An automated drought monitoring system for New Zealand

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Key words: drought, drought monitoring, drought index, New Zealand

Abstract

A daily-updated web-based drought monitoring system for New Zealand is presented. Map and time series products are based on the newly-developed New Zealand Drought Index (NZDI), which is derived from four commonly-used base indices: the Standardised Precipitation Index (SPI), the Soil Moisture Deficit (SMD) and its anomaly (SMDA), and the Potential Evapotranspiration Deficit (PED). The NZDI products have been reviewed by several stakeholders from the meteorological, agricultural and government sectors, with excellent feedback received and integrated into refinements of the products. Historic 'adverse event' declarations in New Zealand have been used to qualitatively validate the drought monitor products, with very good agreement shown, though more in-depth comparative studies are warranted and suggested, together with assessing the potential seasonal predictability of the NZDI. The New Zealand Drought Monitor webpage is currently operational and provides a decision support service that can be applied to many uses, as needed and determined by the users.

1. Introduction

Droughts are a regular natural hazard in New Zealand that particularly affect the agricultural sector. Severe and prolonged droughts can have a significant impact on agricultural production and animal health, and hence can impact the wellbeing of farmers, their communities, agricultural businesses and, ultimately, the nation's economy. As an example, the 2013 drought is estimated to have had a negative effect of 0.6% on GDP and 3% on the exchange rate (Kamber et al., 2013). However, many of the risks associated with the detrimental impacts of drought can be reduced by regular and consistent monitoring of up-to-date drought conditions, combined with effective drought risk management strategies (Hao et al., 2014).

Droughts typically develop slowly, and result from an extended period of time (e.g. several weeks or months) when precipitation is less than normal for a given region. Drought monitors, defined here as systems (usually web-based) for regularly updating drought conditions for an area (often an entire country or larger region) enable the development of drought conditions over time to be assessed. There are a number of drought monitoring systems operational around the world (e.g. Svoboda, et al., 2002; Yan, et al., 2016; Cammalleri, et al., 2016). Such drought monitors utilise a range of observations,

Submitted: 11 August 2017
Accepted: 26 October 2017

including rainfall, soil moisture and satellite imagery, to enable assessment of the spatial and temporal variability of drought conditions.

One of the major challenges to New Zealand's agricultural sector is how to reduce the impacts of droughts. Droughts impact agricultural systems economically as well as environmentally. Economically, droughts reduce agricultural production (particularly pasture-based and crop production), can affect animal health (due to dehydration and malnutrition), can disrupt industries connected to agricultural production, and often result in economic (and mental) hardship to farmers and rural communities. From an environmental perspective, droughts can deprive soils of essential moisture, which can lead to higher rates of erosion, soil and stream/river/estuary health issues, and can stress plants to the point where they become highly susceptible to disease and/or die from wilting (Mishra & Singh, 2010).

To mitigate these impacts of drought, a monitoring system with extensive geographic coverage producing timely regularly-updated information is required. Real-time monitoring of droughts can aid in developing a Climate Risk Early Warning System (CREWS is a major global initiative of the UN Sendai Framework for Disaster Risk Reduction). An objective evaluation of the current drought condition is the first step of a CREWS, leading to better long-term strategic planning on water storage options, sources of supplementary feed, optimum herd size and forward contracts, and improved short-term tactical decision-making on the efficient use of available water, feed, off-site grazing and financial resources for selling and purchasing decisions. An additional component of a CREWS is a reliable forecast of drought conditions for the near future (forecasts are not addressed in this paper, but the potential predictability of drought conditions is currently under investigation). This combination of long- and short-term consideration of options is often termed drought risk management (Wilhite et al., 2010).

Drought risk management is highly context specific. It is a management process that is situation-dependant and evolves over time, given the almost unique climatic and financial pressures experienced during each drought event (Clark, 2001). Drought policy or decision-making during times of drought should be based on risk management practices, the context of the policy or decision, and a reliable standardised index of drought that provides guidance on the historic, current, and potentially future drought conditions at a relevant scale (Nelson et al., 2008; Steinemann and Cavalcanti, 2006).

1.1 Definition of drought

Droughts, as any natural hazard, impact a variety of natural, social and economic processes. As a consequence, definitions of drought differ depending on context and application. Wilhite (2000) categorises droughts into three major groups as shown in Figure 1; meteorological, agricultural and hydrological. Meteorological drought is characterised by the degree of dryness and the duration of the dry period, and is considered region-specific based on the typical rainfall regime of a given region. Agricultural drought is comprised of the agricultural impacts associated with precipitation shortfalls, differences in potential and observed evapotranspiration, and soil moisture deficits. Hydrological droughts refer to the reduction in surface or subsurface water supply (i.e. river flow, lake levels and groundwater) resulting from periods of meteorological drought, and inherently lag the onset of meteorological and agricultural drought (Wilhite, 2000).

The New Zealand Drought Monitor uses meteorological observations as well as water balance and evapotranspiration models to quantify drought conditions. In the above scheme that would place it in the meteorological and agricultural categories.

