Climate Change Impacts on Rainfall Erosivity and Hillslope Erosion in New South Wales

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Executive summary

There are considerable seasonal and inter-annual changes in rainfall amount and intensity in South-East Australia (SEA). Consequently, soil erosion rates may be expected to change in response to changes in the erosive power of rainfall, known as rainfall erosivity. Recently, the downscaled 10 km rainfall projections from the NSW and ACT Regional Climate Modelling (NARCliM) project have become available for the SEA region for the baseline (1990–2009), near future (2020–2039) and far future (2060–2079) periods. The aim of this study was to model and assess the impacts of climate (rainfall) change on rainfall erosivity and hillslope erosion risk in SEA based on the NARCliM projections from all 12 model member ensembles. Outcomes from this study are to assist in long-term climate change adaptation and regional planning such as in the NSW state planning regions (SPRs).

A daily rainfall erosivity model specifically developed for SEA has been used to calculate monthly and annual rainfall erosivity values using NARCliM projected daily rainfall data for the baseline and future periods. Monthly and annual hillslope erosion risks for the same periods were estimated using the Revised Universal Soil Loss Equation (RUSLE). Finer scale (100 m) surfaces of rainfall erosivity and hillslope erosion have been produced using spatial interpolation techniques. Automated scripts in a geographic information system (GIS) have been developed to calculate the time-series rainfall erosivity and hillslope erosion so that the processes of large quantity NARCliM data are realistic, repeatable and portable.

Adequate random sampling points were used to sample and assess the accuracy of the modelled rainfall erosivity from the NARCliM projections. The GIS modelled mean annual rainfall erosivity values using the NARCliM projected daily rainfall were compared with those calculated using the gridded daily rainfall data from the Bureau of Meteorology for the baseline period (1990–2009). The overall coefficient of efficiency (E_c) is 0.9753 (R^2 = 0.9762), and RMSE is 13.2% or 143 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$), indicating the relative size of the error bars from the 1:1 line.

The modelled baseline annual rainfall erosivity in NSW varies from less than 300 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) on parts of western NSW to over 15,000 on parts of the North Coast, with a mean of 1112. Both rainfall erosivity and hillslope erosion risk are predicted to increase by about 7% in the near future, and by about 19% in the far future, compared with the baseline period. The change is highly uneven in space and time; the high erosion risk areas are predicted to be the Central Coast, North Coast and Hunter regions, particularly in summer time.

Overall, the hillslope erosion on NSW agricultural and plantation lands is expected to increase only slightly, largely due to their generally flat topography. The lands with ‘Intensive uses’ will have a high erosion risk due to the combined effects of terrain and rainfall erosivity. The ‘hot-spot’ erosion risk areas have been identified and mapped to assist decision-makers to develop the best management practices.

1. Introduction

Climates in NSW are highly variable, ranging from subtropical in the north-east part with summer-dominated rainfall to temperate climates with uniform or moderately winter rainfall in the southern part. The temporal and spatial variations in rainfall have enormous implications for soil conservation, food security, and natural resource management. One of the key climate drivers for soil erosion and land degradation is rainfall erosivity or R-factor, as defined in the Revised Universal Soil Loss Equation (RUSLE, Renard et al. 1997).

Rainfall erosivity is largely a function of rainfall amount and peak rainfall intensity, and the R-factor, in units of $MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$, is a multi-annual average index that measures rainfall's kinetic energy and intensity to describe the effect of rainfall on sheet and rill erosion (Renard et al. 1997). Among the factors used within RUSLE and its earlier version, the Universal Soil Loss Equation (USLE), rainfall erosivity is of high importance as precipitation is the driving force of erosion and has a direct impact on the detachment of soil particles, the breakdown of aggregates and the transport of eroded particles via runoff. A precise assessment of rainfall erosivity requires recordings of precipitation at short time intervals (1–60 minutes) for a period of at least several years. The rainfall erosivity is calculated by multiplying the kinetic energy by the maximum rainfall intensity during a period of 30 minutes for each rainstorm. The R-factor accumulates the rainfall erosivity of individual rainstorm events and averages this value over multiple years. When factors other than rainfall are held constant, soil losses due to water erosion are directly proportional to the level of rainfall erosivity (Wischmeier & Smith 1978). When using the RUSLE, the R-factor is multiplied with other component factors relating to slope and slope-length (LS-factor), soil erodibility (K-factor), groundcover (C-factor) and soil conservation practices (P-factor) to predict the average annual soil loss per unit area.

Hillslope erosion is the major form of water erosion including sheet and rill erosion, and it has been identified as a significant emerging threat in NSW. The erosion information (hazard or risk, in units of $t.ha^{-1}.year^{-1}$) is required for informed target setting to protect and conserve land and biodiversity. In NSW, hillslope erosion risk (or the likelihood of) maps are routinely used in land-use planning, water quality monitoring, catchment management and forestry planting and harvesting operations. For example, hillslope erosion risk maps have been used to help assess the relative degree of constraints for various land-use purposes (Yang et al. 2008) and streamlined environmental assessment for bush fire hazard reduction work (Brompton et al. 2006).

Earlier work on rainfall erosivity in NSW was focused on the R-factor values calculated using pluviograph data at selected sites, and empirical relationships between the R-factor and rainfall intensity were used to map rainfall erosivity (Rosewell & Turner 1992; Rosewell 1993). Isoerodent rainfall erosivity maps for NSW so produced are static in nature, and unable to capture the seasonal and inter-annual variability in rainfall erosivity.

While changes in rainfall amount and intensity are expected to have significant effects on rainfall erosivity and hillslope erosion, the magnitude of the impact is not well quantified because of the non-linear nature of the relationship between rainfall amount and rainfall erosivity, and the extreme nature of large erosive events. Natural resource management targets can be more easily achieved if the hillslope erosion hazard and land degradation is well understood, and if the mean as well as extreme erosivity values are accurately mapped at a range of temporal and spatial scales. The high resolution R-factor maps, in both spatial and temporal contexts, can provide detailed information for climate (rainfall) impact assessment, and inform measurable and cost-effective means in sheet erosion identification and rehabilitation.

A daily erosivity model has been developed and the required parameter values can be estimated from long-term climate averages or geographical attributes to allow efficient large-scale erosion assessment (Yu & Rosewell 1996; Yu 1998, Lu & Yu 2002). The technology has been widely used to estimate the magnitude and spatial distribution of hillslope erosion at a range of temporal and spatial scales (Lu & Yu 2002; Lu et al. 2003), and for assessment of the impact of projected future climates on hillslope erosion and catchment health in NSW (Yang et al. 2015). With the regional relationship for model parameters (Yu 1998; Lu & Yu 2002), rainfall erosivity can now be estimated with gridded daily rainfall data anywhere in Australia. The improved rainfall erosivity model (Yang & Yu 2015) may also have the potential to predict spatial and temporal changes of rainfall erosivity and hillslope erosion risk using future climate projections.

NARCliM (NSW and ACT Regional Climate Modelling) funded by the NSW Office of Environment and Heritage (OEH) is an initiative to produce regional climate projections for South-East Australia. Twelve climate member ensembles were used to provide robust and unbiased projections that span the range of likely future changes in climate. A wide variety of climate variables have been made available at high temporal and spatial resolution for use in impacts and adaptation research including precipitation at daily and hourly steps which are the major input data in this study.

The aim of this study was to model and assess the impacts of climate (rainfall) change on rainfall erosivity and hillslope erosion across South-East Australia (SEA) based on simulations from the NARCliM project, and produce finer scale (up to 100-m resolution) time-series R-factor maps using spatial interpolation techniques. This report outlines the data and methods used to produce the time series of rainfall erosivity maps for NSW and SEA, and the impact assessment of baseline and future rainfall on erosivity and hillslope erosion risk in the state planning regions (SPR) of NSW.

2. Data and methods

2.1 Study area and input data sets

The NARCliM model domain is bounded by 21.669º–39.749ºS and 132.724º–165.725ºE (Evans et al. 2014). SEA is the landmass area within the NARCliM model domain (Figure 1). There are 124 rainfall pluviograph sites within SEA which can be used for model development, such as the geo-referenced model parameters (Yang & Yu 2015) representing the regional relationships and spatial distribution.

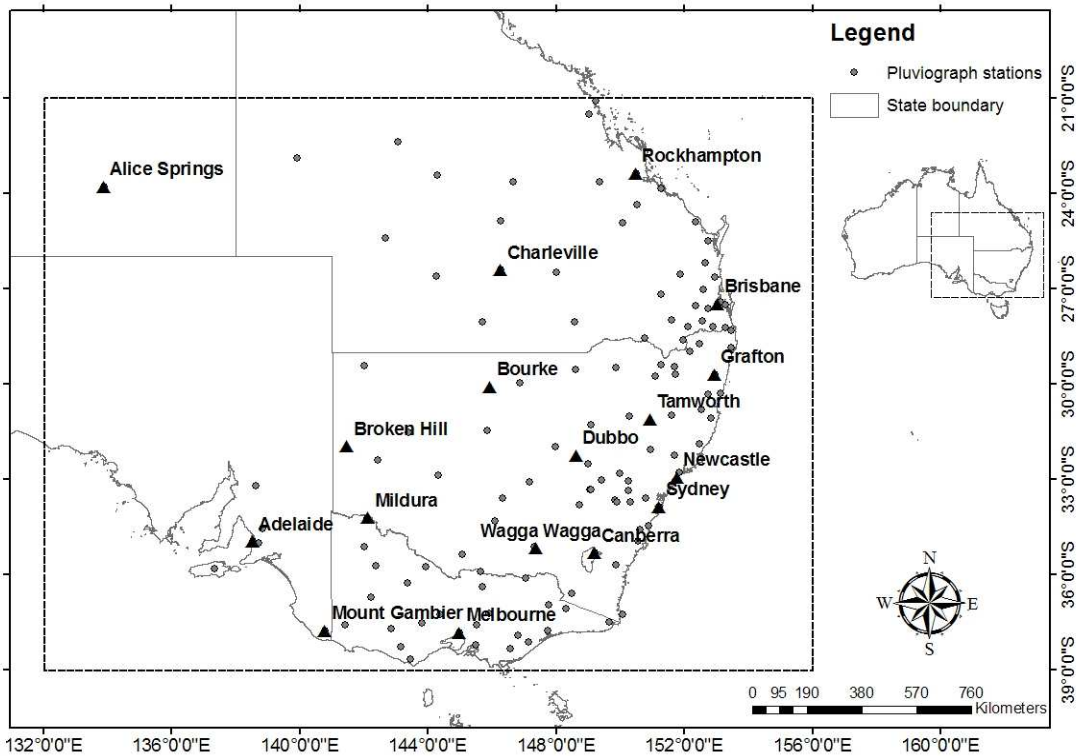

Figure 1: The South-East Australia (SEA) landmass area and the locations of rainfall pluviograph sites within SEA used to develop the daily rainfall erosivity model

The input data sets include: 1) NARCliM projected daily rainfall with bias correction for all 12 member ensembles (see Table 1) from four Global Climate Models (GCMs) and three Regional Climate Models (RCMs) for all three time slides (1990–2009, 2020–2039, 2060–2079); 2) Gridded Daily Rainfall (Bureau of Meteorology 2009) for historical periods (1910–2013, 1961–1990, 1990–2009) as a reference or baseline; 3) 1-second (about 30 m) hydrologically corrected Digital Elevation Model (DEM-H, Gallant et al. 2011); and 4) NSW Great Soil Groups (GSG) map and Soil and Land Information System (SALIS).

