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Predicting Changes of Rainfall Erosivity and Hillslope Erosion Risk Across Greater Sydney Region, Australia

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Abstract

Rainfall changes have significant effect on rainfall erosivity and hillslope erosion, but the magnitude of the impact is not well quantified because of the lack of high resolution rainfall data. Recently, the 2-km rainfall projections from regional climate models have become available for the Greater Sydney Region (GSR) at daily time step for the current (1990-2009) and future (2040-2059) periods. These climate projections allow predicting of rainfall erosivity changes and the associated hillslope erosion risk for climate change assessment and mitigation.

In this study, we developed a daily rainfall erosivity model for GSR to predict rainfall erosivity from the current and future daily rainfall data. We produced time-series hillslope erosion risk maps using the revised universal soil loss equations on monthly and annual bases for the two contrasting periods. These products were spatially interpolated to a fine resolution (100 m) useful for climate impact assessment and erosion risk mitigation. The spatial variation was assessed based on the state plan regions and the temporal variation on monthly and annual bases. These processes have been implemented in a geographic information system so that they are automated, fast, and repeatable. Our prediction shows relatively good correlation with point-based Pluviograph calculation on rainfall erosivity and the previous study (both R^2 and $E_c > 0.70$). The results indicate that hillslope erosion risk is likely to increase 10-60% in the GSR within the next 50 years, and changes are greater in the coastal and the Blue Mountains, particularly in late summer (January and February). The methodology developed in this study is being extended to south-east Australia.

Keywords

rainfall erosivity, hillslope erosion, risk mitigation, modelling, climate change, GIS, RUSLE

Acknowledgements

This project was funded by the NSW Government and managed through the Office of Environment and Heritage (OEH). Many OEH staff, particularly Dr Brian Murphy, Greg Chapman, Dr Andrew Rawson and the soil assessment (SALIS) team, contributed to this project and their effort is greatly appreciated. We specially thank the NARCliM project team at the University of New South Wales and the OEH Climate Science team for providing the projected daily rainfall data. We also thank Jiangsu State Government in China for providing scholarship for Dr Xiaojin Xie for her six-month visit to OEH where she worked on this project.

1. INTRODUCTION

Historical rainfall data indicate considerable inter-annual variability and significant multi-decadal change over the past 100 years in New South Wales (NSW), particularly across the Greater Sydney Region (GSR). While this change in rainfall amount and intensity are expected to have significant effect on rainfall erosivity and soil erosion (Rawson and Murphy 2012; 2011), 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.

In recent decades, changes in climate extremes have attracted many attentions in the world because extreme climate events are often more important to natural and human systems than their mean values (You et al. 2011; Aguilar et al. 2009). Rainfall extremes have been studied on global, regional and national scales. These studies found some significant changes in percentiles and frequency of extreme events, and the magnitude and the sign of the changes vary with the season and the region.

Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, the most direct of which is the change in the erosive power of rainfall (Nearing et al. 2004; Nearing 2001). More importantly, soil erosion occurs mostly during a few severe storm or extreme events. Large and erosive storms are even more variable than annual rainfall totals. Trends and changes in erosive storms or rainfall extremes are therefore much more important but also difficult to detect in comparison with rainfall totals.

Recently, global climate models (GCMs) are widely used for assessing the responses of the climate system to changes in atmospheric forcing. Projections of potential climate change are essential for sustainable natural resources planning and management (Ji et al. 2013). GCMs provide information (e.g. rainfall, temperature) at a spatial resolution (above 50 km) that is too coarse to be used directly in local ground impact studies or regional planning. The NSW Office of Environment and Heritage (OEH) and the University of New South Wales (UNSW) have recently developed finer-scale (10-km resolution) climate projections for South-East Australia (SEA) as part of the NSW and Australian Capital Territory (ACT) Regional Climate Modelling (NARCliM) project (Evans et al. 2014). The NARCliM modelling project also produced a higher resolution (2 km) regional climate projection to 2059 for the GSR. Time slices of recent climate (1990-2009) and future climate (2040-2059) were simulated using Weather Forecasting and Research (WRF) model (Skamarock et al. 2008) and the outputs include daily rainfall and temperature.

These recent climate projections allow detailed impact assessment in terms of sheet and rill erosion (or hillslope erosion in combination) and their changes over time and space. Although the nature of future groundcover and soil conservation practices cannot be easily predicted, rainfall erosivity (essentially the power of rainfall to dislodge soil particles) is dependent solely on climatic parameters and can therefore be used in conjunction with climate change models to predict the likely extent and trajectory of future soil erosion risk. However, erosion prediction needs to be validated to quantify the accuracy and uncertainty associated with erosion impact assessment using these regional climate model (NARCliM) outputs.

By definition, rainfall erosivity (or R-factor in revised universal soil loss equation, RUSLE) is the mean annual sum of individual storm erosivity values, EI30, where E is the total storm kinetic energy and I30 is the maximum 30-min rainfall intensity (Renard et al. 1997). When factors other than rainfall are held constant, soil losses due to water erosion are directly proportional to the level of rainfall erosivity (Wischmeier and 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), ground cover (C-factor) and soil conservation practices (P-factor) to predict the average annual soil loss per unit area.

Historically, an R-factor contour map was produced for NSW from point measurements at 29 meteorological stations across NSW with over 20 years of records (Rosewell 1993; Rosewell and Turner 1992). The R-factor map was interpolated to create a continuous rainfall erosivity surface (Yang et al. 2006), but this is essentially a single static layer which does not adequately represent the underlying variability of rainfall erosivity.

Lu and Yu (2002) predicted seasonal rainfall erosivity and spatial distribution from 20 years rainfall data and produced seasonal rainfall erosivity for Australia at a ground resolution of 5 km using a daily rainfall erosivity model (Yu 1998; Yu and Rosewell 1996). Yang and Yu (2015) improved the model accuracy for Southeast Australia by using regionalised parameters, and enhanced the spatial resolution using high-resolution digital elevation models and spatial interpolation techniques. This model was further customised for the GSR with rainfall intensity data from additional weather stations to estimate the R-factor and its seasonal and inter-annual variations.

