Science of the Total Environment 601–602 (2017) 109–121

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Soil erosion predictions from a landscape evolution model – An assessment of a post-mining landform using spatial climate change analogues

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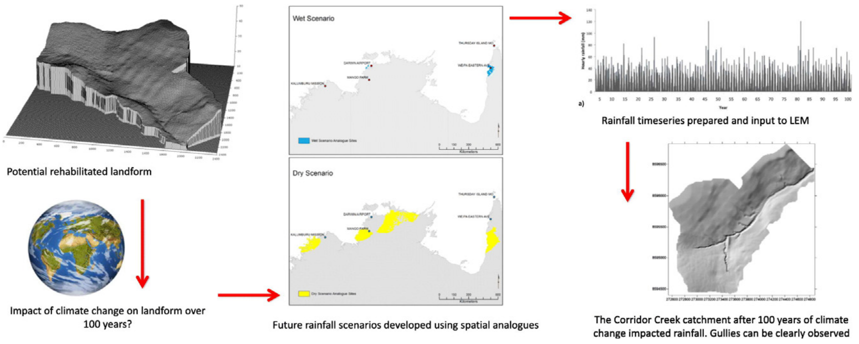
HIGHLIGHTS

- Rainfall variability is rarely considered in post-mining landscape assessment.
- We show that rainfall greatly influences erosion on a post-mining landscape.
- The outcomes and approach will improve post-mine rehabilitation design.
- Methods for developing rainfall data are provided.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 January 2017
Received in revised form 5 April 2017
Accepted 5 April 2017
Available online xxxx

Editor: D. Barcelo

Keywords:
Sediment transport
Climate change
Climate analogues
Landscape evolution model
CAESAR
Mine rehabilitation

ABSTRACT

Landscape Evolution Modelling (LEM) technologies provide a means by which it is possible to simulate the long-term geomorphic stability of a conceptual rehabilitated landform. However, simulations rarely consider the potential effects of anthropogenic climate change and consequently risk not accounting for the range of rainfall variability that might be expected in both the near and far future. One issue is that high resolution (both spatial and temporal) rainfall projections incorporating the potential effects of greenhouse forcing are required as input. However, projections of rainfall change are still highly uncertain for many regions, particularly at sub annual/seasonal scales. This is the case for northern Australia, where a decrease or an increase in rainfall post 2030 is considered equally likely based on climate model simulations. The aim of this study is therefore to investigate a spatial analogue approach to develop point scale hourly rainfall scenarios to be used as input to the CAESAR - Lisflood LEM to test the sensitivity of the geomorphic stability of a conceptual rehabilitated landform to potential changes in climate. Importantly, the scenarios incorporate the range of projected potential increase/decrease in rainfall for northern Australia and capture the expected envelope of erosion rates and erosion patterns (i.e. where erosion and deposition occurs) over a 100 year modelled period. We show that all rainfall scenarios produce sediment output and gullying greater than that of the surrounding natural system, however a 'wetter' future climate produces the highest output. Importantly, incorporating analogue rainfall scenarios into LEM has the capacity to both improve landform design and enhance the modelling software. Further, the method can be easily transferred to other sites (both nationally and internationally) where rainfall variability is significant and climate change impacts are uncertain.

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http://dx.doi.org/10.1016/j.scitotenv.2017.04.038
0048-9697/

1. Introduction

Rainfall intensity, frequency and duration are the primary influences on soil erosion, sediment delivery and landscape evolution (Burt et al., 2016). There have been many field and modelling assessments to quantify the influence of different rainfall amounts and intensity on soil erosion (i.e. the rainfall erosivity factor "R" in the Universal and Revised Universal Soil Loss Equation(s) being a good example (Esling and Drake, 1988; Renard and Freimund, 1994; Renard et al., 1991, 1994; Toy et al., 1999). The simplest approach is to use a static set of historical rainfall and/or climate data. However, there are two significant issues with this approach. Firstly, the historical record may be short or incomplete and therefore not representative of longer-term trends or extremes. This is particularly important as it is recognised that significant annual, decadal and multi-decadal variability of rainfall exists for many parts of the world (e.g. Cayan et al., 1998; Reason and Rouault, 2002; Giannini et al., 2003; Marengo, 2004; Verdon et al., 2004). In some cases rainfall data may not exist locally and therefore has to be inferred from nearby sites, which may only have a relatively short-term data record. Secondly, compounding the challenge of capturing natural variability is the uncertain effect of anthropogenic climate change on rainfall amounts, intensity and timing. Potential change in rainfall amount and intensity (Dowdy, 2014) is particularly important not just for natural and or agricultural landscapes but also for disturbed and rehabilitated systems such as post-mining landscapes. The first issue of short, unrepresentative rainfall records in landscape evolution modelling (LEM) has recently been addressed by Hancock et al. (2017), while this paper focuses on the second issue of addressing the potential effects of anthropogenic climate change.