Table 1: NARCliM 12 member ensembles

ID	Ensembles	GCM	RCM
M1	CCCMA31_R1	CGCM 3.1	R1
M2	CCCMA31_R2	CGCM 3.1	R2
M3	CCCMA31_R3	CGCM 3.1	R3
M4	CSIROMK30_R1	CSIRO mk3.0	R1
M5	CSIROMK30_R2	CSIRO mk3.0	R2
M6	CSIROMK30_R3	CSIRO mk3.0	R3
M7	ECHAM5_R1	ECHAM5	R1
M8	ECHAM5_R2	ECHAM5	R2
M9	ECHAM5_R3	ECHAM5	R3
M10	MIROC32_R1	MIROC-medres 3.2	R1
M11	MIROC32_R2	MIROC-medres 3.2	R2
M12	MIROC32_R3	MIROC-medres 3.2	R3

For reporting purposes, the spatial variation and comparisons are focused on state planning regions (SPRs) of NSW (Figure 2). NSW Regional Action Plans focus on actions the NSW Government will take to improve outcomes in each region. In addition, SPRs, land use and bioregions are also used in the impact assessment and comparisons of changes in rainfall erosivity and hillslope erosion.

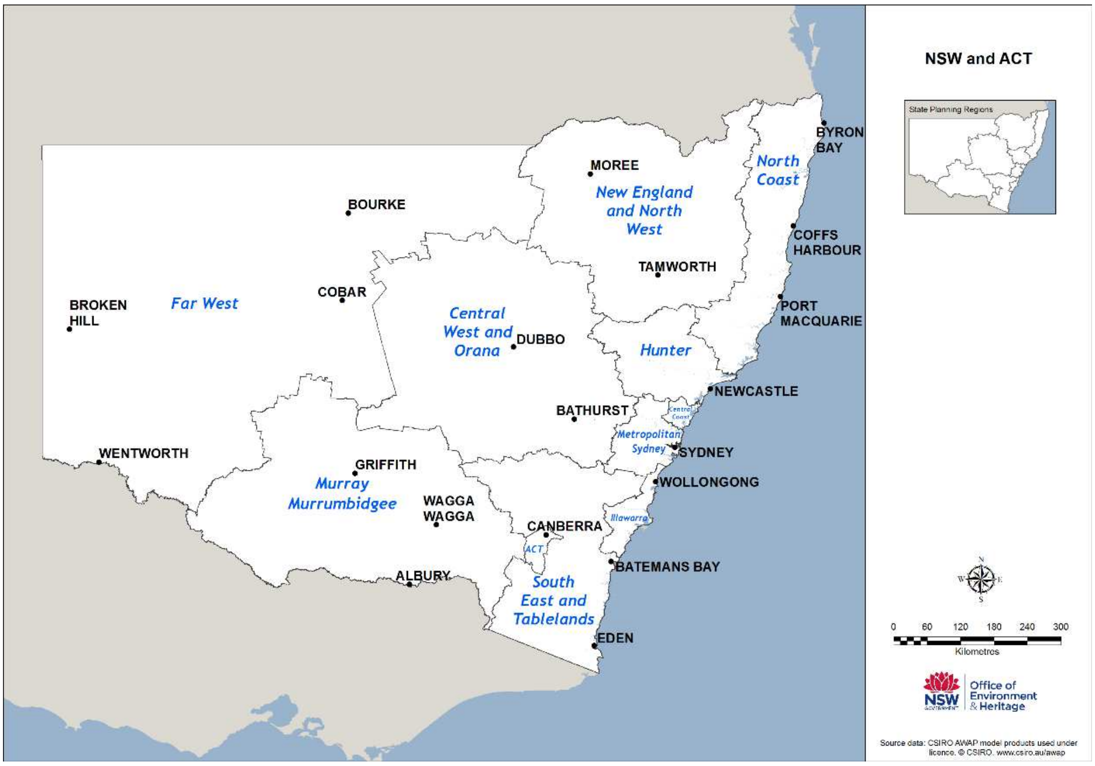

Figure 2: NSW state planning regions (SPR)

2.2 The daily rainfall erosivity model

The daily rainfall erosivity model follows that of Yu and Rosewell (1996) and Lu and Yu (2002) with significant improvements on model parameters (Yang & Yu 2015). Briefly, the model to estimate the sum of total kinetic energy from storms and the peak 30-min (5 x 6-min) intensity values for the month *j* (or monthly rainfall erosivity in units of $MJ.mm.ha^{-1}.hr^{-1}.month^{-1}$) from daily rainfall amounts is based on

$$\hat{E}_j = \alpha[1+\eta\cos(2\pi fj-\omega)]\sum_{d=1}^{N} R_d^{\beta} \qquad (1)$$

where R_d is the daily rainfall amount (mm/day), *N* is the number of rain days in the month, and α, β, η, and ω are model parameters. The model assumes a non-linear relationship between daily rainfall amount and daily rainfall erosivity values via the parameter β. For the same amount of rainfall, however, rainfall erosivity can vary depending on the time of year and the location, especially the latitude and elevation. The remaining three parameters in Equation (1), namely α, η, and ω, were used in an attempt to capture these effects in a relatively parsimonious fashion.

For the exponent β, the following regression equation was developed for SEA:

$$\beta = 1.02 - 0.0209L \qquad (2)$$

where *L* is the latitude in decimal degrees, which is a negative value for the southern hemisphere. Equation (2) was based on pluviograph calibrated parameter values (Yang & Yu 2015) for the exponent β for these 124 sites as shown in Figure 1. This suggests that at the higher latitude, the relationship between rainfall amount and rainfall erosivity is much more non-linear. At the higher latitude, there is a much greater range of rainfall intensity than in the subtropical and tropical regions where the rainfall intensity is, in general, consistently high.

Once the exponent β is determined from equation (2), the reference α_0 value can be determined from the following equation:

$$\alpha_0 = 1.05 \text{ x } 10^{(2.08\text{-}1.58\beta)} \qquad (3)$$

Note also that when Equation (3) is used to estimate the coefficient α_0 from the exponent β, a correction factor of 1.05 needs to be applied to remove the bias introduced in anti-log transformations (Duan 1983).

Multi-variable regression relationship for the departures is given by:

$$\frac{\alpha}{\alpha_0} = 2.349 + 0.04040\text{L} - 0.0002684\text{E} \qquad (4)$$

where *E* is the elevation above the sea level in metres from DEM (DEM-H). Equation (4) was also based on calibrated parameter values from the 124 sites. The equation suggests that for the same amount of rain in the same month, the rainfall erosivity is likely to be higher at lower latitude (northward) and at lower elevation. As the latitude increases, i.e. moving from south to north in NSW (negative latitude), rainfall erosivity would increase for a given amount of rain. Likewise, as the elevation increases, rainfall would become less and rainfall erosivity would decrease for a given amount of rain as the regression suggests. This may well be related to the variation in the size distribution of rain drops as a function of the latitude and elevation.

The annual rainfall erosivity (*R*-factor, in units of MJ.mm.ha^{-1}.hr^{-1}.month^{-1}) for a given year is simply the sum of the monthly rainfall erosivity in the year as calculated using Equation 1.

2.3 Hillslope erosion

The time-series (monthly) rainfall erosivity layers produced in this study are further used to estimate monthly hillslope erosion based on RUSLE (Renard et al. 1997):

$$A = R \times K \times LS \times C \times P \qquad (5)$$

where *A* is the predicted hillslope erosion (t.ha^{-1}.month^{-1}), *R* is rainfall erosivity (*R*) factor (MJ.mm.ha^{-1}.hr^{-1}.month^{-1}) as calculated above, *K* is the soil erodibility factor (t.ha.hr.ha^{-1}MJ^{-1}mm^{-1}), *LS* is the slope and steepness factor (unitless). Note that the cover and management (C) factor (unitless) and erosion control (P) factor (unitless) in the future were not considered in this work as the relevant future data are not available, thus the results are the likelihood of hillslope erosion or erosion risk. The *K*-factor map was prepared from the GSG and LS-factor calculated from DEM-H (Yang 2015). The hillslope erosion was calculated monthly and annually from for each year and step for each year.

2.4 Procedures

The input data include the NARCliM bias-corrected daily rainfall projections (in ASCII grids) for all three periods (1990–2009, 2020–2039, 2060–2079) from all 12 member ensembles (Evans et al. 2014), a total of 262,800 data layers. The elevation layer was prepared from 1-second (30 m) hydrological DEM (DEM-H) from GeoScience Australia. The latitude layer (in decimal degrees) was created based on SEA extent at the same spatial resolution (30 m) as DEM.

Due to the large quantity of data sets, automated GIS scripts have been developed to process the daily rainfall data and calculate the monthly and annual rainfall erosivity. The procedures include:

- convert NARCliM modelled daily rainfall (from UNSW in NetCDF) to ASCII and ESRI ArcInfo grids (total 262,800 data layers)
- check and remove abnormal rainfall values (e.g. >350 mm/day)
- calculate daily and monthly R_d (the right-most section of the equation)

- spatial interpolation of monthly R_d to finer resolution (100 m) and fill non-data gaps originating from NARCliM rainfall projections
- calculate monthly rainfall erosivity based on the above equation
- calculate annual rainfall erosivity (sum of monthly erosivity)
- calculate monthly hillslope erosion using RUSLE (assuming bare soil or C-factor = 1)
- calculate annual hillslope erosion (sum of monthly soil loss)
- calculate average rainfall erosivity and hillslope erosion from all periods and all member ensembles, and their seasonal means.

2.5 Model performance assessment

Model performance is measured by the coefficient of efficiency, E_c (Nash & Sutcliffe 1970) as:

$$E_c = 1 - \sum_{i=1}^{M} (y_i - \hat{y}_i)^2 / \sum_{i=1}^{M} (y_i - \bar{y})^2 \tag{6}$$

where y_i and $\hat{y}_i$ are observed and modelled values, respectively; $\bar{y}$ is the average of observed values, and *M* is the sample size. Essentially, E_c is an indicator of how close the scatters of predicted versus actual values are to the 1:1 line which can be considered as a measure of model efficiency for any other types of models. In addition, mean relative error (MRE) and root mean squared error (RMSE) are also used for accuracy assessment.

The accuracy assessment compares the annual mean rainfall erosivity in the baseline period (1990–2009) from NARCliM projected daily rainfall (all 12 member ensembles) against that from the BoM gridded daily rainfall for the same period. The latter has been assessed against the calibrated rainfall erosivity in a recent study (Yang & Yu 2015).

3. Results and discussion

3.1 GIS layers and accuracy assessment

Based on the daily rainfall erosivity model (Eqs 1–4) and procedures as outlined above, we produced monthly and annual rainfall erosivity GIS layers for all of NSW and SEA from the daily rainfall data from all 12 NARCliM ensembles for all the three projection periods (1990–2009, 2020–2039, 2060–2079). Multi-model mean annual and seasonal rainfall erosivity and the changes were further calculated and spatially interpolated into fine spatial resolution (100 m) using a spatial interpolation method (SPLINE).

The modelled rainfall erosivity data were further used to estimate hillslope erosion based on RUSLE (Eq. 5), and the same sets of hillslope erosion layers (monthly, seasonal and annual) have been produced for the same periods for NSW and SEA, as well as spatial interpolation and multi-model means. The total GIS layers were over 30,000 and the entire calculation took about three months on a high-end PC (Thinkstation D30 Workstation) with 3.7 GHz processor and 128 GB memory.

Rainfall erosivity values calculated from the 12 NARCliM member ensembles vary significantly (Figure 3). Compared with the results from the gridded daily rainfall data (Bureau of Meteorology 2009), the percent changes of mean rainfall erosivity values from the 12 member ensembles range from about –8% to about 8%, with an overall change of about 2% (2.26%). All 12 member ensembles, except GCM CCCMA3.1, resulted in an overestimate of the mean annual rainfall erosivity, while results from CCCMA31_R1 and CSIROMK30_R2 have less than 1% variation compared to the BoM mean value. CCCMA31_R3 and MIROC32_R3 have less than 2% variation compared to the result from BoM data. The overall 2.26% overestimate of rainfall erosivity is due to the 1.65% overall increase in the NARCliM projected mean annual rainfall (525 mm.year^{-1}) compared with the BoM rainfall (519 mm.year^{-1}) in the same period (1990–2009).