The objective of this study is to predict and map monthly and annual rainfall erosivity across the GSR for climate impact assessment. In this project, we apply the methodology specifically developed for the GSR to calculate monthly and annual erosivity values using recent (1990-2009) and future (2040-2059) daily rainfall data. We further produce finer scale (at 100 m resolution) R-factor maps using spatial interpolation techniques. We implement the calculation in a geographic information system (GIS) using automated scripts so that the entire process is efficient, repeatable and easily updated. The time series high resolution R-factor maps can provide detailed information for climate (rainfall) impact assessment, and cost- effective products for hillslope erosion identification and rehabilitation.

This paper outlines the data and method used to produce the time series R-factor maps for the GSR, and presents the impact assessment of recent and future rainfall on erosivity and soil erosion in the state plan regions (SPR) within the GSR.

2. STUDY AREA AND DATASETS

We chose the Greater Sydney Region (GSR) as the study area. The extent of GSR is defined as: Longitude Min = 149.08 °E, Longitude Max = 152.10 °E, Latitude Min = 35.13°S, and Latitude Max = 32.40°S (Figure 1).

There are six state plan regions (SPR) in the GSR, namely Eastern/inner, Northern, Northern Beaches, Southern, South Western and Western (Figure 1). The SPRs are used in NSW regional action plans which focus on immediate and future actions the NSW Government will take to improve outcomes in each region. The key actions include land use planning to protect both the local environment and prime agricultural land. Our results are presented for SPRs so that the research outcomes can be directly used in the regional action plans.

The NARCliM project provides projected climate data for adaptation to a future climate for NSW and the Australian Capital Territory. The Sydney climate projections used in this study have been developed by UNSW as a pilot study using the GCM (CSIRO MK3.5) and regional climate models (Evans et al. 2014). This model is just one of a suite of GCMs available for the GSR and was chosen because it performed best in replicating observed climate despite uncertainties in the downscaling sourced from the GCMs (Teng et al. 2012; Chiew et al. 2010). CSIRO MK3.5 is considered a 'wetter' model (Gordon et al. 2010); projecting higher rainfall compared with the other GCMs (e.g. CCCMA3.1). CSIRO MK3.5 was then dynamically downscaled to 2 km using the Weather Research and Forecasting model (Evans et al. 2012; Skamarock et al. 2008) for two time slices of recent climate (1990-2009) and future climate (2040-2059) at daily temporal resolution. In this study, all daily rainfall at both time slices was spatially interpolated, but only the rainfall data of recent time period were used for evaluation and comparisons.

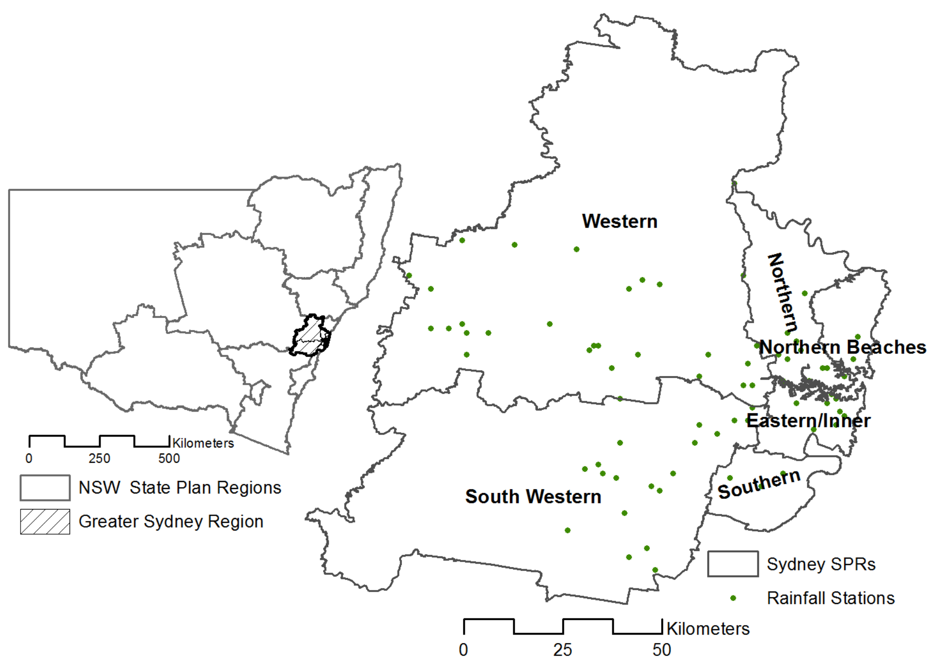

Figure 1. Locational map of the Greater Sydney Region, rainfall station sites, and six-state plan regions within the Greater Sydney Region.

3. RAINFALL EROSIVITY MODEL

The daily rainfall erosivity model used to estimate rainfall erosivity for the month j from daily rainfall amounts is adapted from Yu and Rosewell (1996) and Yang and Yu (2015):

$$\hat{E}_j = \alpha[1 + \eta \cos(2\pi fj - \omega)] \sum_{d=1}^{N} R_d^{\beta} \quad \text{when } R_d > R_0 \tag{1}$$

where R_d is the daily rainfall amount, N is the number of rain days in the month, and α, η, β and ω are model parameters. The parameter R_0 is fixed at 12.7 mm because storms with less than 12.7 mm rainfall are generally discarded in the R-factor calculations (Lu and Yu 2002; Wischmeier and Smith 1978).

The parameter ω is set to π/6, implying that for a given amount of daily rainfall the corresponding rainfall intensity is the highest in January when the temperature is the highest in GSR. The sinusoidal function with a fundamental frequency f = 1/12 is used to describe the seasonal (here monthly) variation of the coefficient. This implies that for the study area, it was assumed that other things being equal (i.e. latitude, elevation, and rain amount), rainfall erosivity would be higher in summer months, and the highest in January.