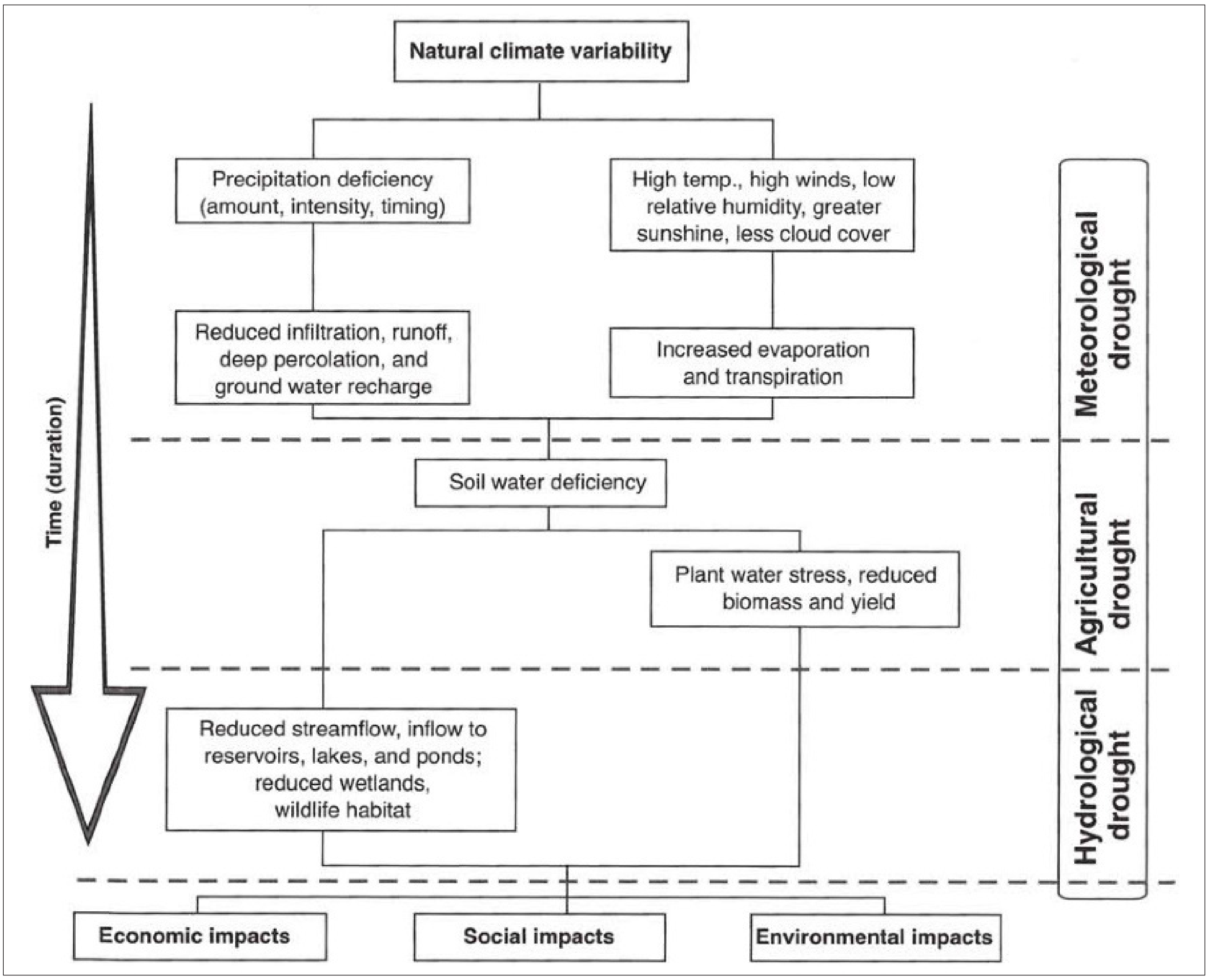

Figure 1: Relationship between various types of drought and duration of drought events. Sourced from (Wilhite, 2000).

1.2 Aims of the New Zealand Drought Monitor

This paper describes the design and development of an automated drought monitoring system for New Zealand based on a newly-developed New Zealand Drought Index (NZDI). The principal aims of the New Zealand Drought Monitor are: 1) to present to the user, in a simple and insightful format, products representing the three main aspects of drought: severity, duration and spatial extent; and 2) to be the single definitive drought information service for the entire country. To achieve this, a composite index called the New Zealand Drought Index (NZDI) is created from four existing drought indicators, serving as a measure of the severity. This index is then presented to the user as an interpolated map (providing information spatial extent) and spatially-aggregated time series charts (providing information on duration), both of which are updated on a daily basis and made freely available online (the New Zealand Drought Monitor is located on the National Institute of Water and Atmospheric Research (NIWA) webpages at www.niwa.co.nz/drought-index.).