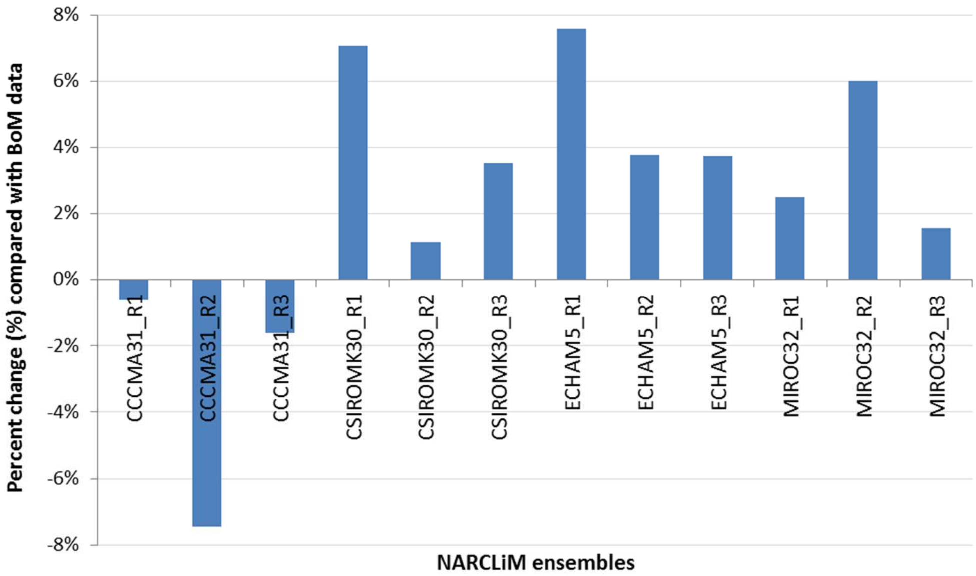

Figure 3: The relative error (%) of mean annual rainfall erosivity calculated from 12 NARCliM member ensembles compared with BoM data

Adequate random sampling points (4991 in total) were used to sample and assess the accuracy of the modelled rainfall erosivity from the NARCliM projections. The GIS modelled mean annual rainfall erosivity values using the NARCliM projected daily rainfall were compared with those calculated using the BoM gridded daily rainfall data at 5 km spatial resolution (Bureau of Meteorology 2009) for the baseline period (1990–2009). The overall E_c for the rainfall erosivity is 0.9753 (R^2 = 0.9762), overall bias is 0.9925 suggesting a slight under-estimation, and RMSE is 13.2% or 143 (MJ.mm.ha^{-1}.hr^{-1}.year^{-1}) indicating the relative size of the error bars from the 1:1 line (Figure 4). The seasonal patterns between the NARCliM and BoM data are also similar, both showing high rainfall erosivity in summer and low in winter (Figure 5).

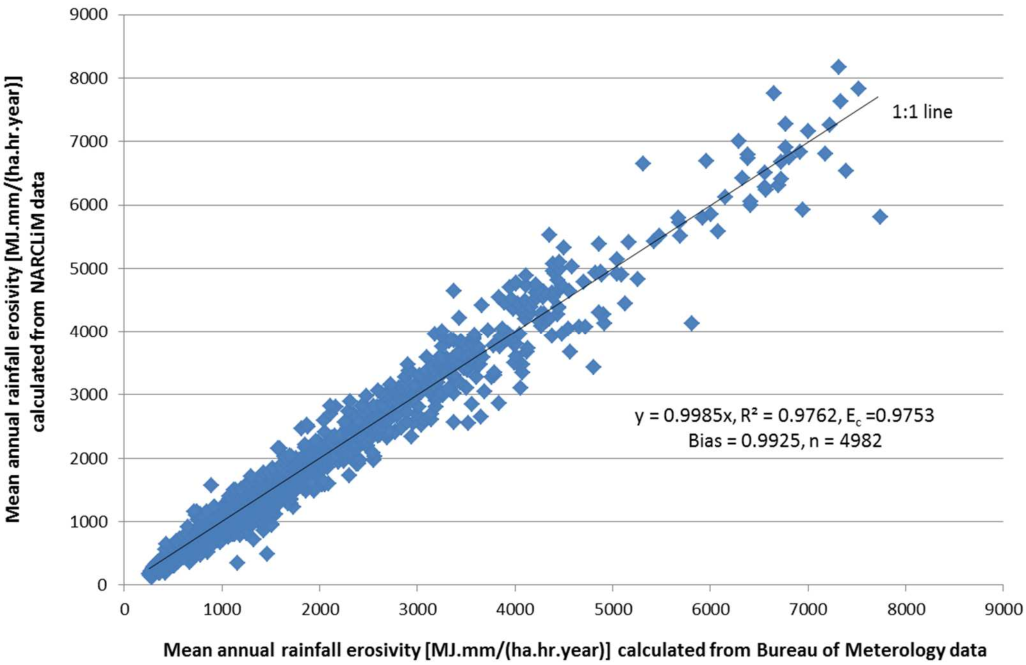

Figure 4: Comparison of mean annual rainfall erosivity calculated from NARCliM projections and BoM rainfall data

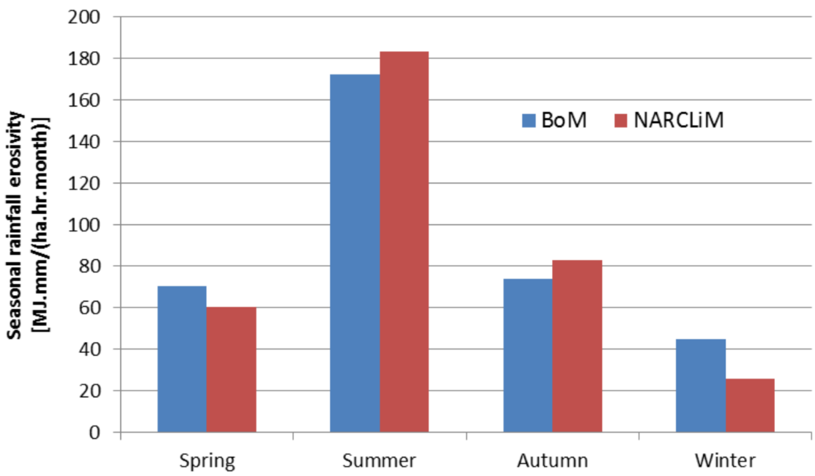

Figure 5: Comparison of seasonal rainfall erosivity (MJ.mm.ha^{-1}.hr^{-1}.month^{-1}) calculated from 12 NARCliM member ensembles and BoM data

3.2 Baseline rainfall erosivity and hillslope erosion

Three historical baseline periods were used to better describe and compare the overall trend and changes in rainfall erosivity and erosion risk. These include a 20-year baseline period (1990–2009) for comparison with the NARCliM projections, and a standard 30-year baseline period (1961-1990) and longer (100+ years) baseline period (1910–2013) for better understanding the overall historic changes. The rainfall erosivity values for the three baseline periods were calculated using the achieved daily rainfall grids from BoM.

There is great similarity in the seasonal changes in rainfall erosivity in all three baseline periods, revealing higher erosivity in summer and lower in winter, about seven times difference between July and February (Figure 6).

There was significant annual variation in rainfall erosivity in the past 100+ years, ranging from 523 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) in 1915 to 2094 in 1974, with a mean of 1071 and standard deviation (SD) of 327. The annual rainfall erosivity values in the period 1961–1990 range from 588 to 2094 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) with a mean of 1152 and SD of 357. The annual rainfall erosivity values in the baseline period 1990–2009 range from 680 to 1428 ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) with a mean of 1085 and SD of 220.

The mean annual rainfall erosivity values among these baseline periods vary by up to 7% (Figure 7). These variations show that the same baseline period should be used throughout the comparisons and assessment process for current and future changes. Using different baseline periods could result in a variation of up to 7%. For this study, the NARCliM projection for the period 1990–2009 was used as the baseline to compare with the near (2020–2039) and far future (2060–2079) projections as they were from the same source (NARCliM) with the same time slice (20-year period).

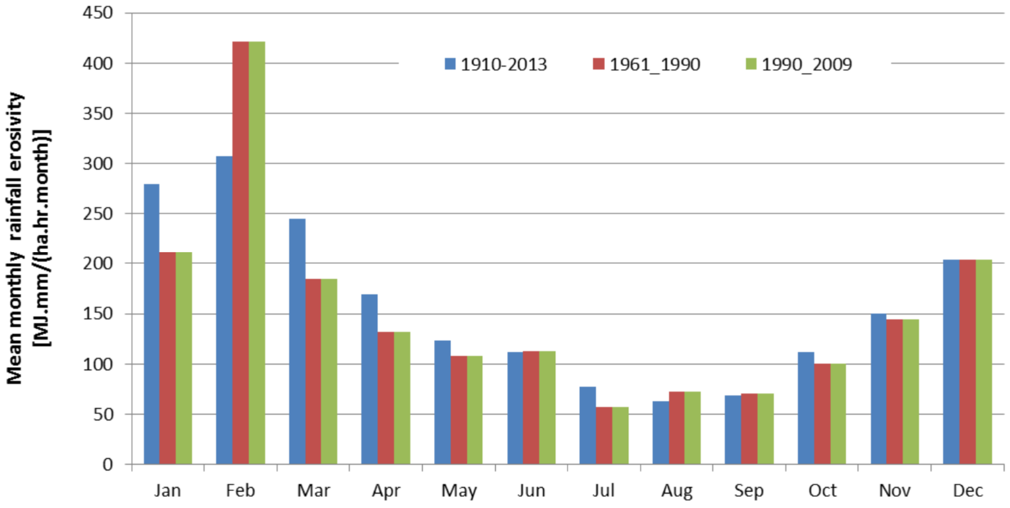

Figure 6: Monthly mean rainfall erosivity ($MJ.mm.ha^{-1}.hr^{-1}.month^{-1}$) in three historical periods from BoM data

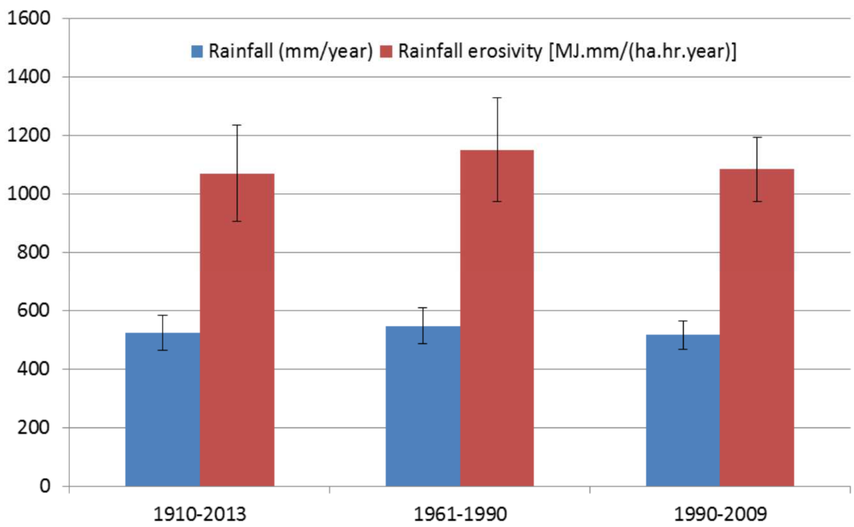

Figure 7: Mean annual rainfall ($mm.year^{-1}$) and rainfall erosivity ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) in three historical periods calculated from BoM data

The spatial patterns of rainfall erosivity in the three historical periods are also very similar and they all show the general trends of rainfall erosivity, increasing from west to east and south to north (Figure 8). Across NSW state planning regions, the mean annual rainfall erosivity generally increases from west to east, with the lowest in the Far West (about 500) and the highest in the North Coast (about 4000). The large spatial variation means that erosion risk could vary about eight times across the SPRs. Such relatively large regional variations were also noted in previous studies in NSW (e.g. Edwards 1987). Figure 9 shows the spatial variations of annual mean rainfall erosivity in the three baseline periods calculated using historical BoM data.

