Int. J. of GEOMATE, March, 2015, Vol. 8, No. 1 (Sl. No. 15), pp. 1138-1142
Geotech., Const. Mat. and Env., ISSN:2186-2982(P), 2186-2990(O), Japan

DESIGN DROUGHTS: A NEW PLANNING TOOL FOR ECOSYSTEM REHABILITATION

Devanmini Halwatura[1], Alex M. Lechner[1,2] and Sven Arnold[1]
[1]Centre for Mined Land Rehabilitation, Sustainable Mineral Institute, The University of Queensland, Australia. [2]Centre for Environment, The University of Tasmania, Hobart, Australia

ABSTRACT: Droughts are one of the most devastating natural hazards, often causing severe economic and environmental damage. Across Eastern Australia climate is highly variable and frequent floods and droughts affect large areas over prolonged periods of time. Understanding the variations and trends in these weather extremes is critical for ecologists to assess the adequacy of management plans for anthropogenically affected landscapes such as agricultural or post-mining land, where water often plays a critical role for ecosystem persistence. In this study we use a new approach developed as a management and/or risk assessment tool for degraded land rehabilitation to quantify periods of water deficit using the severity-duration-frequency (SDF) of rainfall, known as design droughts. This approach is based on the intensity-duration-frequency (IDF) design rainfall concept used by engineers for designing hydrological infrastructure. This study focuses on analysing drought events of four selected locations (Cairns, Melbourne, Wagga Wagga, Quilpie) across Eastern Australia using the Reconnaissance Drought Index (RDI). We used monthly total rainfall and evaporation data of the past 40 years (1972-2013) to identify drought events. We categorised the drought events according to their severity and duration and analysed separately the historic time series as two parts of 20 years (1972-1992 and 1993-2013). We calculated the recurrence intervals of droughts to assess trends in the occurrence of drought events. Results show that the recurrence intervals of Melbourne and Quilpie barely changed over time, while the drought recurrence intervals decreased in Wagga Wagga and Cairns. These findings have critical implications for any rehabilitation and management plans for post-mining and agricultural land.
Keywords: Drought, Reconnaissance Drought Index, Recurrence intervals, Land rehabilitation

1. INTRODUCTION

Human alteration from mining, urbanisation and industrial development can degrade lands, significantly impacting the natural environment [1]. Re-establishment of these lands has become a priority in this century. In recent years ecologists have focused more on global climate change [2] in average conditions such as mean temperature and rainfall. However, weather events such as intense storms, changes in El Niño and La Niña cycles, coastal flooding, extreme temperatures and droughts [4, 5] have intensified in the last decades and are the barriers for successful rehabilitation practices [5].

Droughts are one of the most harmful climatic events and often have significant impacts on environment and socio-economic assets all over the world, including Australia [2]. In proportion to its area, Australia has a very low percentage of runoff to rainfall. This, together with moisture deficits that occur for decades, makes Australia a very dry place [3]. Eastern Australia, in particular, has highly variable and frequent droughts that affect large areas over prolonged periods of time.

Eastern Australia comprises a broad range of agro-climatic environments which support globally significant biodiversity and holds vast mineral and energy resources [4]. These environments include a number of abandoned and ongoing mines. There are over 34,000 recorded abandoned mines in the eastern states of Australia (New South Wales, Queensland, and Victoria) that potentially need restoration owing to the legislative requirement for maintaining a sustainable mining industry in Australia [5]. The quantification of severity, duration, and frequency of drought events is crucial for planning for successful regeneration of these post-mined lands.

Drought analyses vary according to their purpose. Meteorological droughts are the most frequently studied type of drought, and standardized drought indices, such as the Reconnaissance Drought Index (RDI), provide the foundation for quantifying the duration, severity, and eventually the frequency or recurrence of meteorological drought events [6]. Drought severity, duration and frequency of occurrence are some of the key drivers of ecosystem rehabilitation because water availability is the primary abiotic factor for ecosystem rehabilitation in semi-arid climates [4].

In this study we use a new approach, known as design droughts [4]. This approach has been proposed as a management and/or risk assessment tool for post-mining ecosystem rehabilitation.