The principal users of the New Zealand Drought Monitor are expected to be representatives from the country's primary sector (including farmers, growers, foresters, business consultants and advisors, primary sector organisations, and the Ministry for Primary Industries). However, the service will also be extremely valuable to other drought-sensitive users, such as Regional and Local Councils, the Rural Fire Authority, conservation authorities and organisations, and hydroelectricity generation companies. In all cases, it will be up to the users to determine how they can best utilise the service. It is envisaged that some users will apply the information as guidance only, while others may develop an action plan which includes set thresholds of the NZDI. With the onus on the user to determine the application of the information, the New Zealand Drought Monitor can be clearly defined as a decision support system (Power and Sharda, 2009).

2. Methods

The NZDI is calculated from four base indices: the Standardised Precipitation Index (SPI), the Soil Moisture Deficit (SMD) and its anomaly (SMDA), and the Potential Evapotranspiration Deficit (PED). The choice of these indices was based on sensitivity to rainfall and soil moisture, real-time data availability, good spatial coverage of data, familiarity for intended users (each of these indices has been presented either as maps or charts on the NIWA webpage for some time), and a balance of absolute and relative drought indices (World Meteorological Organization and Global Water Partnership, 2016). There are many other candidate indices that could be used, such as the Palmer Drought Severity Index (PDSI; Palmer, 1965) and the Standardised Precipitation-Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2015). However, several studies have shown that there is often a high correlation between drought indices (e.g. Guttman, 1998; Keyantash and Dracup, 2002; Jain et al., 2015), so adding additional indices or substituting the chosen indices for others is unlikely to add information. Furthermore, the PDSI and SPEI are not currently displayed as maps or charts on the NIWA webpage (or other New Zealand websites), so users will have less familiarity with these indices, in general.

2.1 Base indices

The SPI (McKee et al., 1993) is a widely used drought indicator throughout the world and is based solely on precipitation data. It compares the total precipitation over a certain fixed timespan to its long-term average. The SPI is a relative measure of precipitation, and enables the comparison of precipitation variation between locations with different precipitation regimes. This is especially relevant in New Zealand, where mean annual rainfall exhibits considerable spatial variability. For the NZDI, 60 days is used as the accumulation period. This is an arbitrary choice (other common periods used internationally are 30, 90 and 120 days), and for some regions of the world even longer periods are used (e.g. Van Loon and Van Lanen (2012) note that a 6-month accumulation period corresponds well to both rainfall-deficit and snow-based droughts in Europe). For New Zealand, a period of around two months with well-below normal rainfall is usually sufficient to trigger drought-like conditions (pers comm., Alan Porteous, NIWA). For example, the Waikato region experienced a severe drought in the summer and early autumn of 2007/08 which was initiated by very low rainfall in December 2007 and January 2008 (rainfall anomalies for these months for this region were between 10 and 30 percent of normal, with some locations (e.g. Ruakura) receiving record low January rainfalls (4 mm; the lowest January total since records began in 1906)). A gamma distribution is fitted to the historical precipitation data and transformed into a normal distribution. The SPI value is then defined as the z-score on that distribution. Negative (positive) SPI values represent less (greater) than median precipitation, and application-specific SPI thresholds can be defined to characterise the onset and conclusion of drought conditions (Guttman, 1998).

The SMD is the amount of water (expressed in mm) the soil is short of full capacity. This number is estimated using a simple single soil layer water balance model (Porteous et al., 1994), which adds moisture to the soil through rainfall and removes it through evapotranspiration (ET). A single soil moisture holding capacity of 150 mm is used for all soils. This value is based on field experiments and is generally typical for loam soils in New Zealand (Porteous et al., 1994). While it is recognised that different soil types do have varying soil moisture holding capacities, the use of the single value of 150 mm for calculating soil moisture deficit has been shown to be sufficient for representing broad patterns of dryness for the country, particularly in lowland agricultural regions (pers comm, Alan Porteous, NIWA). ET is assumed to continue at its potential rate (the potential evapotranspiration, PET) until half of the water available to plants is used up (referred to as the plant wilting point), whereupon it linearly decreases, in the absence of rain, as further water extraction takes place. ET is assumed to cease if all the available water is used up. Porteous et al. (1994) show that this simplified model of ET, related to PET and available soil water, is a reasonable representation of the drying characteristics of loam soils in New Zealand. The SMD anomaly is calculated with respect to the 30-year (1981-2010) SMD normal. If the SMD is less than -110 mm and the anomaly is less than -20 mm, then soils are often referred to as 'severely drier than normal' and drought conditions (if not present already) may be imminent.

The PED is the difference between PET and actual evapotranspiration (AET) (Mullan et al., 2005). PET is the amount of water that could evaporate and transpire given sufficient available water (Lu et al., 2005), and is calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998). Note, the FAO-56 Penman-Monteith method calculates the evapotranspiration rate from a hypothetical grass reference crop of 0.12 m height, with a fixed surface resistance of 70 s m-1 and an albedo of 0.23 (Allen et al., 1998). AET is the actual water loss from a vegetative surface by evaporation from soils and from plants, given the prevailing water availability (Rana & Katerji, 2000; Stephenson, 1998). Based on the simple water balance model of Porteous et al. (1994), if half or more of the total soil moisture capacity is available, potential and actual ET are set equal, so PED is 0. If less than half of the total soil moisture capacity is available, actual ET will be smaller than potential ET and PED becomes positive. Days when the water demand is not met (i.e. positive PED), and pasture growth is reduced, are often referred to as days of potential evapotranspiration deficit. As a rule of thumb, an accumulation of 30 mm more PED corresponds to an extra week of reduced grass growth (Mullan et al., 2015).