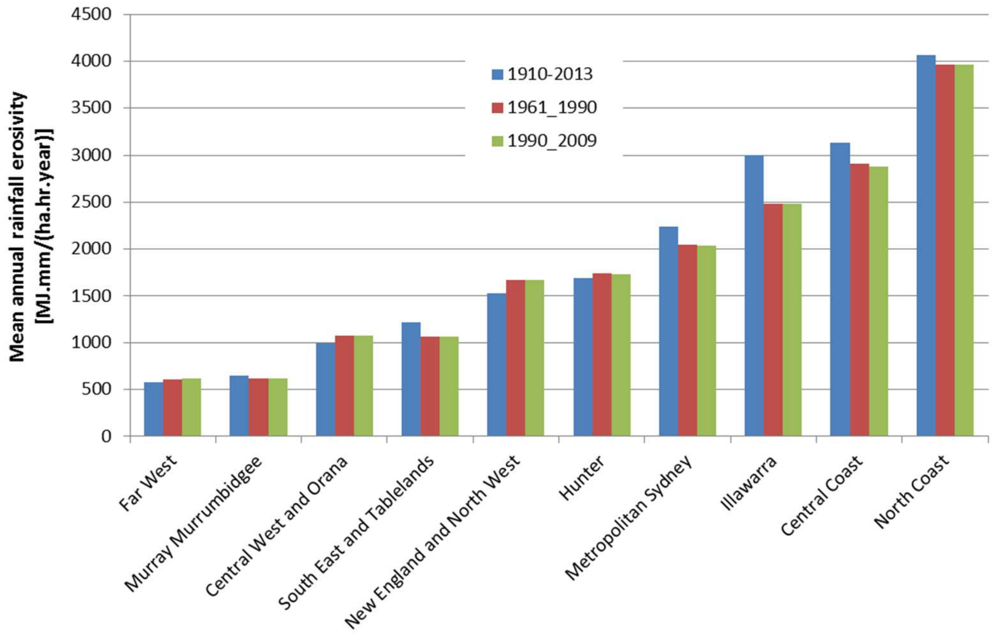

Figure 8: Annual mean rainfall erosivity across NSW state planning regions in three reference periods (1910–2013, 1961–1990, 1990–2009)

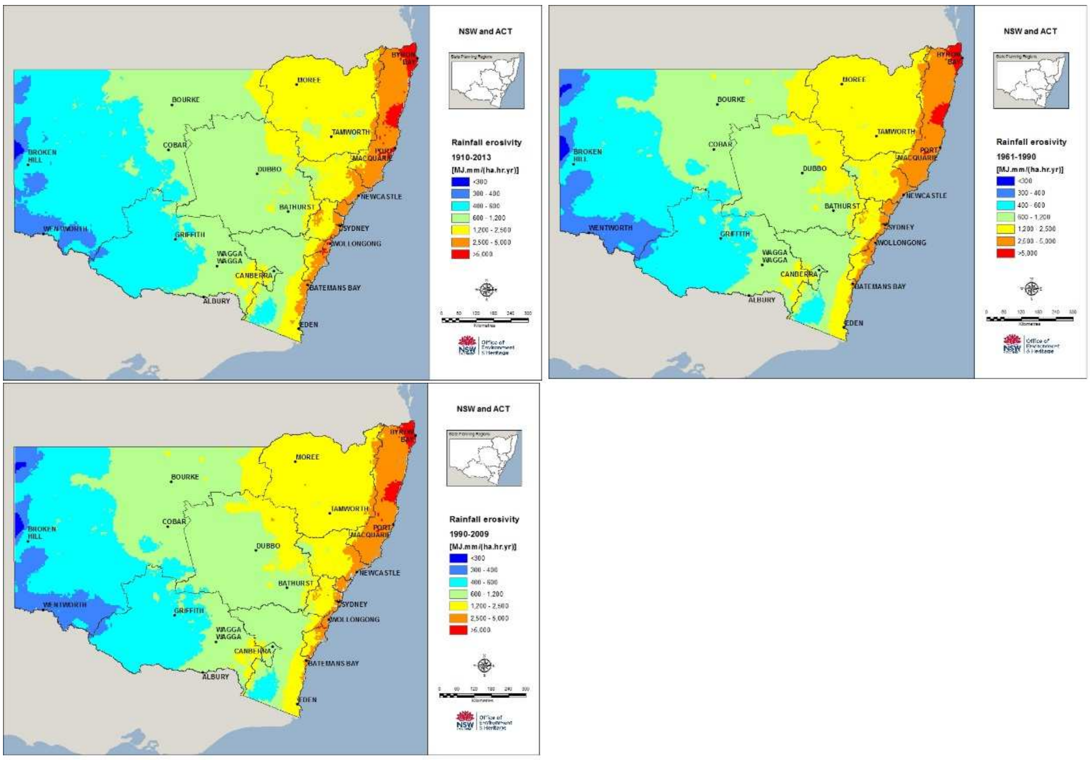

Figure 9: Mean annual rainfall erosivity in reference periods (top-left: 1910–2013, top-right: 1961–1990, bottom: 1990–2009) calculated from BoM historical data

Hillslope erosion in these baseline periods has similar seasonal and spatial variations as that of rainfall erosivity. Figure 10 shows the mean annual hillslope erosion ($t.ha^{-1}.year^{-1}$) for the baseline period (1990–2009) with the current groundcover conditions. The map shows the high erosion risk areas are generally along the Great Dividing Range due to the combined effects of steep terrains and high rainfall erosivity. North Coast, Hunter and Central Coast regions are predicted to have a mean hillslope erosion rate over 4 $t.ha^{-1}.year^{-1}$ in the near and fur futures even if the current groundcover conditions are maintained. This is primarily due to the presence of more erosive rainfall (storm events) and steep terrains in these regions (Yang 2015).

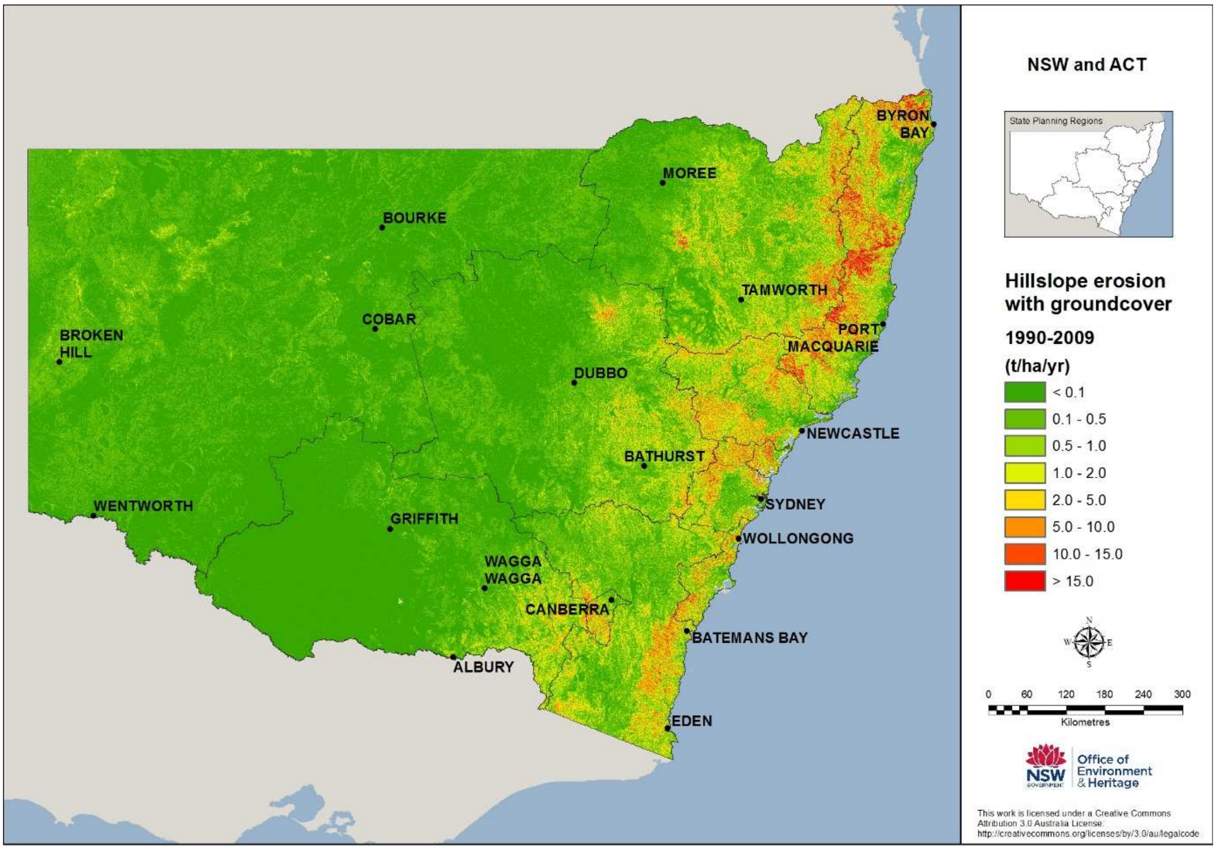

Figure 10: Predicted mean annual hillslope erosion ($t.ha^{-1}.year^{-1}$) in the baseline period (1990–2009) with current groundcover conditions

Figure 11 shows the mean seasonal (monthly mean in a season) hillslope erosion ($t.ha^{-1}.season^{-1}$) for the baseline period (1990–2009) with the current groundcover conditions. It shows great seasonal variation (about a 7-fold difference) with the highest erosion rate in summer and the lowest in winter.

The high erosion risk areas (i.e. North Coast and Central Coast regions) in summer have implications for water quality, agricultural productivity and biodiversity due to the significance of the regions and their current erosion levels. It is important to maintain good groundcover in these areas, otherwise there will be a significant increase in erosion risk in these regions.

As these maps are in time series for a long period, they are useful for continuous and consistent soil condition monitoring and management. Post-fire erosion is becoming an emerging environmental threat due to its potential adverse effects on soil and water quality. For example, a storm event in the severely burnt Warrumbungle National Park in February 2013, which lasted approximately 45 minutes, caused considerable flooding and hillslope erosion with the catastrophic consequence of long-term landscape change in this iconic park. The time-series erosion risk maps (i.e. at monthly steps) could be used to monitor post-fire erosion and recovery.