The following set of parameter values are recommended for the Greater Sydney Area: β = 1.69, η = 0.41, and $2\pi f$ = 0.523598 (= 2 x 3.1416 / 12), thus:

$$\hat{E}_j = \alpha\left[1 + 0.41\cos(0.523598j - 0.523598)\right] \sum_{d=1}^{N} R_d^{1.69} \tag{2}$$

Given the highly correlated nature of the relationship ($\log\alpha = 1.97 - 1.53\beta$, $r^2 = 0.94$), the model assumes a non-linear relationship between daily rainfall amount and daily rainfall erosivity (EI30) values via the parameter α which varies depending on location, especially the latitude and elevation (Yu 2012).

$$\frac{\alpha}{\alpha_p} = 1.215 + 0.0354(L + 30) - 0.000205E \tag{3}$$

where L is latitude in degrees (NB use negative values for the southern hemisphere); and E the elevation above sea level in meters, and α_p = 0.2433 (Yu 2012). Therefore Equation 3 can be further simplified as:

$$\alpha = 0.5540 + 0.008613L - 0.00004988E \tag{4}$$

The model used to estimate EI30 (or monthly R-factor, in MJ.mm.ha^{-1}.hr^{-1}.month^{-1}) for the month j from daily rainfall amounts can be re-written in the specific form for the GSR:

$$\hat{E}_j = \left[1.215 + 0.0354(L + 30) - 0.000205E\right] \times 0.2433 \times \left[1 + 0.41\cos(0.523598j - 0.523598)\right] \sum_{d=1}^{N} R_d^{1.69} \tag{5}$$

The elevation layer was prepared from 1 second (about 30 m) hydrological Digital Elevation Model (DEM-H) from GeoScience Australia (Gallant et al. 2011). The latitude layer (in decimal degree and negative) was created based on GSR extent at the same spatial resolution (30 m) of DEM-H.

The time-series R-factor maps produced in this study are further used to estimate soil erosion risk (hillslope erosion for bare ground) along with K-factor and LS-factor based on RUSLE (Renard et al. 1997). Briefly, the K-factor was estimated from the great soil group map and soil database. The LS-factor was calculated from hydrologically corrected DEMs based on RUSLE specifications and incorporated an improved method to detect of the beginning and the end of each slope length (Yang 2015). It is also possible to incorporate the emerging time series fractional cover products from Moderate Resolution Imaging Spectroradiometer (MODIS) into RUSLE to provide a variable and timely estimate of ground cover impacts on soil erosion for the recent period (Yang 2014).

Automated GIS scripts (in ESRI's ArcGIS workstation) have been developed to process the daily rainfall data and calculated the monthly and annual rainfall erosivity and hillslope erosion. The procedures include 1) convert NARCliM modelled daily rainfall (in NetCDF) to ASCII and ESRI ArcInfo grids; 2) reproject the rainfall grids to Geographic coordinates so that to match with existing data (e.g. rainfall from BoM); 3) remove abnormal rainfall values (maximum cut-off daily rainfall set to 500 mm); 4) calculate daily and monthly R_d (the right-most section of Equation 5); 5) interpolate monthly R_d to finer resolution (100 m) and fill nondata gaps; 6) calculate monthly rainfall erosivity based on the above equation; 7) calculate annual rainfall erosivity (sum of monthly erosivity); 8) calculate monthly hillslope erosion using RUSLE (assuming bare soil or C-factor = 1); and 9) calculate annual hillslope erosion (sum of monthly soil loss).

Model performance, hence its predictive capacity, is measured by the coefficient of efficiency, E_c (Nash and Sutcliffe, 1970). It is the fraction of total variation in the original data that can be explained by the model:

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

where y_i and $\hat{y}$ are observed and modelled values, respectively; $\bar{y}$ is the average of observed values, and M sample size. Essentially, E_c is an indicator of how close the scatters of predicted versus actual values are to the 1:1 line. It is equivalent to the coefficient of determination (R^2) for linear regression models and can be considered as a measure of model efficiency for any other types of models. E_c is commonly used to assess model performance in hydrology (Loague and Freeze, 1985) and soil sciences (King et al. 1996; Risse et al. 1993).

4. RESULTS AND DISCUSSIONS

4.1 ACCURACY ASSESSMENT

Based on the daily rainfall erosivity model as outlined above, we produced monthly and annual rainfall erosivity and hillslope erosion risk GIS layers (at a ground resolution of 100 m) for entire GSR for the recent (1990-2009) and future (2040-2059) periods.

The modelled R-factor values for the recent period were compared with those calculated using the available pluviograph data from the Bureau of Meteorology stations within the GSR (Figure 2). The overall E_c for the R-factor is 0.7261 (R^2 = 0.7438) with a relative error of 10% indicating the relative size of the error bars from the 1:1 line (overestimate). The GIS modelled R-factor values were also compared with the previous study in NSW (Rosewell 1993; Rosewell and Turner 1992) which covered an early period between 1960-1990. 30,000 random points were used to sample and compare the rainfall erosivity values and the comparison is shown in Figure 3. There is relatively good correlation (both E_c and $R^2 > 0.50$) even though the two periods compared are different. This reveals that the modelled R-factor in this study is generally in agreement with the previous study but with large relative errors from the 1:1 line (underestimate) largely due to the difference of the modelling periods.