2.2 Combining the indices

The SMD and PED indices depict water shortage as positive values (there are no negative values), while the SPI and SMD anomaly have both positive and negative values. Since we are only interested in the 'dry' values, only the negative (i.e. drier than normal) part of the SPI is used by setting positive SPI values to 0. The remaining negative values are then changed in sign so that, similar to SMD and PED, a strictly non-negative scale is obtained where increasing values indicate drier conditions. For the same reasons, only the drier than normal positive SMD anomalies are used.

Another difference between the indicators is the sensitivity. The SPI scale gets more sensitive as conditions get drier, whereas the others do not. To introduce a similar behaviour in the other indices the following transformation is applied:

$$x' = -\log_2 \frac{x}{x_{max}} \qquad (1)$$

For the SMD and its anomaly the maximum value (xmax) is the total soil moisture capacity. For the PED the maximum value is determined per station based on all available data (and is updated if a new maximum value is observed). After transformation, the indices are multiplied by a scaling factor so all have similar

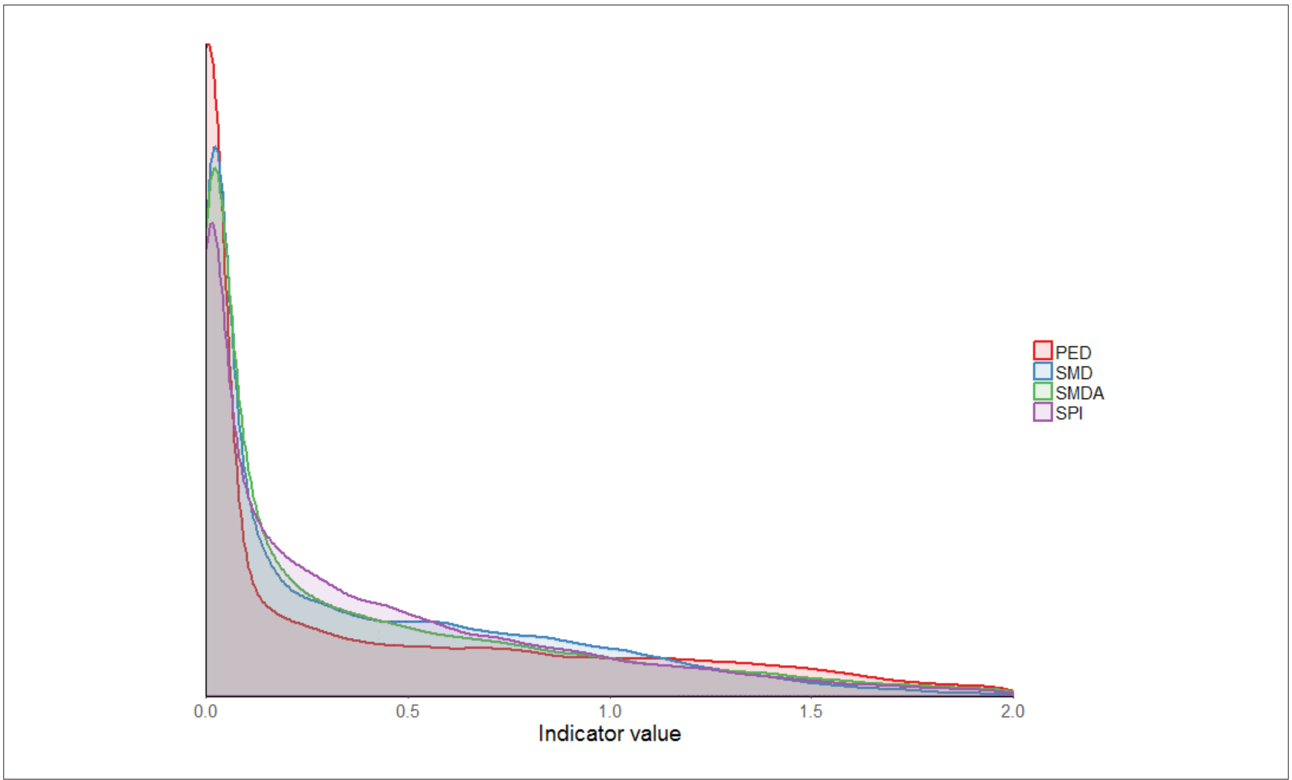

Figure 2: Density distributions of the regional values of the four base indices over the period 2007-2017.

distributions. This is illustrated by the density plot in Figure 2 showing the distribution of the base indices after transformation and scaling over the last 10 years. Having all indices on a similar scale allows for the NZDI to be obtained as the simple unweighted average of the four indices.