Design droughts quantify periods of water deficit using the severity-duration-frequency (SDF) of rainfall, similar to the intensity-duration-frequency (IDF) analysis of rainfall events, commonly used as a standard tool by engineers to design infrastructure such as storm water drains, flood mitigation levees, or retarding dams. The objective of this study was to quantify the design droughts at four selected locations in Eastern Australia based on the RDI. Two historic time series of rainfall and evaporation data for the past 40 years (1972-1992 and 1993-2013) were used to estimate the recurrence intervals of droughts for each of these sites in order to investigate climatic trends. We conclude by discussing the potential use of the method outlined in this paper as a management and risk assessment tool for rehabilitation of disturbed landscapes.

2. METHODOLOGY

We selected four sites across Eastern Australia (Cairns, Melbourne, Wagga Wagga, Quilpie) (Figure 1) across different agro-climatic classes [7] and agricultural environments [8] (Table 1). For these sites rainfall and potential evaporation (PET) data was most comprehensive, i.e. longest (40 years) and most complete [9]. For a detailed description of the methodology described in this paper refer to [4].

Table 1. Climate indices and climatic classifications of selected locations across Eastern Australia.

Location and climate classification[10]	R/PET [11]	R_w/R_s [a]	
		1972-1992	1993-2013
Cairns (Tropical)	0.91	0.12	0.11
Melbourne (Temperate)	0.51	1.20	1.11
Wagga Wagga (Temperate)	0.30	1.75	1.23
Quilpie (Temperate)	0.14	0.73	0.51

[a] Based on average of three months of rainfall during the winter (June-August) and summer (December-February)

We estimated drought severity and duration using RDI at a 3-monthly time scale [12] based on monthly rainfall and PET. The standardized RDI_{st} is given as:

$$\boldsymbol{RDI_{st}(k)} = \frac{\boldsymbol{y_k - \bar{y}_k}}{\boldsymbol{\hat{\sigma}_k}} \qquad (\boldsymbol{1a})$$

with

$$\boldsymbol{y_k = \ln \frac{\sum_{j=1}^{j=k} P_j}{\sum_{j=1}^{j=k} PET_j}} \qquad (\boldsymbol{1b})$$

where $\hat{\sigma}$ is the standard deviation, y_k is the month k during the year, $\bar{y}_k$ is arithmetic mean of y_k, and $\hat{\sigma}_k$ is the standard deviation of k, P_j and PET_j are precipitation and potential evapotranspiration for the j^{th} month of the hydrological year [6].

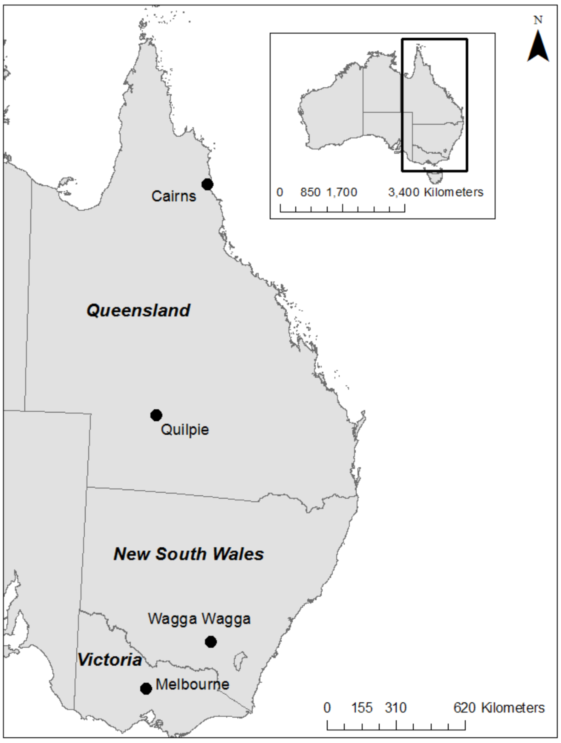

Figure 1. Selected locations of interest in Eastern Australia.