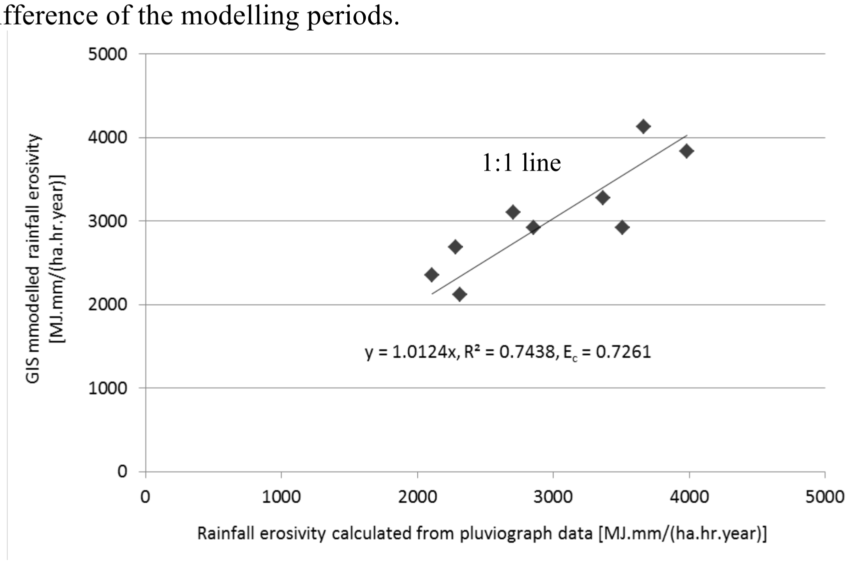

Figure 2. Comparison between modelled rainfall erosivity and that calculated from pluviograph data for the recent period (1990-2009).

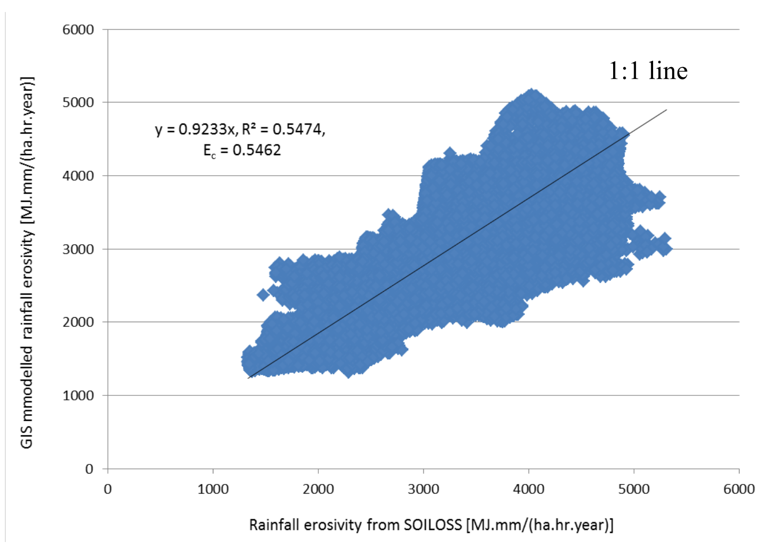

Figure 3. Comparison between modelled rainfall erosivity (recent period 1990-2009) and that from the previous study (1960-1990).

4.2 SPATIAL VARIATION AT STATE PLAN REGIONS

We extracted rainfall, erosivity and hillslope erosion rates within each state plan region (SPR) and the entire GSR over recent (1990-2009) and future (2040-2059) periods so that we can examine the spatial variation across SPRs. The mean rainfall (mm yr^{-1}), rainfall erosivity (MJ mm ha^{-1} hr^{-1} yr^{-1}), hillslope erosion (tonnes ha^{-1} yr^{-1}) and their changes over the two contrasting periods (1990-2009 and 2040-2059) are listed in Table 1.

Table 1. Mean rainfall (mm yr^{-1}), rainfall erosivity (MJ mm ha^{-1} hr^{-1} yr^{-1}), hillslope erosion (tonnes ha^{-1} yr^{-1}) and their changes over the two contrasting periods (1990-2009 and 2040-2059).

SPR-Name	Eastern/ inner	Northern	Northern Beaches	Southern	South Western	Western	All SPRs
Recent annual rainfall	1094.46	1120.51	1243.44	1142.75	851.60	948.59	946.18
Future annual rainfall	1516.21	1410.26	1643.75	1550.36	1043.67	1215.87	1202.2 7
Annual rainfall change (%)	38.25	25.73	32.14	35.17	21.72	26.92	25.83
Recent rainfall erosivity	3381.53	3480.30	3985.32	3534.32	2162.49	2722.00	2654.1 3
Future rainfall erosivity	6027.67	5481.52	6604.56	6222.66	3622.83	4261.81	4295.5 7
Rainfall erosivity change (%)	78.41	57.51	66.52	86.23	65.94	55.21	60.94
Recent hillslope erosion	0.99	8.48	8.54	4.97	3.22	8.41	6.79
Future hillslope erosion	2.05	13.57	14.57	9.82	6.00	13.56	11.04
Hillslope erosion change (%)	78.40	57.51	66.51	86.24	65.94	55.21	60.94

Note: Change% is calculated as Change% = (Future - Recent) / Recent.

These results suggest that the both rainfall erosivity and erosion are expected to increase about 61% within 50 years in Sydney SPRs if there is no ground cover or protection. The 60%+ extra hillslope erosion for unprotected soil is a serious concern with implications for Sydney water quality. Review of erosion and sediment control standards for construction and re-assessment of land management practices (e.g. for market gardens on high erosion hazard landscapes) may be required pending verification. However, the hillslope erosion rate will be significantly reduced if the ground cover or materials (i.e. urban built-up) are considered (once the future ground cover data become available).

The changes in rainfall erosivity and hillslope erosion rates are noticeably uneven in state plan regions. Changes are the greatest near the coast and in the west. The SPRs projected to be more affected by the erosivity changes include all of the coastal regions (Northern, Northern Beaches, Eastern Inner, Southern) as well as the western half of Western Region (Figure 4).

Areas where an approximate doubling of erosivity is expected to occur include many of the plateau areas of the Great Dividing Range (e.g. Upper Blue Mountains, Boyd Plateau, Newnes Plateau) and their intervening valleys (e.g. Capertee, Grose, Hartley, Lithgow, Kanangra Valleys). While most of these areas are in National Parks and therefore mostly well protected by forest, they correspond to some of the world’s most fire prone regions. Significant post-fire erosion is likely when severe wildfire is followed by summer thunderstorms.