2.3 Product generation and feedback

The base indices are calculated and transformed on a daily basis using data from every available climate station in New Zealand that has the necessary observational data. Presently, there are around 100 automatic climate stations distributed around New Zealand that have the necessary data for the daily NZDI calculations. These stations are nearly all located in low elevation (less than 500m elevation above sea level) locations (Figure 3).

The daily NZDI is calculated at these climate stations, and then a thin plate smoothing spline interpolation is applied using the anusplin package (ANUsplin v4.2; Hutchinson, 2017) to produce NZDI values on a nationwide 0.005° (approximately 500m) resolution grid. The gridded data are then used to create daily maps and calculate spatially-aggregated values presented as time series charts. As with any spatial interpolation, the accuracy of the interpolated data is highly dependent upon the number and location of the input data sites (Tait, 2008; Tait and Macara, 2014). In this case, while the spatial coverage of climate stations is good for most areas below 500m in elevation (where the majority of the country's agricultural land is located), the coverage is poor in higher elevation locations hence caution should be used when interpreting the NZDI values in these areas.

In August and September 2016, a NZDI review document was circulated to several stakeholders in the meteorological, agricultural and government sectors in New Zealand (Mol, 2016). The document briefly outlined the proposed new NZDI and asked participants to

Figure 3: Location of presently-open climate stations (as at October 2017) where daily NZDI calculations are made.

comment on the sample maps and time series products. Excellent feedback was received from the stakeholders, much of which was implemented when finalising the NZDI products.

In summary, the feedback centred on the following four topics:

- Duration and intensity – Could the area under the curve in the time series plots be considered as another indicator of drought severity? It's quite possible that a long duration drought event is more severe that a short duration but more intense event;

- Spatial divisions – In most cases district boundaries (Territorial Local Authorities; TLAs) are a useful spatial division for the time series plots, but some eastern TLAs span both coastal and hill country and it would be better to sub-divide these areas;

- Weighting of indices – Currently the NZDI component indices are equally weighted, but perhaps there should be more weighting to the soil moisture anomaly, since this index shows winter time droughts more significantly than the other indices; and

- Classification scale – The NZDI scale should be classified using the following divisions and terminology:

0.75 Dry

1.00 Very dry

1.25 Extremely dry

1.50 Drought

1.75 Severe drought

Some of these suggested changes were made immediately (e.g. the classification scale/terminology and spatial subdivisions), while others (e.g. the weighting of indices and integrated values) will require more research and will be potentially implemented over time.

3. Results

One of the main challenges for any drought indicator is the absence of an objective independent ground truth that can be used for validation. Since the main purpose of the NZDI is to provide insight into the spatial extent, duration and severity of extreme events, past severe droughts are used to qualitatively assess its usefulness. In the case of severely dry conditions, the New Zealand Ministry for Primary Industries (MPI) may declare an 'adverse event' for a particular part of the country (MPI, 2017). Importantly, meteorological conditions are an important factor in this decision process, but other aspects, such as social and economic impacts are also taken into account. As a result, drought conditions may exist in a location but if there are relatively few social and/or economic impacts (i.e. people are generally coping with the dry conditions) then an adverse event will not be declared. Understanding the limitations, these declarations can serve as an indicator for the occurrences of severely dry conditions over the past 10 years and hence can be qualitatively compared with the NZDI values.

3.1 The 2013 drought

The 2012-2013 drought was one of the most extreme droughts on record. It affected almost the entire North Island as well as western coastal areas of the South Island (Porteous and Mullan, 2013).

Figure 4 shows the declarations of drought related adverse events during the 2012-2013 summer and autumn period. For comparison, Figure 5 shows the NZDI maps corresponding to these declarations. Qualitatively, the