We categorized the drought events according to their severity and duration and split the historic time series into two parts of 20 years (1972-1992 and 1993-2013). Drought severity refers to the extent to which precipitation is below a threshold, whereas the drought duration is the period of rainfall deficit, preceded and followed by periods with no deficit [13]. Drought severity and duration were fitted to a gamma and logistic distribution, respectively [4]. We used the Frank copula to form a multivariate distribution of the fitted distributions of severity and duration. The copula parameter was then estimated according to the Inference Function for Margins (IFM) [4]. Recurrence intervals of drought events exceeding specific values of severity *or* duration (indicated by the logical operator "∨") were calculated as:

$$\boldsymbol{T}^{\vee}_{\boldsymbol{RDI}} = \frac{1}{P(S \geq s \vee D \geq d)} = \frac{1}{1-C[F_S(s),F_D(d)]}. \quad (2)$$

3. RESULTS

The recurrence intervals depicted in figure 2 describe site-specific rainfall patterns. In arid Quilpie the recurrence interval for droughts with a severity of 13 or duration of 17 months is one in 50 years, whereas in tropical Cairns the recurrence interval for the same drought is one in 100 years (1972-1992) or one in 1000 years (1993-2013). Temperate Wagga Wagga has a similar pattern of prolonged and severe droughts as arid Quilipe (1972-1992) (Figure 2) with a recurrence interval of one in 50 years for a drought of severity 12 or duration of 18 months.

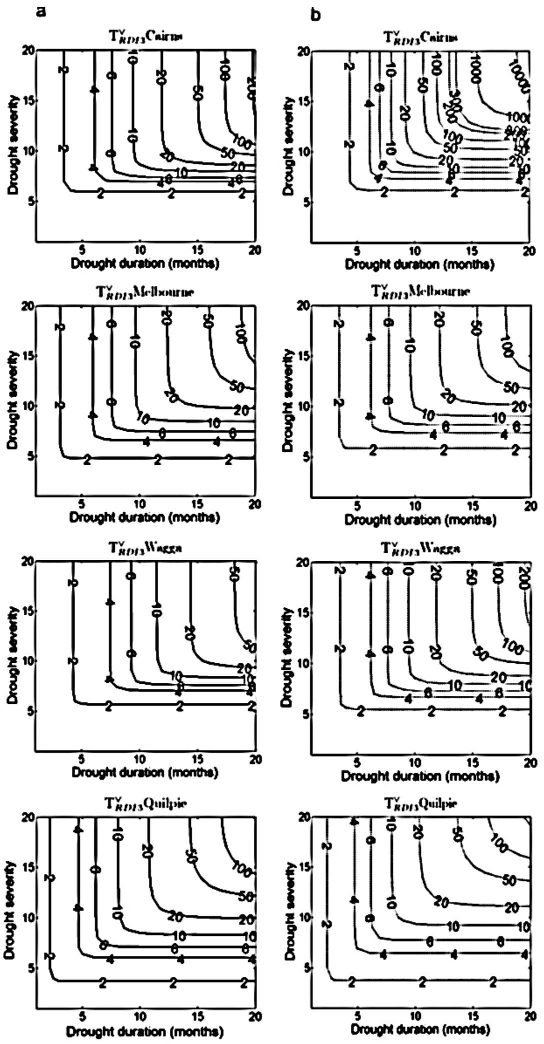

Figure 2. Recurrence intervals of drought events of any severity or duration of interest based on historic rainfall data for: (a) 1972-1992 and (b) 1993-2013.

For Quilpie and Melbourne there was very little difference in the frequency of drought events between the two 20-years time series (1972-1992 and 1993-2013), whereas for Cairns and Wagga Wagga the frequency of severe and prolonged droughts decreased over time (Figure 2). For all locations, except for Wagga Wagga, drought severity and duration increased between the first and the second period (Table 2). In the first period from 1972 to 1992, Wagga Wagga had the highest drought severity and duration, and Quilpie the lowest (Table 2). For the second period, from 1993 to 2013, drought severity and duration were highest in Cairns and lowest in Quilpie (Table 2).

Table 2. Mean severity (μ_S) and duration (μ_D) of selected locations across Eastern Australia and corresponding coefficients of variation CV_S and CV_D for short-term (RDI_3) droughts from 1972 to 1992 and 1993 to 2013.