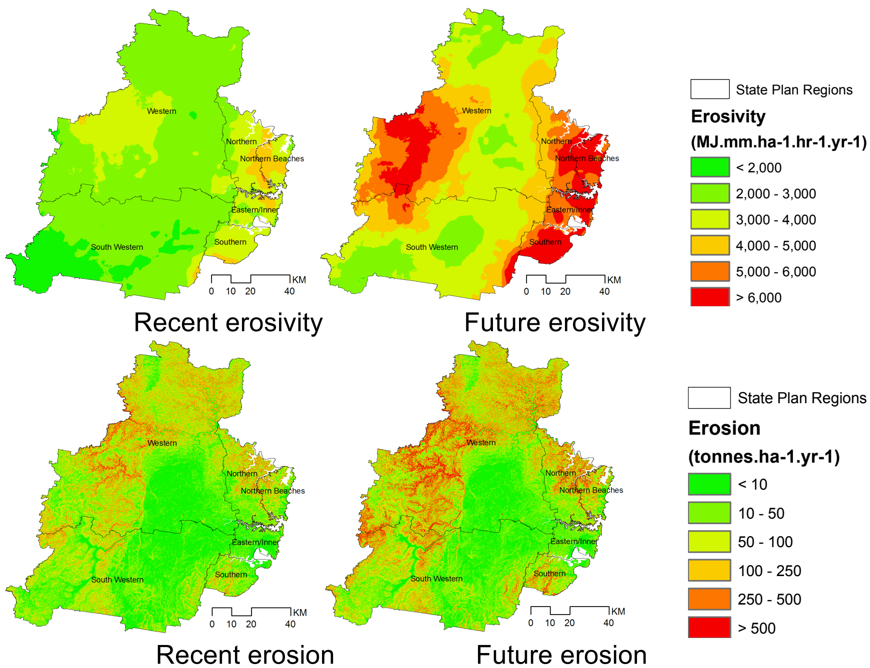

Figure 4. Modelled mean annual rainfall erosivity and hillslope erosion in the Greater Sydney Region.

4.3 Seasonal variation

Significant seasonal variations also exist in the GSR, and there is more rainfall in January to May, and less from July to September. The maximum, minimum, annual values of future rainfall are increasing compared with recent rainfall (Table 2).

Table 2. Seasonal changes of maximum, minimum, mean and standard deviation values during 1990-2009 and 2040-2059.

Month	1999-2009 years				2040-2059 years			
	Maximum (mm)	Minimum (mm)	Mean (mm)	SD	Maximum (mm)	Minimum (mm)	Mean (mm)	SD
Jan.	189.89	62.12	96.92	20.27	286.95	95.54	165.31	31.54
Feb.	189.89	62.12	96.92	20.27	315.24	63.59	171.49	38.02
Mar.	163.33	52.22	88.79	18.30	396.89	82.01	194.83	46.82
Apr.	145.10	37.13	71.70	18.65	382.78	73.24	189.34	58.63
May	161.74	37.26	70.15	23.19	336.38	46.88	158.71	57.40
June	146.00	36.94	71.46	17.35	184.79	33.70	79.95	26.15
July	108.19	27.77	47.96	12.55	142.36	16.90	47.47	23.18
Aug.	110.25	27.43	53.74	13.11	160.92	19.37	48.61	20.52
Sept.	103.06	31.63	54.21	9.38	117.59	22.00	55.03	14.81
Oct.	106.87	40.07	62.25	9.75	124.35	36.33	71.36	18.63
Nov.	131.93	56.48	82.00	13.35	265.84	54.00	130.47	40.57
Dec.	54.94	153.16	86.96	14.45	292.53	68.58	150.73	43.75
Mean	134.26	52.03	73.59	15.88	250.55	51.01	121.94	35.00

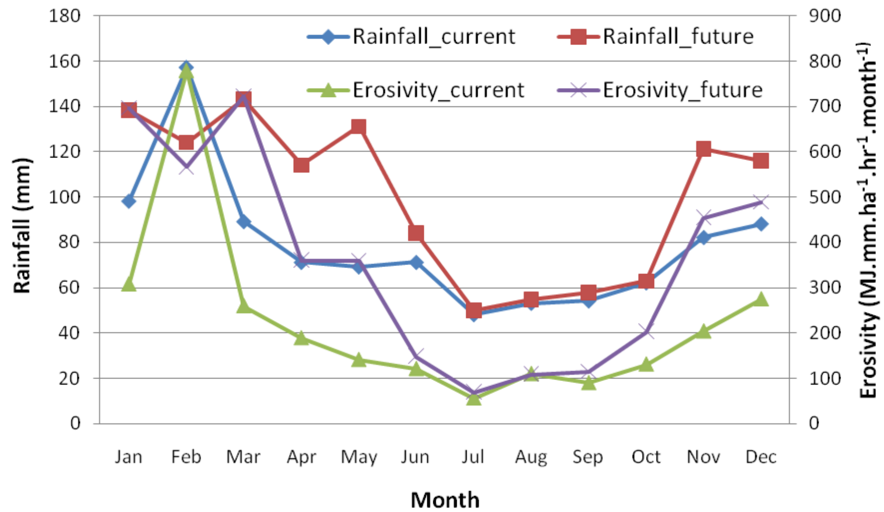

Figure 5. Predicted monthly change of rainfall erosivity for recent and future periods.

The Greater Sydney Region is projected to experience an increase in rainfall erosivity and soil erosion. The increase reflects a shift in rainfall seasonality – with more rainfall in late summer/autumn, coupled with more intense summer storms projected for 2050. This suggests that late summer/autumn is critical to maintain ground cover because it is the period the rainfall erosivity and the changes are mostly greater than those in other months. Figure 5 shows the predicted monthly change of rainfall erosivity for recent and future periods. Note that the general trends are common between the recent and future rainfall seasonality (e.g. summer higher than winter), but variations exist in different months particularly in summer (e.g. February).

