, resulting in less surface runoff during spring.

The impacts related to recharge to groundwater include that:

- Changes in recharge in the near future are small compared to changes in the far future.
- In the near future, less recharge is predicted across much of NSW, especially in the south east of the state.
- Considerably less recharge is likely in alpine areas.
- Some areas of western NSW show a predicted slight increase in recharge but these increases are relatively small.
- In the far future, more recharge is likely across much of the state with the exception of alpine areas, where very large reductions in recharge are predicted.
- In the far future, the majority of models predict increases in recharge in summer, autumn and winter, with the largest increases in the summer months.

The impacts in the far future are more significant with more surface runoff and recharge likely across much of the state. The main exception is the southern areas of NSW, which are likely to have less runoff and recharge. The largest reductions in both surface runoff and recharge are likely in the alpine areas of southern NSW. These reductions are highest in the far future.

Two key impacts relating to seasonal patterns of runoff and recharge are predicted. Across most of NSW, higher runoff and recharge in autumn months is likely, due to higher autumn rainfall. In the southern parts of the state, significant drying during spring months is likely, resulting in less spring runoff and recharge.

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