Location	μ_S	CV_S	μ_D	CV_D
1972-1992				
Cairns	4.5	0.5	6.1	0.4
Melbourne	4.3	0.7	5.3	0.5
Wagga Wagga	5.5	0.9	6.8	0.7
Quilpie	3.4	1.1	4.5	0.7
1993-2013				
Cairns	4.8	0.4	6.4	0.3
Melbourne	4.5	0.7	6.1	0.4
Wagga Wagga	4.6	0.6	5.7	0.4
Quilpie	3.5	1.1	4.7	0.7

4. DISCUSSION

Land rehabilitation is a continuing issue in Eastern Australia due to below average rainfall resulting in decreased water availability along with high variable rainfall [4, 14]. However, across Eastern Australia, site specific rainfall and drought metrics have rarely been used [4, 15]. In this study we assessed trends in recurrence intervals of droughts for selected locations across Eastern Australia, extending a previous study on recurrence intervals as a planning tool for ecosystem establishment in post-mining landscapes [4]. The findings of this study and the methods developed may help to understand the variation of temporal drought patterns and encourage land managers to apply recurrence intervals of droughts as an early rehabilitation assessment tool.

Australia is often referred to as the driest inhabited continent on Earth as it includes a large in arid zone with significant temperature and precipitation variability [16]. Generally, the Australian climate can rapidly alternate between dry and wet periods, occasionally exhibiting sharp transitions or sudden shifts between the extreme events [17]. In Eastern Australia these climatic extremes are mainly controlled by large variations of the El Niño Southern Oscillation (ENSO) [4], which affects different regions at different times of the year [18]. These extreme climatic events impact on rainfall, influencing the average severity and duration of droughts, a primary abiotic factor driving rehabilitation (Table 2) [4].

The RDI_3 detected most severe and prolonged droughts in the tropical locations of Eastern Australia [4]. For the historic time series of 1972-1992 and 1993-2013 the most severe and prolonged droughts were detected in Wagga Wagga (temperate) and Cairns (tropical). The two locations have seasonal rainfall patterns, e.g. in Wagga Wagga winter rainfall is high, while in Cairns summer rainfall is high (Table 1). In arid Quilpie evaporation was high and seasonal rainfall patterns were absent. In contrast to tropical Cairns and temperate Wagga Wagga (Table 1), Quilpie has lower severity and duration of short term droughts and severe and prolonged long-term droughts [4].

The importance of rainfall variability including extreme rainfall patterns and below average rainfall has been highlighted in many research studies on ecosystem rehabilitation [4, 19, 20]. As plants are vulnerable to plant available water, identifying droughts and their characteristics play a critical role in ecosystem rehabilitation [21]. Recurrence intervals of short term droughts (Figure 2) can be used as metric for risk assessment, management and rehabilitation of degraded lands [15].

Estimated recurrence interval curves incorporate the severity and duration of drought events, also referred to as “design droughts” [4]. They provide the probability of occurrence of drought at a particular severity or duration so that land managers can assess the risk of failure of successful early ecosystem rehabilitation by selecting the suitable plant species for specific climatic conditions. Some plant species are highly sensitive to specific drought characteristics [22]. Similarly recurrence intervals along with known probabilities of plant establishment success for particular drought conditions provide a decision support tool for land managers to undergo a cost-benefit analysis prior to rehabilitation.

Finally, this study demonstrated how differences in recurrence intervals can be identified between two time-series and potentially be used to identify long-term trends. Our results support climatological studies that found increasing drought severity and duration to be more likely due to global climate change [23].

5. CONCLUSION

Recurrence interval curves or design droughts can be used to identify the severity, duration and frequency of occurrence of droughts for a given location. These recurrence intervals can be used to analyze the risk of failure of initial ecosystem establishment due to water deficit and should be implemented into rehabilitation plans of disturbed lands.