Figure 6 shows the seasonal variation of predicted rainfall erosivity for the recent and the future periods at each state plan region within GSR. There is a sharp increase in rainfall erosivity in February for the recent period as there were more storm events in this month during this period (1990-2009). But this pattern does not appear in the future period (2040-2059). Similarly, both figures show that the rainfall erosivity in late summer/autumn is greater than any other months and the changes are greater along the coast and the Blue Maintains areas.

Consequently, the predicted hillslope erosion risks for the recent and the future periods at each state plan region within GSR are shown in Figure 7. They have the similar trends in spatial and temporal patterns as that of rainfall erosivity, but noticeably different as the hillslope erosion risks take into account other factors (soil erodibility and terrain factor) in addition to rainfall erosivity.

The annual changes of recent rainfall erosivity and erosion (in percentage) are presented in Figure 8, and the future changes are presented in Figure 9. They show great annual variations for both periods, and the changes reflect the rainfall changes and emphases the impact of rainfall on hillslope erosion.

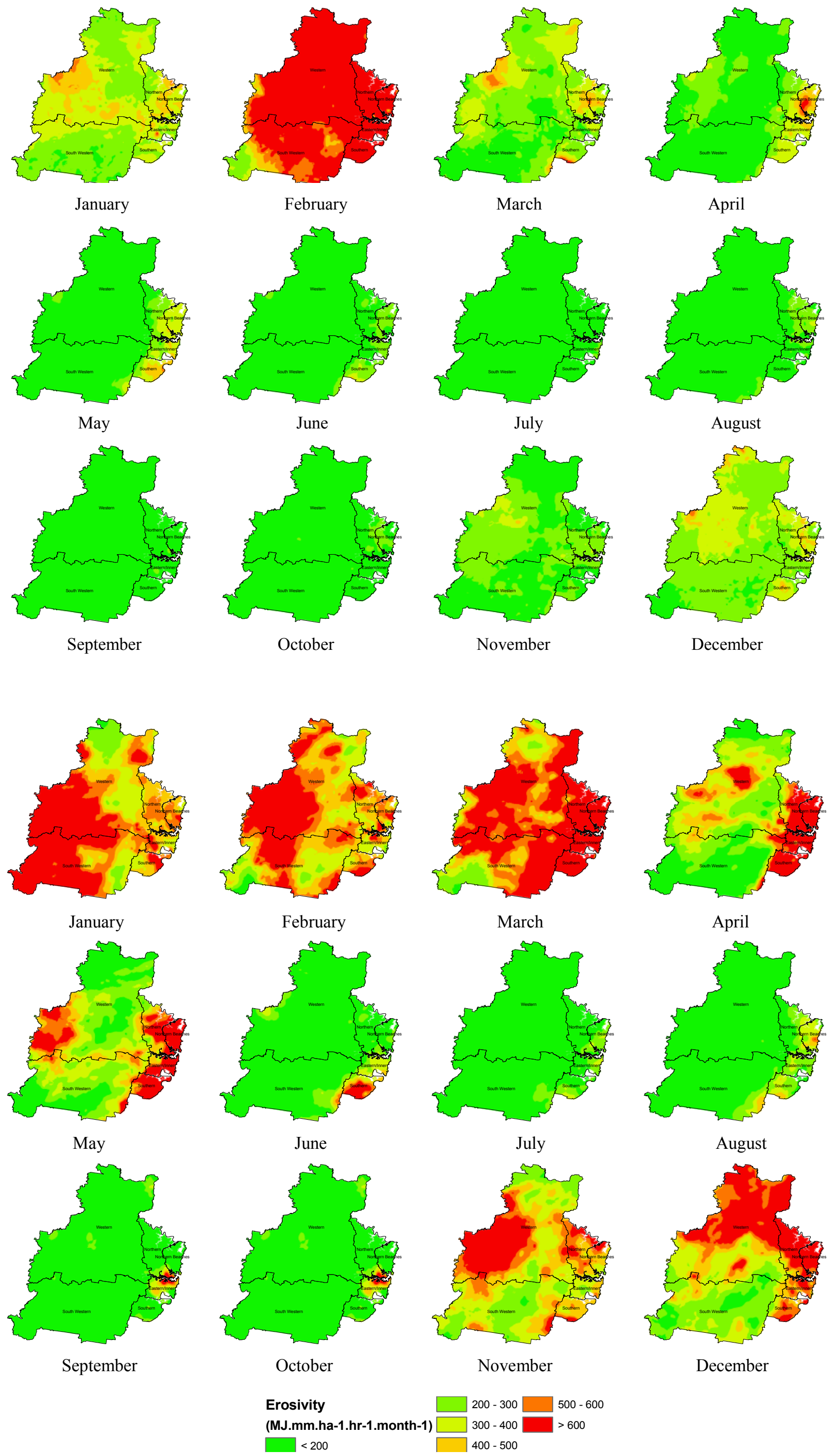

Figure 6. Modelled mean monthly rainfall erosivity for the recent (12 months at the top) and future (12 months at the bottom) periods in the Greater Sydney Region.