These issues are of global importance and techniques are needed to quantify rainfall change and its environmental impact. Here we focus on Australia as a case study. Recent reports for northern Australia based on the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment state that of all variables, temperature changes (i.e. increase in the mean, minimum and maximum) have the highest consensus among global climate models (GCMs). However, there is generally low confidence in projected rainfall changes post 2030, with both decrease in rainfall and increase in rainfall equally likely (Moise et al., 2015). A similar degree of uncertainty in northern Australia rainfall projections was stated in the 4th Assessment Report (Suppiah, 1992). The projections are based on current understanding of the climate system, historical trends and GCM simulations of the climate response to changing greenhouse gas and decreasing aerosol emissions. Therefore, this data represents the best and most recent guidance for the development of future climate data (i.e. rainfall). However, given the high level of uncertainty in the projections for rainfall (which is the variable of focus of this study) and the fact that GCMs are most useful at the continental/seasonal scale (Kiem and Verdon-Kidd, 2011), there is still a mismatch between the information available and that which is required for landform evolution modelling (i.e. point/catchment scale at sub-daily intervals). Importantly, these are problems that are common to many global regions and many disciplines.

The issue of scale can be somewhat overcome using various downscaling methods, where the coarse resolution GCM output is used to generate higher resolution data using either statistical or dynamical approaches. However, downscaling will not result in a reduction in the envelope of future projections for the region in question and in some instances can even increase uncertainty (Wilby et al., 2004). Therefore, in this instance it can be argued that applying sophisticated and costly downscaling techniques is not warranted (as this will not decrease the uncertainty in the projections noting that model output varies not only in magnitude but also direction given the same greenhouse forcing). Rather, a sensitivity analysis to both increases and decreases in rainfall represents a more sensible and realistic approach.

The spatial analogue approach to downscale projected changes of rainfall is one example of a simple method that can be used for sensitivity testing (Ford et al., 2010). This method aims to match the future climate of the target location to the current climate of another site (known as the analogue site). The historical climate from the analogue site can then be used as the future scenario for the target location. This method is particularly popular in species distribution modelling (e.g. McLeman and Hunter, 2010) and assessing potential climate change economic impacts in urban areas (e.g. Hallegatte et al., 2007). The method has also recently been applied by Hayman et al. (2010) who used spatial and temporal analogues as a proxy for a 10% future drier climate in regions of South Australia to investigate climate change effects on the South Australian grain belt. Further, Kellett et al. (2011) used analogues to explore how communities can reorganise their infrastructure, built form and services to adapt to climate change, while Webb et al. (2013) applied analogues to explore projected climate change and the relative global impacts on the key wine growing regions of the world.

In this study, current and likely future climate change scenarios using spatial climate change analogues for a post-mining landscape and develop a series of likely rainfall change scenarios are examined. We focus on the decadal scale, that is the first 100 years of landscape development of a reconstructed post-mining catchment located in the Northern Territory, Australia. This initial period is the most dynamic, during which erosion rates are likely to be the highest, gully development is likely to (or may) occur and the surface water drainage network is established and enforced. 100 years is also within a human management time frame where any immediate sub-optimal (if they occur) landscape features (i.e. gullies, high sediment loads) can be observed and necessary rectification be conducted. While our focus is on Australia, the techniques presented in his paper are robust and applicable to other sites and applications.

Of interest here is type of erosion (i.e. rill, sheetwash, gullying) as different rainfall amounts and intensities may produce different forms of erosion. Also, understanding the rate and amount of eroded material leaving a site is necessary as it quantifies whether soil is being lost at a rate faster than it is being produced. Further, quantification of sediment delivered to the receiving stream can provide data that can be used to relate new sediment loads to that which the stream can normally carry or can accommodate. If sediment loads are excessive, it may potentially result in changes to off-site water quality and or siltation of the receiving stream. Type of erosion is significant as gullying (1) can remove large amounts of soil from relatively small areas and (2) depressurize any shallow groundwater table leading to increased loss of soil water. Thirdly, gullies on mine sites may expose buried materials that necessarily require long-term encapsulation. In the case examined here this is particularly pertinent as processing waste and low level radioactive ore will be buried within a re-engineered catchment.

An essential element of post-mining rehabilitation and reconstruction is a landscape or catchment which geomorphically integrates with the surrounding undisturbed landscape. The newly rehabilitated or reconstructed landscape will remain a part of the surrounding landscape system in perpetuity. Therefore it is vital that the hydrological and erosional behavior of these new landscapes is well understood. This allows design issues to be corrected before construction. As the climate is not static, we are interested in both short and long-term landscape behavior as it is important that reconstructed landscapes be evaluated not just for the effects of current climate but also for future climate and rainfall patterns as well. This may highlight any design concerns that may eventuate under different climate regimes.

This paper (1) applies a simple, yet effective technique to derive climate change scenarios at an appropriate temporal and spatial resolution for use in sensitivity testing; (2) employs this data in a landform evolution model (here the CAESAR-Lisflood model) to create a series of landscape predictions examining sediment discharge on a daily time step; and (3) examines the sensitivity of erosion rates and patterns to potential future changes in rainfall. The method outlined provides a robust and transportable procedure that can be employed at all sites.