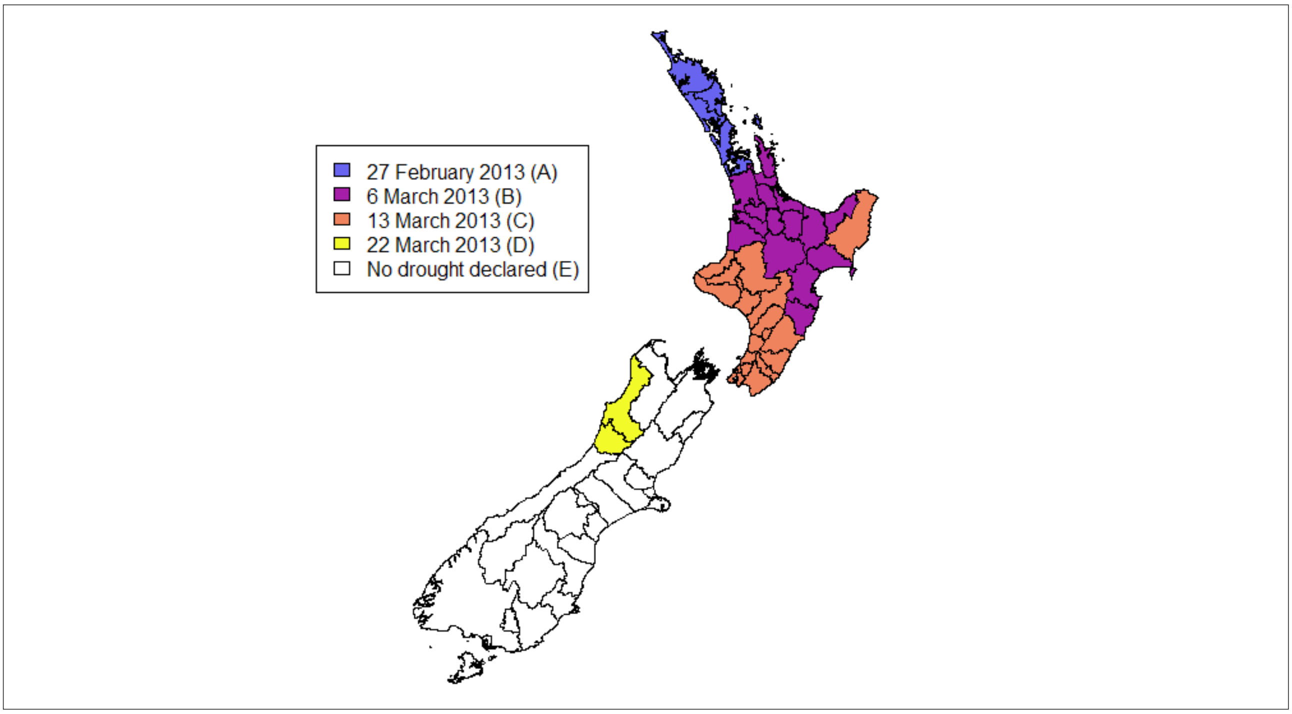

Figure 4: Drought related adverse events declared by the Ministry for Primary Industries during the 2012-2013 drought.

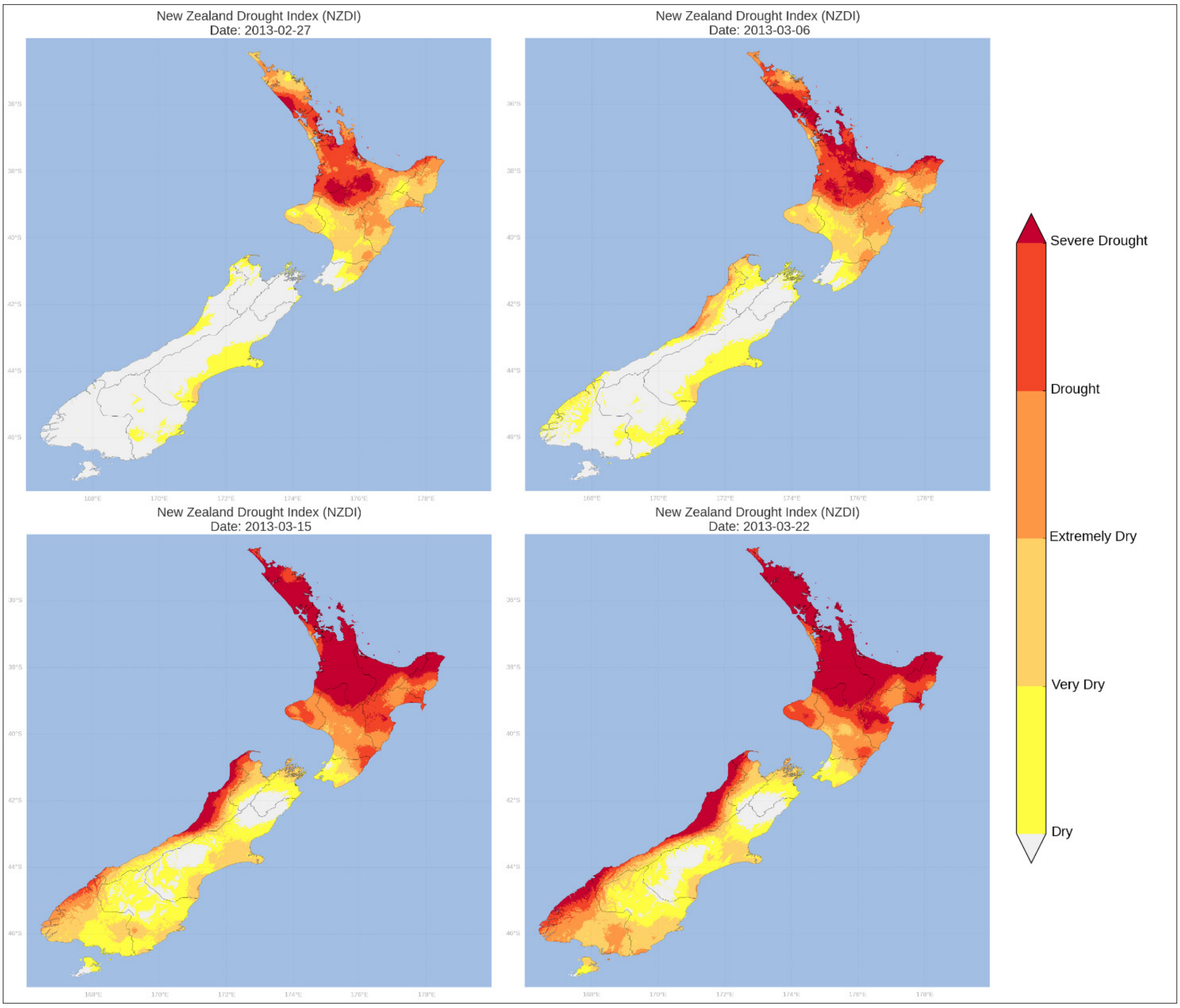

Figure 5: Drought related adverse events declared by the Ministry for Primary Industries during the 2012-2013 drought. NZDI maps for the dates on which drought related adverse events were declared during the 2012-2013 summer and autumn.