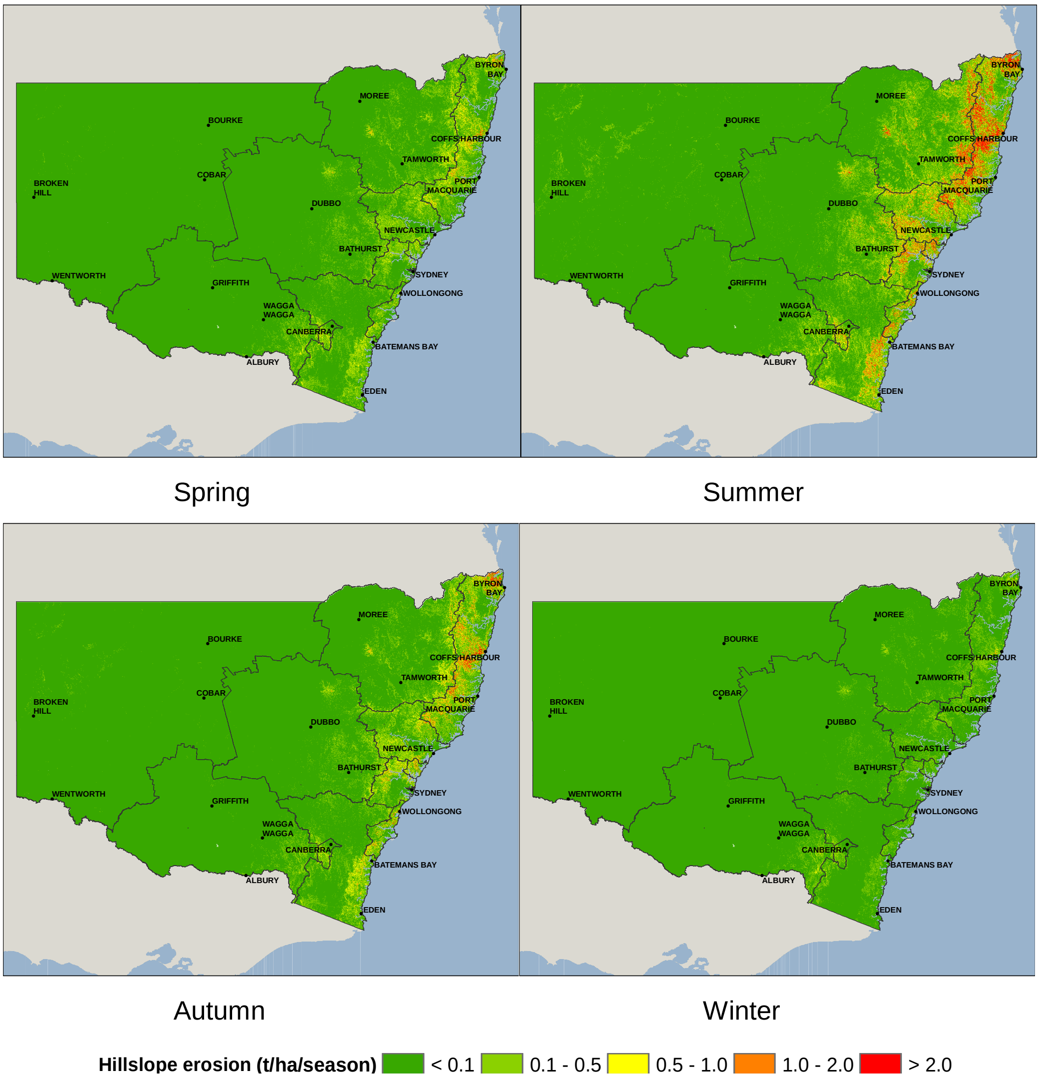

Figure 11: Predicted mean seasonal hillslope erosion (t.ha^{-1}.month^{-1}) in the baseline period (1990–2009) with current groundcover conditions

3.3 Future changes in rainfall erosivity and hillslope erosion

3.3.1 Geographic changes

Predicted future changes (%) in rainfall erosivity from the 12 NARCliM member ensembles vary significantly. To minimise the model biases, the mean annual rainfall erosivity values from all 12 member ensembles are used to assess the overall changes in rainfall erosivity in the near and far future periods (2020–2039, 2060–2079).

Compared with the baseline period (1990–2009), the mean annual rainfall erosivity in NSW is predicted to increase in the future. Statewide, there is about a 7% increase in the near future (2020–2039) and about a 19% increase in the far future (2060–2079). Figure 12 shows the percent change in rainfall erosivity across NSW in the near future and Figure 13 shows the change in the far future.

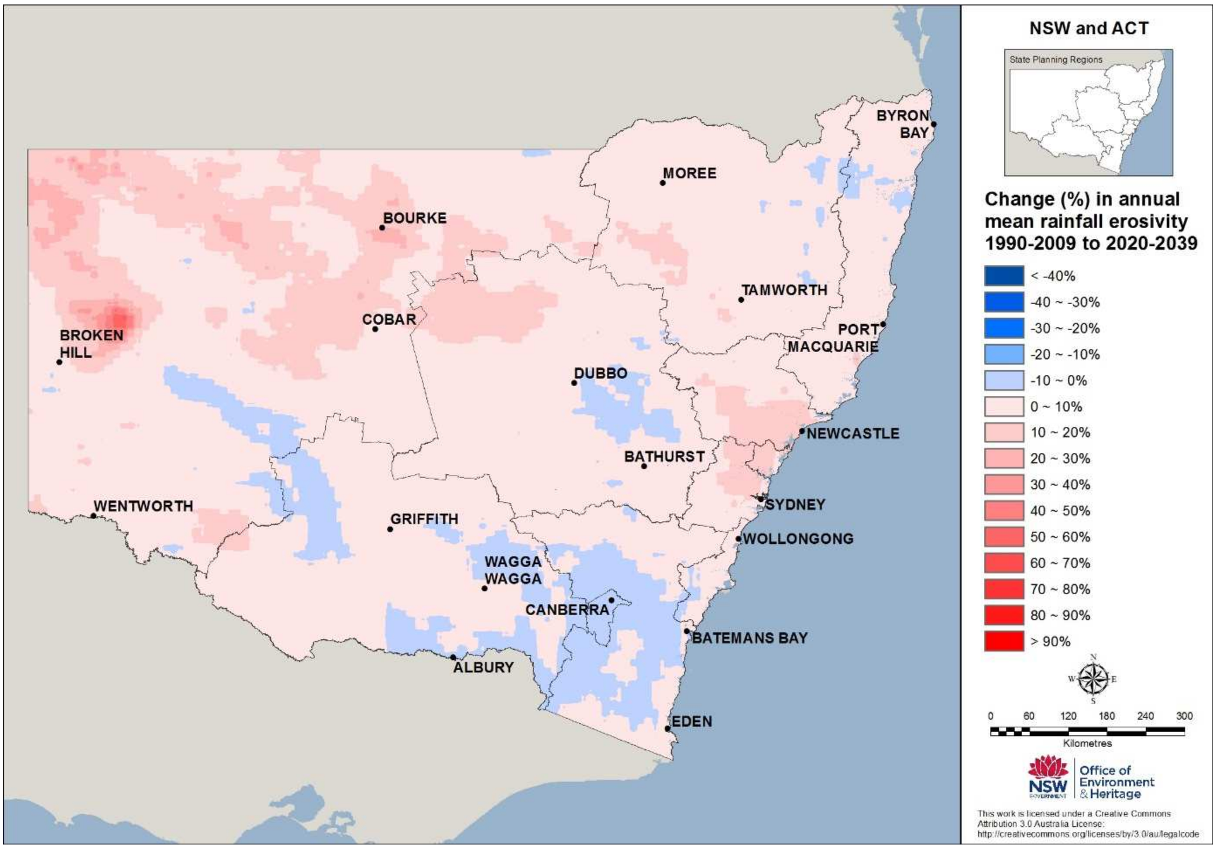

Figure 12: The percent change in rainfall erosivity in the near future (2020–2039) compared with the baseline period (1990–2009)

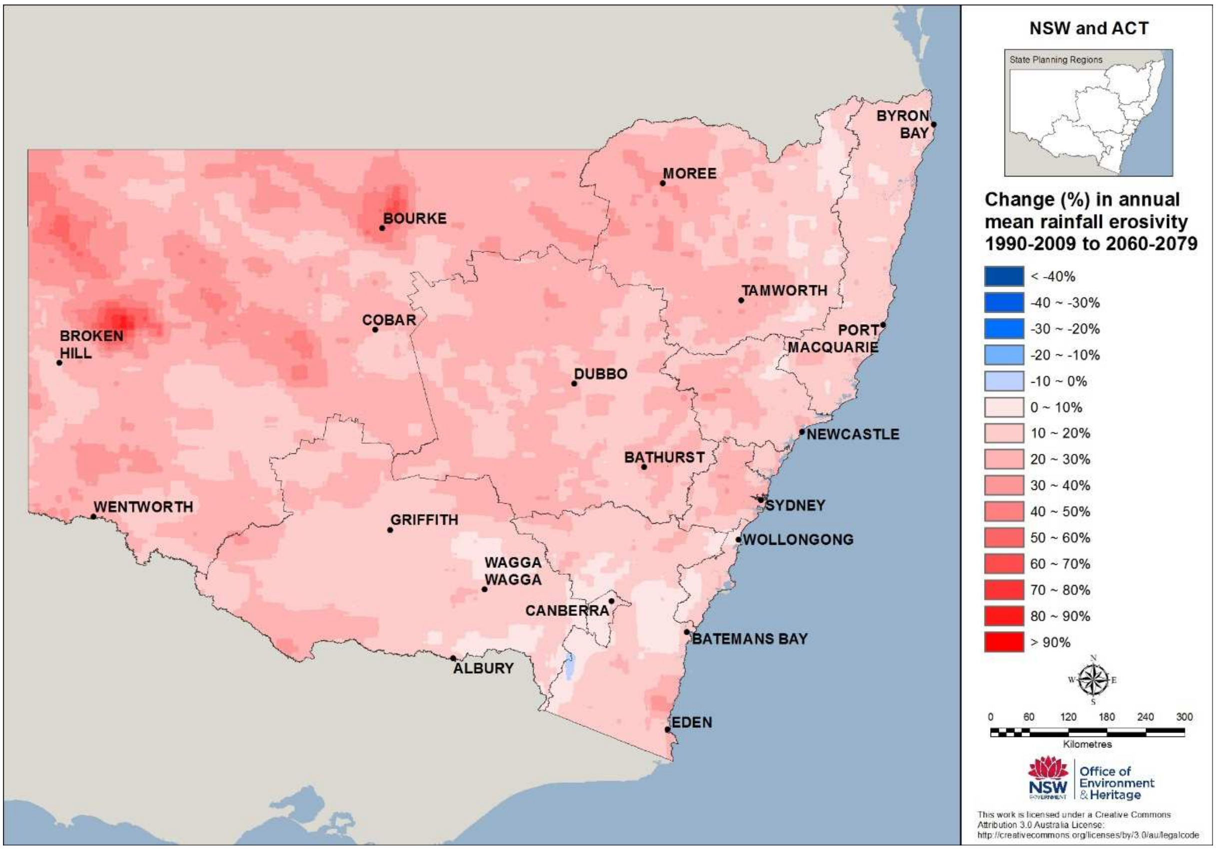

Figure 13: The percent change in rainfall erosivity in the far future (2060–2079) compared with the baseline period (1990–2009)

The mean annual rainfall erosivity and the future changes in each SPR in relation to the baseline period are summarised in Table 2. The changes vary from 1.4% (South East and Tablelands) to 13.8% (Central Coast) in the near future, and from 13.9% (Illawarra) to 27.5% (Far West) in the far future.

Changes in rainfall erosivity lead to changes in hillslope erosion assuming other RUSLE factors remain unchanged. The corresponding changes in hillslope erosion in each SPR in relation to the baseline period are summarised in Table 3. It assumes that the baseline groundcover conditions are maintained in the future.