6. REFERENCES

1. Dobson, A.P., A. Bradshaw, and A.á. Baker, Hopes for the future: restoration ecology and conservation biology. Science, 1997. 277(5325): p. 515-522.
2. Campbell, B., Perspectives: Legislating change. Nature, 2013. 501(7468): p. S12-S14.
3. Gallant, A.J.E., et al., The characteristics of seasonal-scale droughts in Australia, 1911-2009. International Journal of Climatology, 2013. 33(7): p. 1658-1672.
4. Halwatura, D., A.M. Lechner, and S. Arnold, Design droughts as planning tool for ecosystem establishment in post-mining landscapes. Hydrology and Earth System Sciences Discussions, 2014. 11(5): p. 4809-4849.
5. Unger, C., et al., Mapping and Prioritising rehabilitation of abandoned mines in Australia. Proceedings Life-of-Mine, 2012: p. p259-266.
6. Tsakiris, G. and H. Vangelis, Establishing a drought index incorporating evapotranspiration European water 2005. 9/10: p. 3-11.
7. Hutchinson, M.F., et al., Integrating a global agro‐climatic classification with bioregional boundaries in Australia. Global Ecology and Biogeography, 2005. 14(3): p. 197-212.
8. Woodhams, F., et al., Carbon Farming Initiative: A proposed common practice framework for assessing additionality. 2012: Canberra, August.
9. Bureau of Meteorology. Bureau of Meteorology, Climate data. 2013 [cited 2013 April]; Available from: http://www.bom.gov.au/climate/data/.
10. Peel, M.C., B.L. Finlayson, and T.A. McMahon, Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci., 2007. 11(5): p. 1633-1644.

11. UNEP, U.N.E.P., World Atlas of Desertification. 1992: London.
12. Zargar, A., et al., A review of drought indices. Environmental Reviews, 2011. 19(NA): p.333-349.
13. Ganguli, P. and M.J. Reddy, Risk Assessment of Droughts in Gujarat Using Bivariate Copulas. Water Resource Management, 2012. 26: p.3301–3327.
14. Tongway, D.J. and J.A. Ludwig, Rehabilitation of Semiarid Landscapes in Australia. I. Restoring Productive Soil Patches. Restoration Ecology, 1996. 4(4): p. 388-397.
15. Audet, P., et al., Site-specific climate analysis elucidates revegetation challenges for post-mining landscapes in eastern Australia. Biogeosciences, 2013. 10(10): p. 6545-6557.
16. Barua, S., A.W.M. Ng, and B.J.C. Perera, Comparative Evaluation of Drought Indexes: Case Study on the Yarra River Catchment in Australia. Journal of Water Resources Planning and Management-Asce, 2011. 137(2): p. 215-226.
17. Fenby, C. and J. Gergis, Rainfall variations in south-eastern Australia part 1: consolidating evidence from pre-instrumental documentary sources, 1788–1860. International Journal of Climatology, 2013. 33(14): p. 2956-2972.
18. Bureau of Meteorology. Australian Climate Influences. 2014 [cited 2014; Available from: http://www.bom.gov.au/watl/about-weather-and-climate/australian-climate-influences.shtml?bookmark=introduction.
19. Hinz, C., G. McGrath, and A. Hearman. Towards a Climate Based Risk Assessment of Land Rehabilitation. in 1st International Seminar on Mine Closure. 2006. Australian Centre for Geomechanics, Perth: Nedlands WA 6009 AUSTRALIA.
20. Hodgkinson, J.H., et al., Climate adaptation in the Australian mining and exploration industries. 2010, CSIRO Climate Adaptation National Research Flagship,.
21. Engelbrecht, B.M., et al., Drought sensitivity shapes species distribution patterns in tropical forests. Nature, 2007. 447(7140): p. 80-82.
22. Arnold, S., Y. Kailichova, and T. Baumgartl, Germination of Acacia harpophylla (Brigalow) seeds in relation to soil water potential: implications for rehabilitation of a threatened ecosystem. PeerJ, 2014. 2: p. e268.
23. Mason, L., et al., Adapting to climate risks and extreme weather: A guide for mining and minerals industry professionals. 2013, National Climate Change Adaptation Research Facility Gold Coast, p.76.

Int. J. of GEOMATE, March, 2015, Vol. 8, No. 1 (Sl. No. 15), pp. 1138-1142.
MS No. 4133 received on June 13, 2014 and reviewed under GEOMATE publication policies.

Corresponding Author: Devanmini Halwatura