areas with high NZDI values correspond well with the locations where drought was declared. Based on the NZDI only, drought might have been declared in more locations in the South Island during mid- to late-March 2013. However, as noted previously, declarations are not solely based on the meteorological conditions present, so presumably the socioeconomic impacts of the dry conditions were not particularly adverse in these other regions such that drought was not declared there.

Figure 6 shows the time series of the NZDI averaged over the declaration regions A through E, from Figure 4. In each case the declarations were made after a steady build-up of the average NZDI, but before reaching the peak. However, the actual NZDI value reached at the time of declaration varies between declaration regions: around 1.5 for regions A and B, around 1.3 for region C, and around 2.1 for region D. Based on Figure 6, it could be argued that an adverse event should not have been declared for all of region C (especially in the Wellington Region, as shown in Figure 5) and that an adverse event should have been declared earlier for region D. This example demonstrates the potential for using a standardised drought index for adverse event declarations, and is one of the core reasons the Ministry for Primary Industries (MPI) strongly supported the development of the NZDI. MPI have indicated that they will adopt a set of 'trigger' thresholds of the NZDI in their declaration process (similar to a 'watch/warning' system), but will still include an assessment of the socioeconomic impacts before declaring an adverse event.

3.2 Northland

Northland is a region of New Zealand that is frequently affected by droughts. Four drought related adverse events were declared for the Northland region between 2007 and 2017. These events coincide with the four highest peaks in the NZDI for the region over the same period, as shown in Figure 7, indicating that the NZDI is performing very well at identifying these relatively short-lived but intense repeated events.

3.3 The 'Hurunui drought'

One of the longest droughts in recent history occurred in North Canterbury. The official adverse event declaration of the so-called 'Hurunui drought' started at 2 February 2015 and only finished on 31 December 2016. Figure 8 shows the NZDI for the east part of the Hurunui District, which was the most seriously affected area of this relatively localised drought. This event is particularly