Table 2: Mean annual rainfall erosivity values ($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$) and their changes across NSW in the future periods (2020–2039 and 2060–2079)

State planning region	Baseline	Near future	Far future	Near future change		Far future change	
	($MJ.mm.ha^{-1}.hr^{-1}.year^{-1}$)			Value	(%)	Value	(%)
Far West	598	655	762	57	9.6	164	27.5
Murray Murrumbidgee	568	585	665	17	3	97	17
South East and Tablelands	1100	1116	1263	16	1.4	163	14.7
Illawarra	2683	2775	3056	92	3.4	373	13.9
Central West and Orana	1064	1125	1295	61	5.8	231	21.7
New England and North West	1663	1754	2009	91	5.5	346	20.8
North Coast	4043	4248	4647	205	5.1	604	15
Hunter	1736	1923	2074	187	10.8	338	19.5
Central Coast	2933	3339	3520	406	13.8	587	20
Metropolitan Sydney	2075	2293	2523	218	10.5	448	21.6
NSW	**1081**	**1147**	**1300**	**66**	**6.9**	**219**	**19.2**

Table 3: Mean annual hillslope erosion values ($t.ha^{-1}.year^{-1}$) and their changes across NSW in the future periods (2020–2039 and 2060–2079)

State planning region	Baseline	Near future	Far future	Near future change		Far future change	
	(t/ha/year)			Value	(%)	Value	(%)
Far West	0.1116	0.1238	0.1441	0.0122	10.92	0.0325	29.10
Murray Murrumbidgee	0.1725	0.1749	0.1960	0.0024	1.40	0.0235	13.63
South East and Tablelands	1.0519	1.0627	1.2041	0.0107	1.02	0.1522	14.46
Illawarra	2.2276	2.3080	2.4894	0.0804	3.61	0.2618	11.75
Central West and Orana	0.4662	0.4877	0.5593	0.0215	4.62	0.0931	19.97
New England and North West	0.9082	0.9475	1.0663	0.0393	4.32	0.1581	17.41
North Coast	4.0393	4.2359	4.6319	0.1966	4.87	0.5926	14.67
Hunter	3.7431	4.1678	4.5011	0.4247	11.35	0.7581	20.25
Central Coast	4.4057	5.0379	5.2851	0.6323	14.35	0.8794	19.96
Metropolitan Sydney	3.0596	3.3887	3.7087	0.3290	10.75	0.6491	21.21
NSW	**2.0186**	**2.1935**	**2.3786**	**0.1749**	**6.72**	**0.3600**	**18.24**

3.3.2 Seasonal changes

The seasonal changes in rainfall erosivity are highly uneven and variable among the 12 member ensembles. Table 4 shows future seasonal and annual changes (%) compared with the baseline period among the 12 member ensembles, and their changes are also shown in a bar graph for easy comparison (Figure 14). The variations range from –22.2% in spring to 105.3% in autumn for the near future period, and from –33.7% in winter to 101.2% in autumn for the far future period. The majority of models agree that erosivity will increase in summer for both the near future (8/12) and the far future (12/12) (Table 4). For autumn the majority of models project an average increase across the state in the near future (11/12) and the far future (11/12). There is less clarity in the changes to winter and spring erosivity, due to the complex nature of the changes in rainfall in those seasons.

Table 4: Future seasonal and annual changes (%) compared with the baseline period and the variations among member ensembles

	2020 - 2039					2060 - 2079				
CGM_RCM	ANNUAL	SPRING	SUMMER	AUTUMN	WINTER	ANNUAL	SPRING	SUMMER	AUTUMN	WINTER
MIROC32_R1	17.5	11.5	21.1	25.5	-8.5	37.7	43.5	46.1	21.1	47.4
MIROC32_R2	16.0	31.2	22.9	2.7	-13.3	38.2	40.1	36.8	47.8	49.8
MIROC32_R3	20.3	24.6	35.2	1.2	-6.2	71.2	72.0	89.1	55.0	44.6
ECHAM5_R1	-5.8	-4.6	-14.1	23.7	-5.5	22.0	11.6	29.0	20.5	-1.9
ECHAM5_R2	-0.6	-4.8	-5.8	22.4	-5.4	13.7	-15.1	23.3	25.0	2.2
ECHAM5_R3	9.9	-22.2	13.8	40.2	3.3	19.3	0.6	30.6	24.8	-3.4
CSIROMK30_R1	-14.0	-12.9	-18.6	0.7	2.0	0.9	-22.8	9.2	11.6	-33.4
CSIROMK30_R2	-7.8	-2.4	-18.3	23.0	-2.7	5.0	-14.4	13.0	20.9	-33.7
CSIROMK30_R3	-9.7	5.1	-10.9	-11.8	-13.1	1.2	-26.9	14.6	-2.3	-33.4
CCCMA31_R1	26.7	-8.6	18.4	105.3	-1.0	28.4	4.8	14.9	101.2	23.1
CCCMA31_R2	17.8	-11.8	28.0	52.9	3.7	17.0	-1.0	12.2	30.2	49.6
CCCMA31_R3	14.3	-11.6	31.6	28.9	-5.6	15.0	-7.6	16.3	33.6	18.3

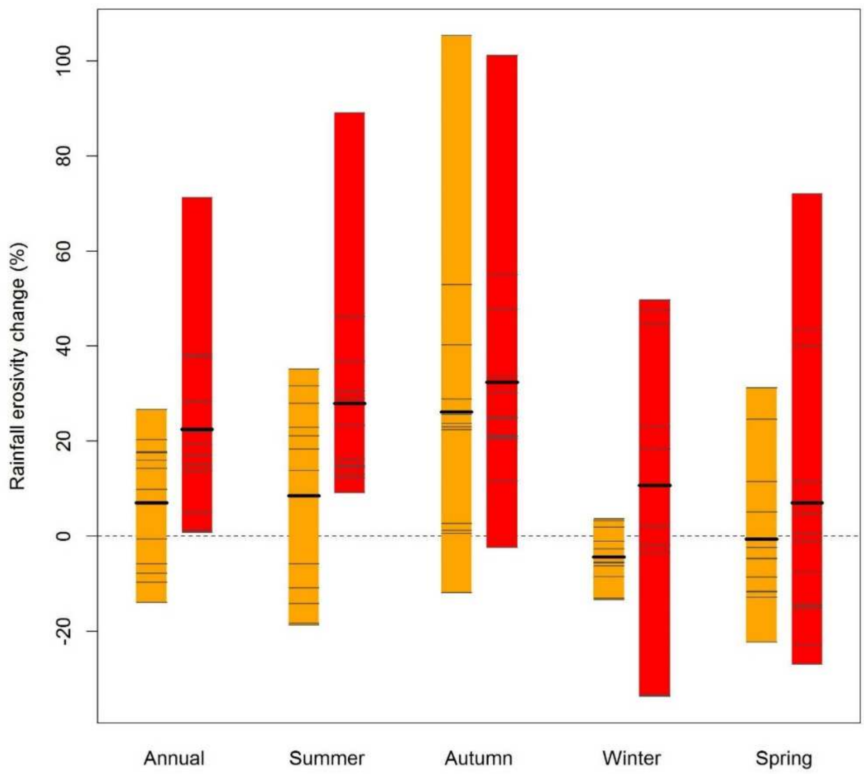

Figure 14: Bar graph representation of future seasonal and annual changes (%) in rainfall erosivity, the yellow bars represent near future scenarios (2020–2039), while the red bars represent far future scenarios (2060–2079)

To reduce the model bias, the mean values from all the 12 member ensembles were used to compare the future seasonal changes in rainfall erosivity. It is predicted that the rainfall erosivity will generally increase in all seasons across NSW. Autumn will have the highest increase with about 22% in the near future and about 29% in the far future. Rainfall erosivity in summer is also predicted to increase significantly, about 5% in the near future and 26% in far future. The only exception is the slight decrease in the near future in spring and winter (Figure 15).

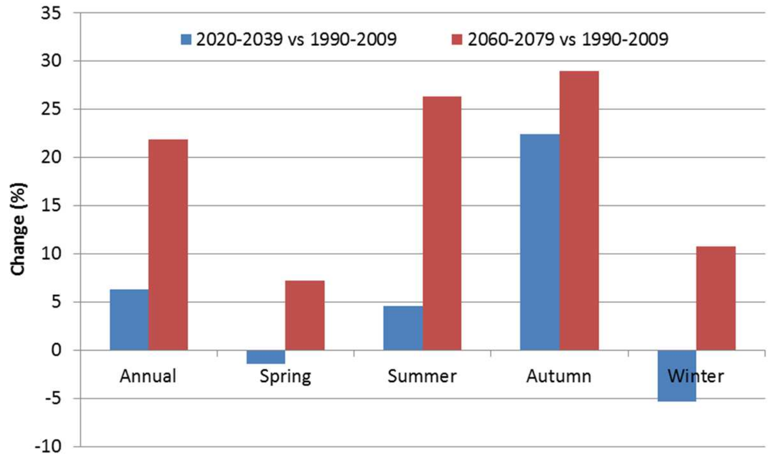

Figure 15: Percent change (%) of annual and seasonal rainfall erosivity in two future periods predicted from NARCliM data

One distinct advantage in using the daily erosivity model in GIS is the ability to predict monthly or seasonal rainfall erosivity and its distribution anywhere in NSW (Yang & Yu 2015). Figure 16 shows the modelled mean monthly rainfall erosivity in the three periods from the NARCliM projections. The seasonal variation is similar to the pattern of the baseline periods showing high rainfall erosivity in summer and low in winter, about a seven-fold difference between February and July. The seasonal distribution of rainfall erosivity will have significant impacts on hillslope erosion. This implies that when all other RUSLE factors remain unchanged, the seasonality of rainfall erosivity alone could cause an approximately seven-fold difference in soil loss.

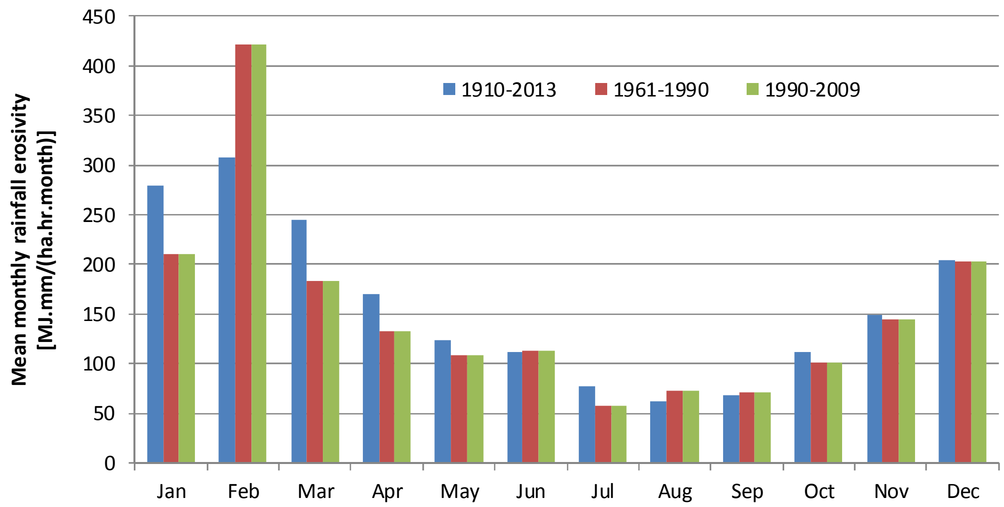

Figure 16: Monthly mean rainfall erosivity ($MJ.mm.ha^{-1}.hr^{-1}.month^{-1}$) calculated from the NARCliM projections (mean of all 12 member ensembles)

Figure 17 and Figure 18 show the seasonal changes in rainfall erosivity in the future, spatially across NSW. Rainfall erosivity generally increases in all seasons in most areas of the state in the future. However, Southern Coast in the near future and North Coast in the far future are predicted to decrease in rainfall erosivity in winter (about 20–30%). This is due to predicted decreases in rainfall in winter in these areas. Contrastingly, Broken Hill and Bourke are projected to have a significant increase in erosivity in the near and far futures (>70% change in autumn). Though the relative changes are high there is little impact on hillslope erosion as historically these areas do not experience significant water erosion (less than 0.1 t.ha^{-1}year^{-1}) due to relatively flat terrains. Even if the rainfall erosivity in these areas increases by 90% in the future, the actual hillslope erosion would be 0.19 t.ha^{-1}year^{-1}, which is still considered very low compared with the coastal areas.