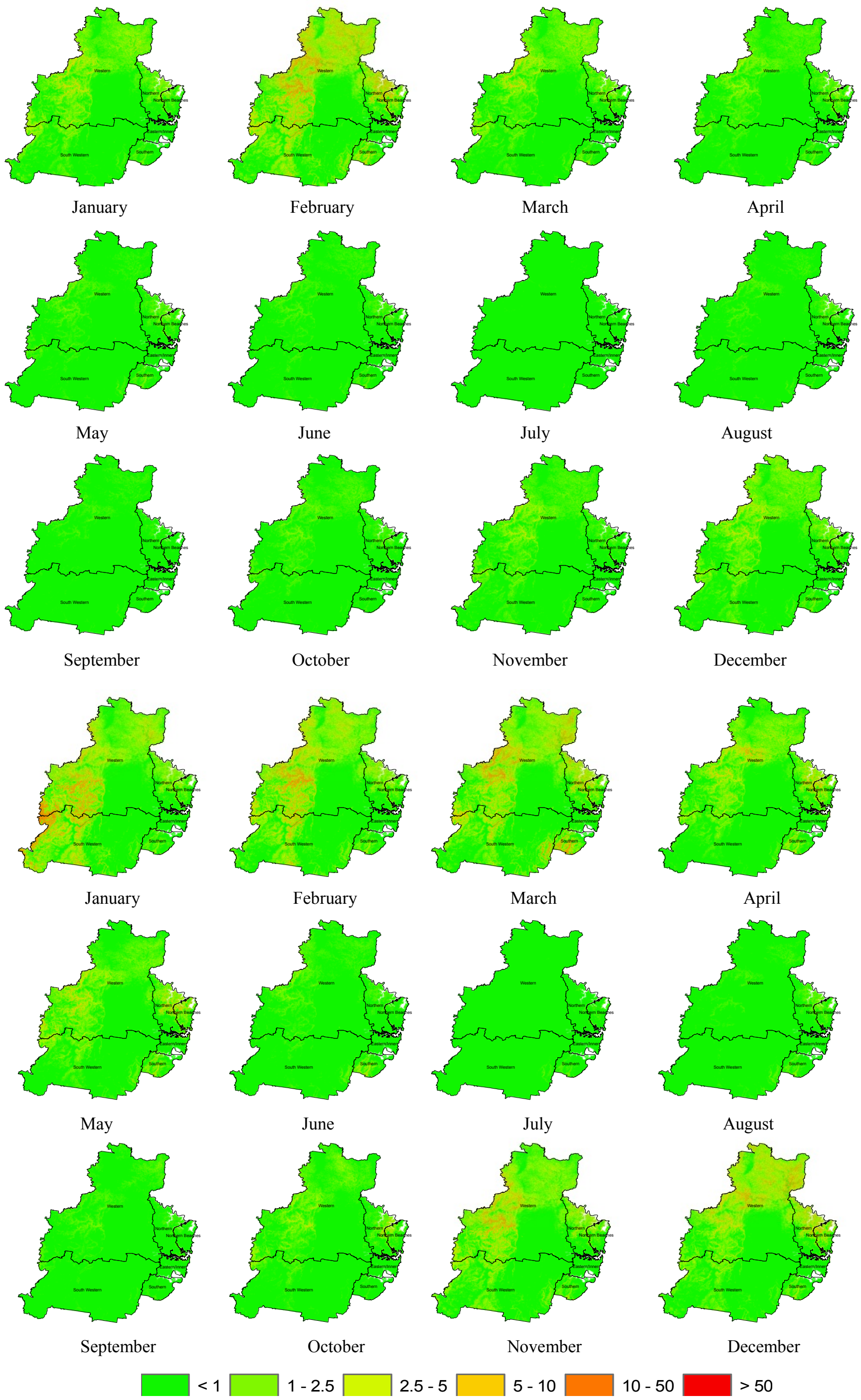

Figure 7. Modelled mean monthly hillslope erosion for the recent (12 months at the top) and future (12 months at the bottom) periods in the Greater Sydney Region.

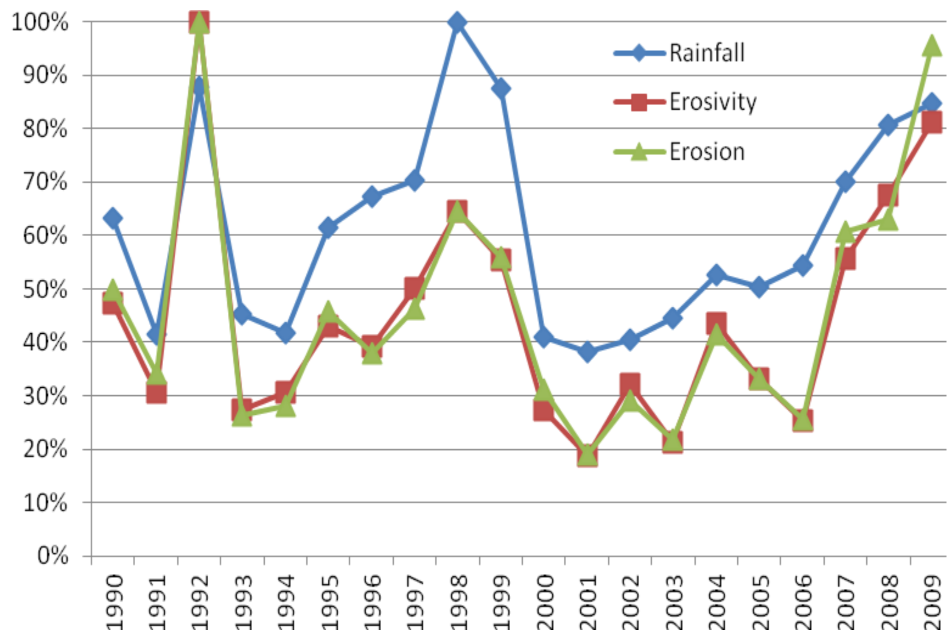

Figure 8. Annual change of recent rainfall, erosivity and erosion in percentage.