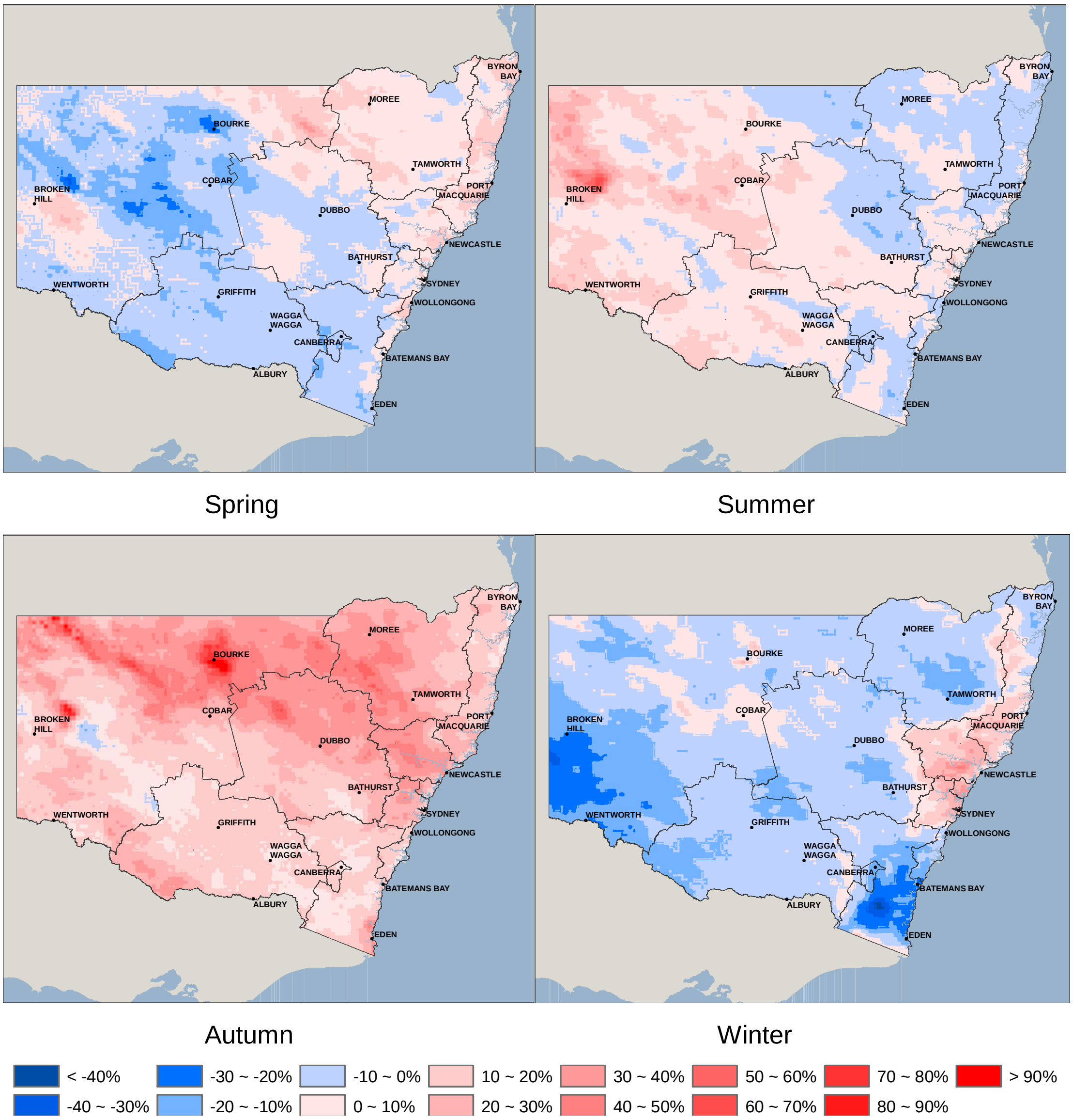

Figure 17: Seasonal changes (%) in rainfall erosivity in the near future (2020–2039) compared with the baseline period (1990–2009)

Importantly, however, areas along the coast and the ranges are projected to experience up to a 40% increase in erosivity in the near and far futures, especially in summer and autumn. Erosivity is also projected to increase considerably in the Central Coast region in winter (20–30%). These increases have implications for water quality, agricultural productivity and biodiversity due to the significance of the regions and their current high erosion risk. It is important to maintain good groundcover in these areas, otherwise there will be a significant increase in erosion risk.

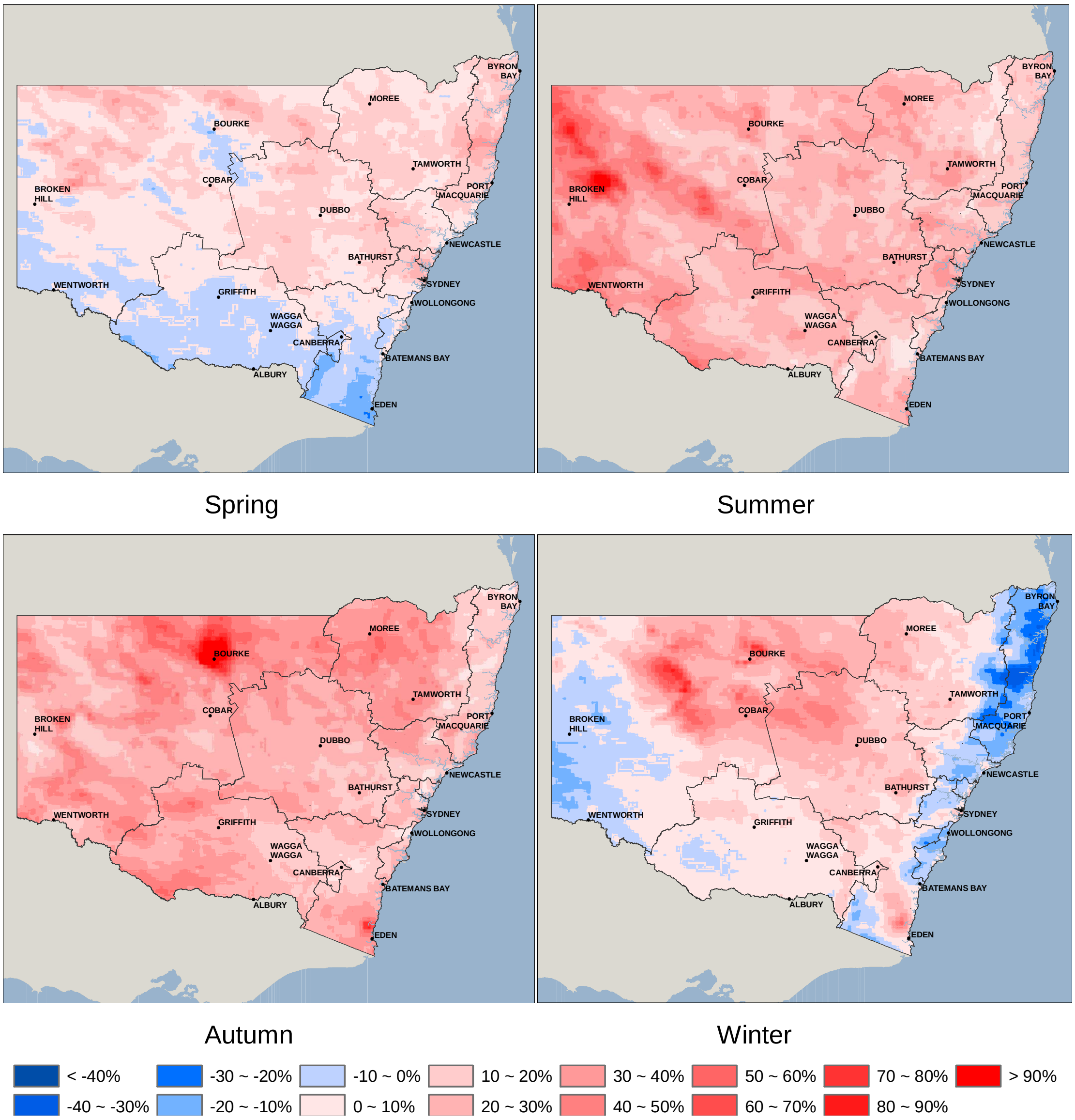

Figure 18: Seasonal changes (%) in rainfall erosivity in the far future (2060–2079) compared with the baseline period (1990–2009)

The seasonal changes in rainfall erosivity are further compared based on the state planning regions of NSW. Figure 19 shows predicted seasonal changes (%) in rainfall erosivity in the near future compared to the baseline period, and Figure 20 shows seasonal changes (%) in the far future in each SPR. The seasonal change is highly uneven across SPRs, ranging from –12% in South East and Tablelands (in winter) to 33% in Hunter (in autumn) in the near future. The far future shows more increases across all SPRs in general, particularly in western NSW, ranging from –18% in North Coast (in winter) to 33% in Far West (in autumn). In contrast, some coastal regions are predicted to experience decreases in rainfall erosivity in the next 50 years, such as North Coast, Central Coast and Illawarra in winter (Figure 20).

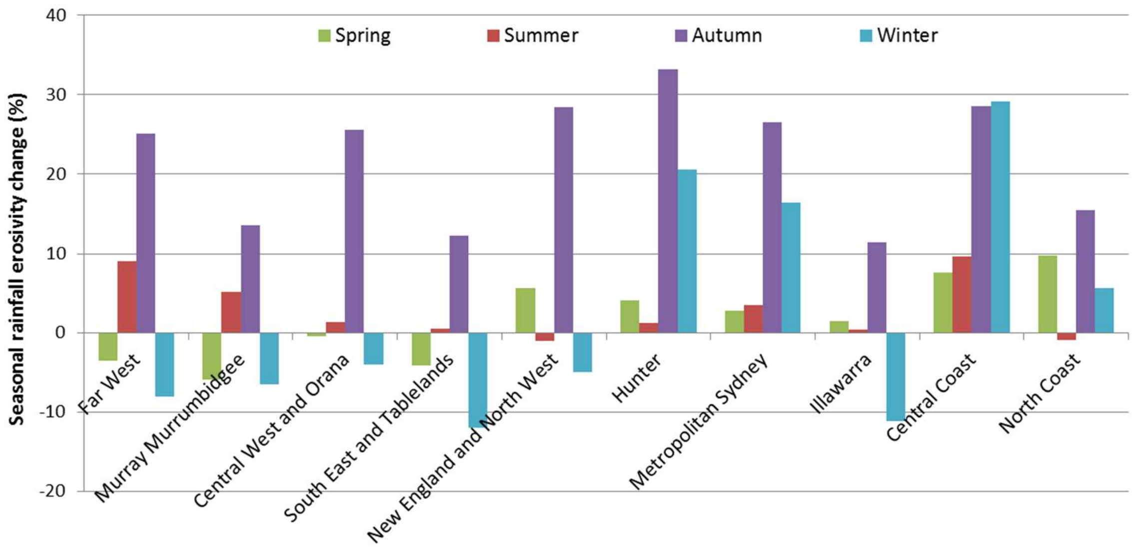

Figure 19: Predicted seasonal changes in rainfall erosivity across NSW SPRs in the near future (2020–2039) in relation to the baseline period (1990–2009)

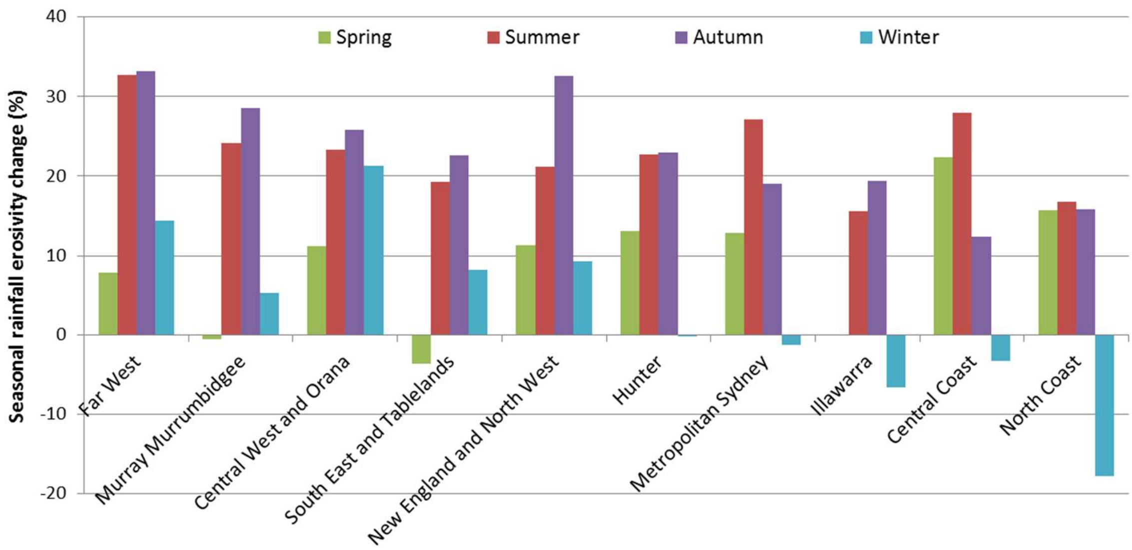

Figure 20: Predicted seasonal changes in rainfall erosivity across NSW SPRs in the far future (2060–2079) in relation to the baseline period (1990–2009)

3.3.3 Land use and hillslope erosion risk

Hillslope erosion has implications for different land uses. There are six primary land-use types in NSW based on Australian Land Use and Management Classification Version 7 (ABARES 2010, Figure 21). The predicted rainfall erosivity and hillslope erosion for each primary land use is shown on Figure 22 and Figure 23.

The land-use type ‘Conservation and natural environments’ (Class 1) covers about 15% of NSW. Figure 23 shows this class has the highest erosion risk as it includes national parks and conservation areas which are normally in steep terrains with a high frequency of bushfires. However, the actual erosion in these areas can be reduced considerably if groundcover is maintained (Yang 2014).

The ‘Intensive uses’ category (Class 5) is projected to have the second highest erosion risk (Figure 23) due to the combined effects of groundcover (bare soil), terrain and rainfall erosivity. This category also includes urban areas and mining; the actual erosion risk is expected to be reduced if erosion control measures (such as concrete or brick surfaces) are in place.

The risk of hillslope erosion on NSW agricultural and plantation lands (Classes 3 and 4) is expected to slightly increase (Figure 23), largely due to the topographic factor of the land uses as they are normally in flat terrains. The 'Intensive uses' category (Class 5) will still have high erosion risk due to the combined effects of terrain and rainfall erosivity. This category includes urban areas; the actual erosion risk is expected to be far less than projected as most urban areas are paved (concrete or bricks) rather than bare soil as the model assumed. This detailed information could help decision-makers to better target and design the best management practices for a given land use type or region.

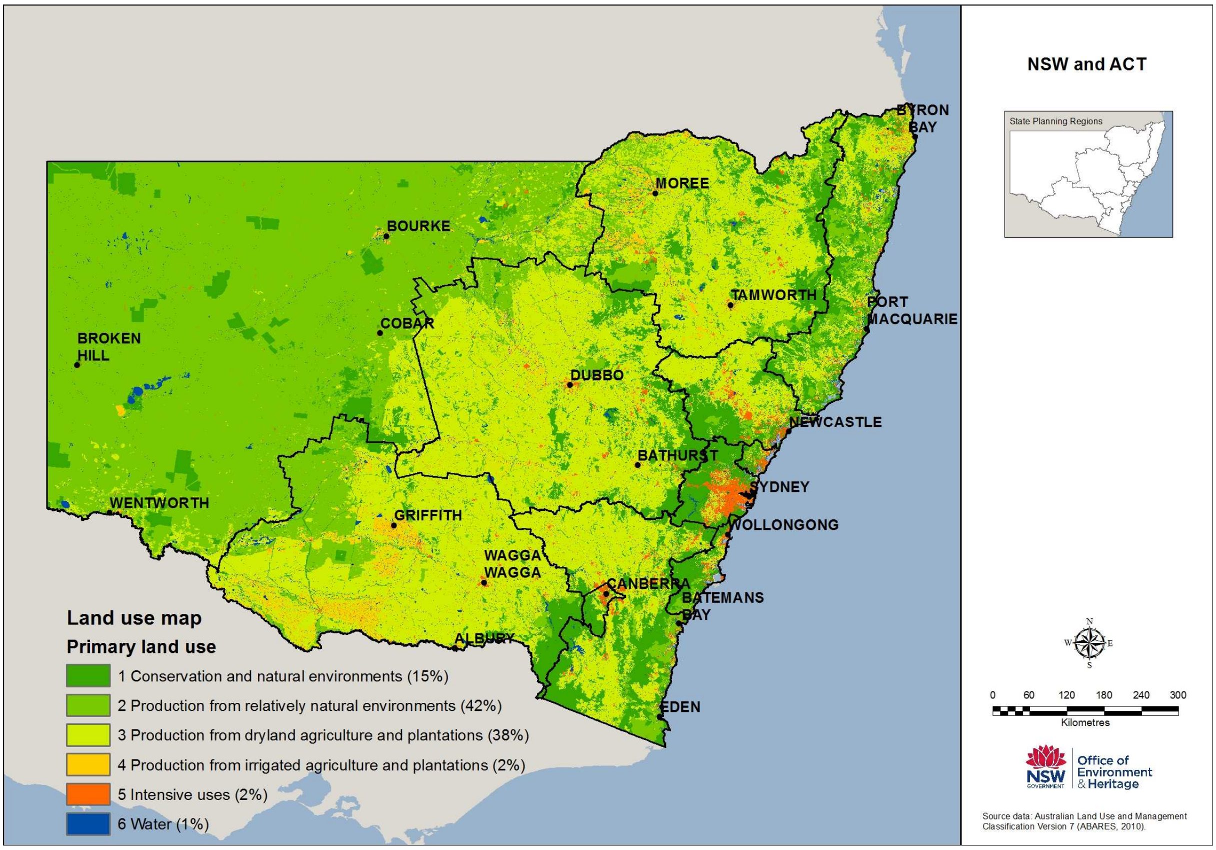

Figure 21: Primary land uses in NSW and their class codes

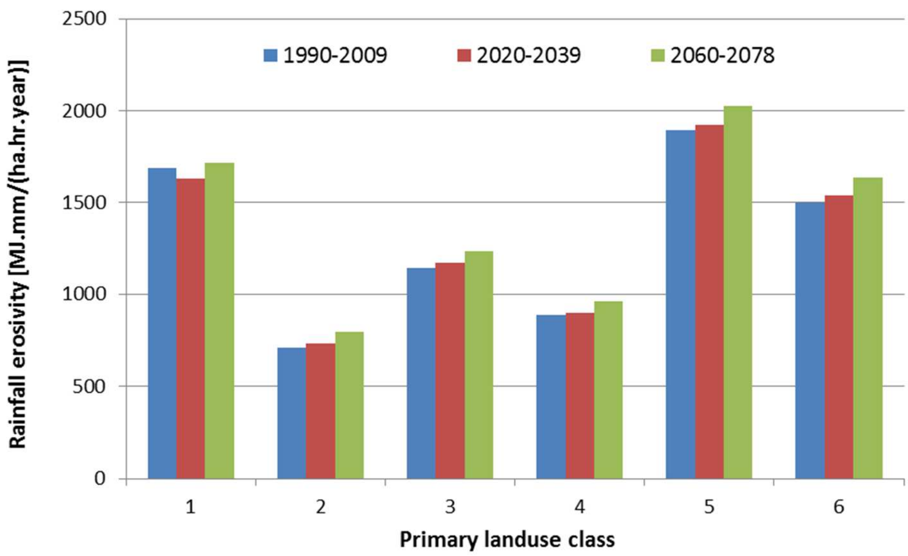

Figure 22: Predicted rainfall erosivity for primary land uses in the baseline (1990–2009), near future (2020–2039) and far future (2060–2079) periods

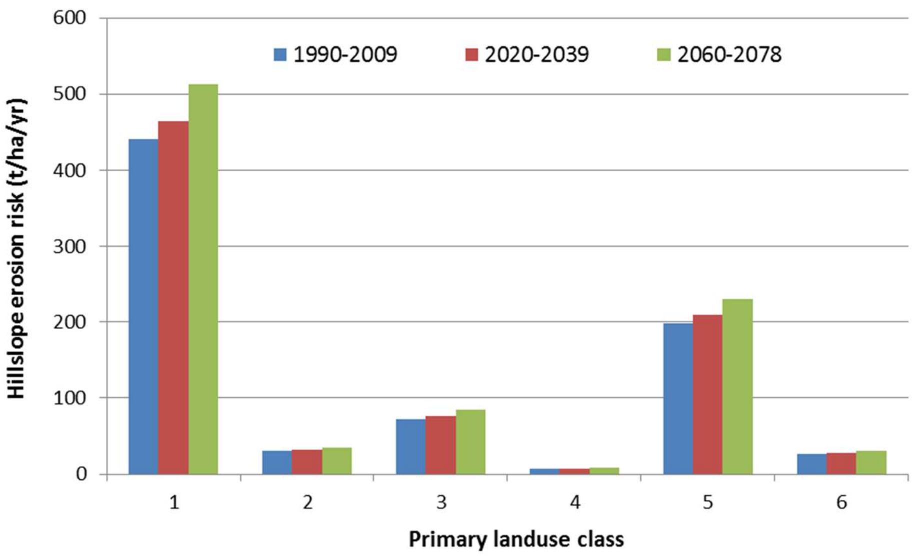

Figure 23: Predicted hillslope erosion risk for primary land uses in the baseline (1990–2009), near future (2020–2039) and far future (2060–2079) periods

4. Conclusion and further studies

NARCliM projected daily rainfall data have been used to predicted rainfall erosivity and hillslope erosion risk and their future changes across NSW and SEA. Rainfall erosivity and hillslope erosion risk across NSW are predicted to increase by about 7% in the near future (2020–2039), and by about 19% in the next 50 years. The change is highly uneven in space and in time, and the spatial and temporal patterns provide meaningful information for climate change assessment and adaptation. Rainfall erosivity and hillslope erosion are mostly greater in summer than in other seasons. This suggests that summer (particularly February) is the critical season for hillslope erosion prevention and management. The 7–19% extra hillslope erosion in the future for unprotected soil is a serious concern. Review of erosion and sediment control standards for construction and re-assessment of land management practices may be required for the predicted high risk areas.

The improved daily rainfall erosivity model performed well and the overall model efficiency (E_c) for estimated rainfall erosivity values is greater than 0.97, with an overall bias slightly greater than one. The set of regional relationships for the model parameters are highly recommended for use for NSW and SEA to estimate and map rainfall erosivity and its spatial and seasonal distribution.

The model outputs are available at high temporal and spatial resolution for use in climate impact assessment and hillslope erosion monitoring for the past, current and future. The time series of rainfall erosivity and hillslope erosion GIS layers in such high spatial (100 m) and temporal (monthly to annual) resolution across SEA are the first available in Australia. The baseline rainfall erosivity layers for the period of climate normals (1961–1990), a reference period (1990–2009) and a longer baseline period (1910–2013) have been produced for better climate change comparisons.

This study has demonstrated an appropriate approach for modelling and mapping monthly and annual rainfall erosivity from daily rainfall data for SEA which is also readily applicable to other regions. The methods have been successfully implemented in GIS for efficient calculation and mapping of the spatial and temporal variation of rainfall erosivity and hillslope erosion across SEA. With the automated GIS process developed in this study, the erosivity maps and erosion modelling can be readily upgraded when better rainfall data and models become available. The spatial interpolation greatly enhanced the level of detail, which is useful for assessing erosion hazard and determining the timing of erosion control practices. The time series of high resolution rainfall erosivity and hillslope erosion maps can provide detailed information for climate (rainfall) impact assessment, and a cost-effective means for hillslope erosion hazard identification and rehabilitation.

Further work will include examining and predicting the impacts of rainfall extremes on rainfall erosivity and hillslope erosion as soil erosion happens mostly during a few severe storm or extreme events. These will provide more useful information for storm impacts on bushfire affected areas so that one can optimise appropriate remedial activities for individual storm events.

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