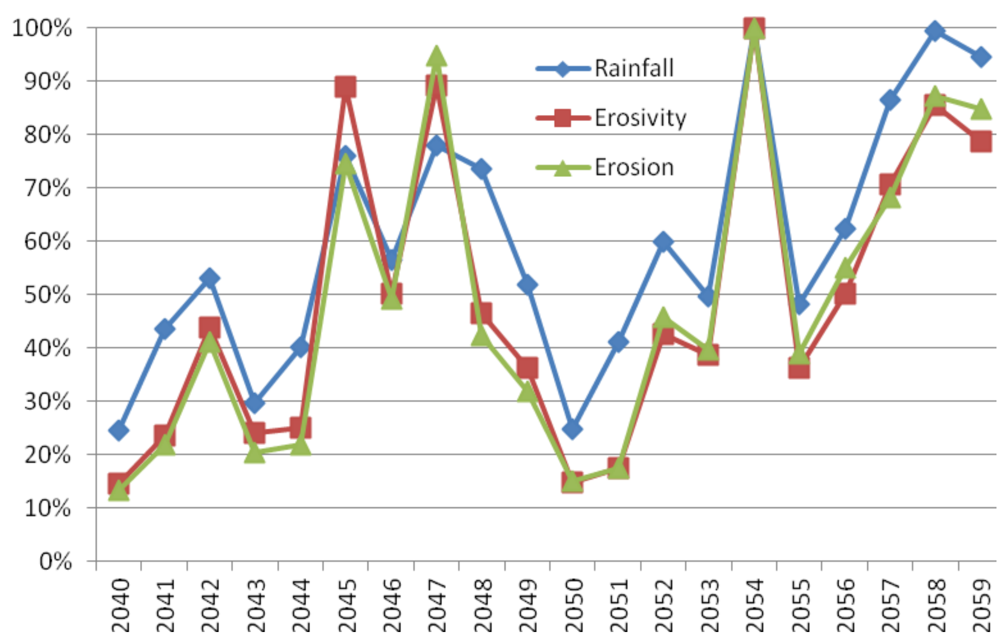

Figure 9. Annual change of future rainfall, erosivity and erosion in percentage.

5. CONCLUSIONS AND FURTHER DIRECTIONS

We produced monthly and annual rainfall erosivity maps for recent (1990-1999) and future (2040-2059) for the GSR (total 520 R-factor GIS layers) from daily rainfall grids using the daily rainfall model developed for the region. The erosivity maps were further spatially interpolated to 100 m resolution. The R-factor maps show good correlation with corresponding point R-factor values calculated from BoM sites within the GSR using pluviograph data (both R^2 and $E_c > 0.70$). The R-factor maps were further used to produce time series hillslope erosion maps (520 erosion risk maps).

This study has demonstrated a suitable approach for calculating monthly and annual rainfall erosivity values based on recent and future daily rainfall data for the GSR. Simple, theory-based models (Equations 1-5) were developed for estimating storm energy from daily rainfall amount and these models worked very well and proven to be useful as alternative methods of calculating erosivity. The methods have been successfully implemented in GIS for efficient calculation and mapping of the spatial and temporal variation of rainfall erosivity and, potentially soil loss across the GSR. The spatial interpolation greatly enhanced the level of detail which is useful for assessing erosion hazard and determining the timing of erosion control practices. 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.

Results indicate rainfall erosivity will increase about 61% for the GSR within the next 50 years, resulting in the same amount increase in hillslope erosion. Such a dramatic increase in the GSR is subject to further validation and assessment. Several factors may have contributed to the reliability of the predicted rainfall erosivity and its spatial variation, but the dominant reason is due to the projected rainfall increases by the specific GCM model (CSIRO MK3.5) which generally overestimates rainfall. As the results presented in this paper are only from one projection of a possible future simulation by a single GCM, they therefore possess a large band of uncertainty, in particular regarding the magnitude of projected changes. Using several models will give us a better understanding of the uncertainty in the projected future climate, as we can see where models agree and where they differ, and temper our interpretations accordingly. Performing multiple model runs also captures more reliable information on important but rare extreme rainfall events.

Based on this daily erosivity model, 1-mm rainfall increase per day (or 365 mm yr^{-1} or 46% of the mean annual rainfall for the GSR could result in about 700 (MJ mm ha^{-1} hr^{-1} yr^{-1}) or 66% increase in rainfall erosivity for the GSR. Assessment of changes in erosion from bare soil is only considered as potential risk as the implications for land use change and land use intensification are not included. However, it is not suitable for modelling actual erosion because the impacts of climate on ground cover dynamics have not been rigorously modelled as yet.

Intense rain from summer thunderstorms could cause massive erosion on steep slopes where there is severe bushfires such as the fires in Warrumbungle National Park in January 2013. The soil erosion risk will increase after severe wildfire and followed by intense rain which is an important climate change scenario for water supply catchments. Findings outlined in this study indicate that the risks associated with significant inflows of sediment, nutrients and organic matter into Sydney's water supply reservoirs, especially Lake Burragorang and the Woronora Plateau dams from rainfall erosivity alone have almost doubled. This could be expected to lead to eutrophication, algal blooms, smothering of aquatic habitats, reductions in drinking water quality and reservoir storage capacity, and potential damage to water delivery infrastructure.

The daily rainfall erosivity model was constructed using historical and recent data and measurements. The model and the associated parameter values developed from the historical or recent datasets may not be suitable for the future climates which appear to be more extreme.

The empirical approach for calculating the coefficient α using just two variables (latitude and elevation) is considered generic and inadequate to account for the dynamic variation of rainfall and erosivity distribution in space. Other factors (such as longitude, aspect, slope position, urban heat islands and distance from the coast) would also influence erosivity for a given amount of rain.

The model applied constant values of coefficients β (1.69) and η (0.41) for the entire GSR, but these coefficients are highly correlated with the parameter α, their relationships can vary in space and time.

Thus, our future studies are to be focused on 1) improving the estimation of model coefficients (such as β and η) and their variations using more appropriate sub-models; and 2) improving the model's capability and consistency for large area, such as South-East Australia (SEA), so that the modelling outputs are more consistent and comparable. Our immediate further direction is to extend the improved model to the entire SEA to produce high-resolution (both spatial and temporal) R-factor and hillslope erosion risk maps. The NARCliM projected daily rainfall data (at 10-km spatial resolution) from all 12 ensembles (4 GCMs and 3 RCMs, Evans et al. 2014) are to be used as model inputs to provide un-biased future prediction on future rainfall erosivity and hillslope erosion risk for two future periods (2020-2039, 2060-2079). Spatial interpolation techniques are further investigated and compared to enhance the efficiency and accuracy of the downscaling process. The model outputs will be available at high temporal and spatial resolution for use in climate impacts assessment and hillslope erosion risk prediction at regional and local scales.

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