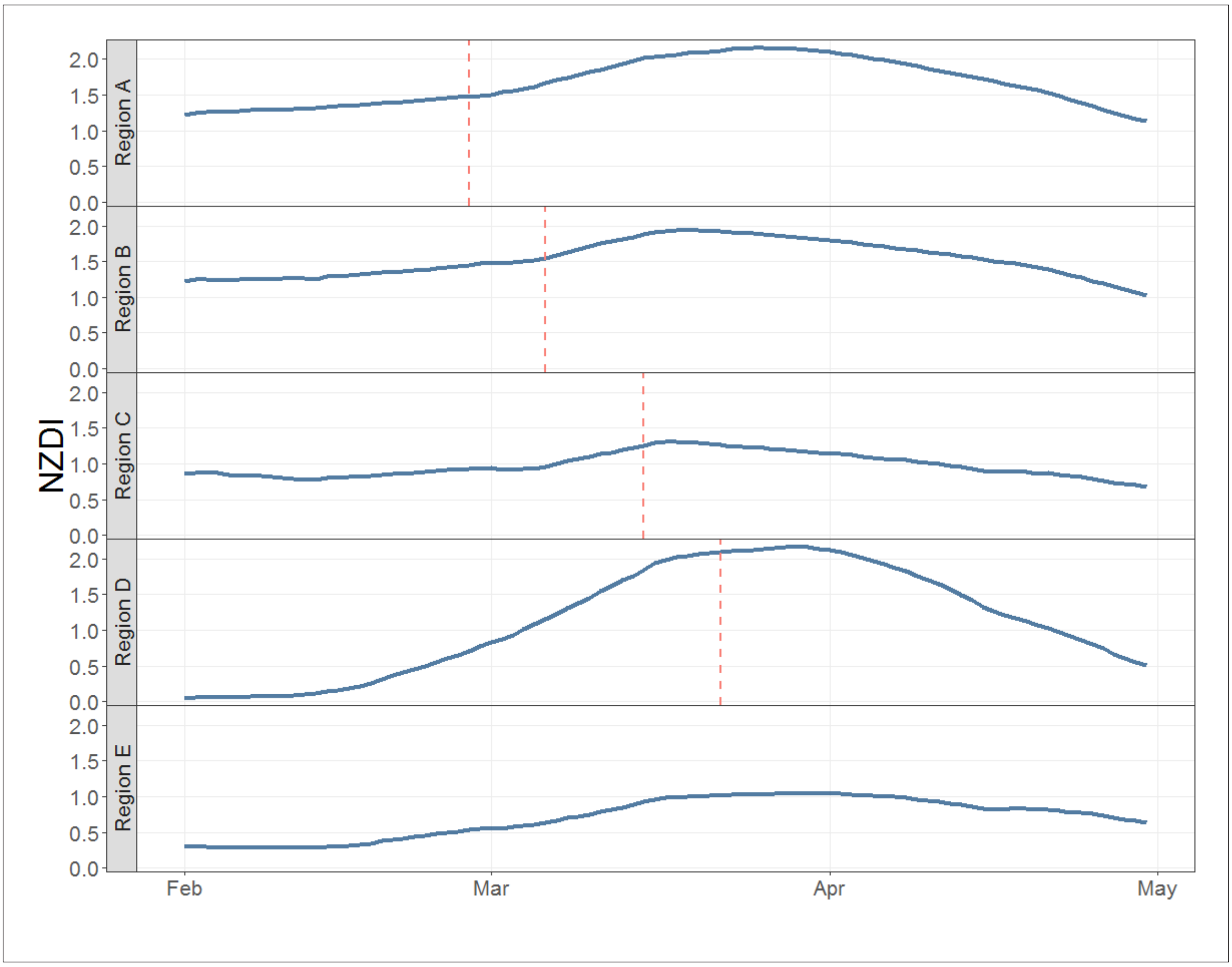

Figure 6: Average NZDI over regions shown in Figure 4 during the 2012-2013 drought (months shown are for 2013). Vertical dashed lines indicate declarations of an adverse event.

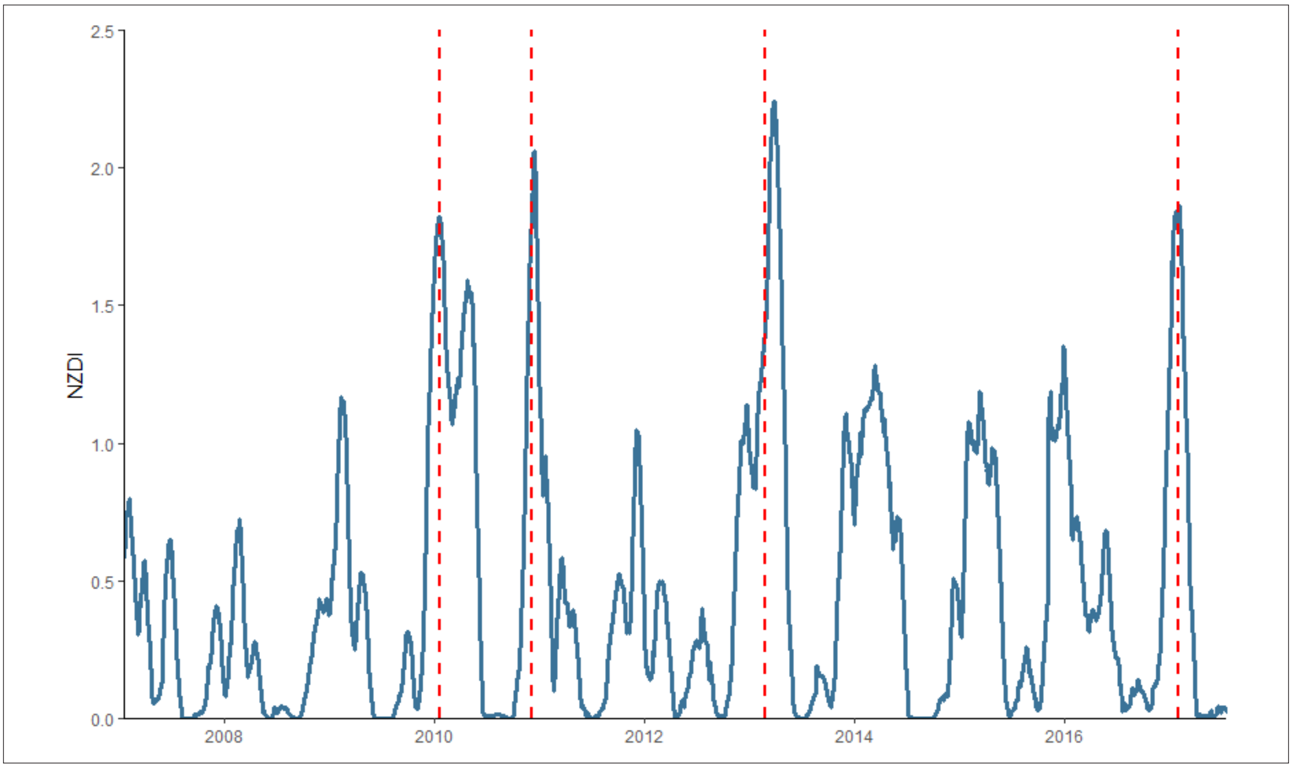

Figure 7: NZDI for the Northland region. Vertical dashed lines indicate declarations of drought related adverse events.

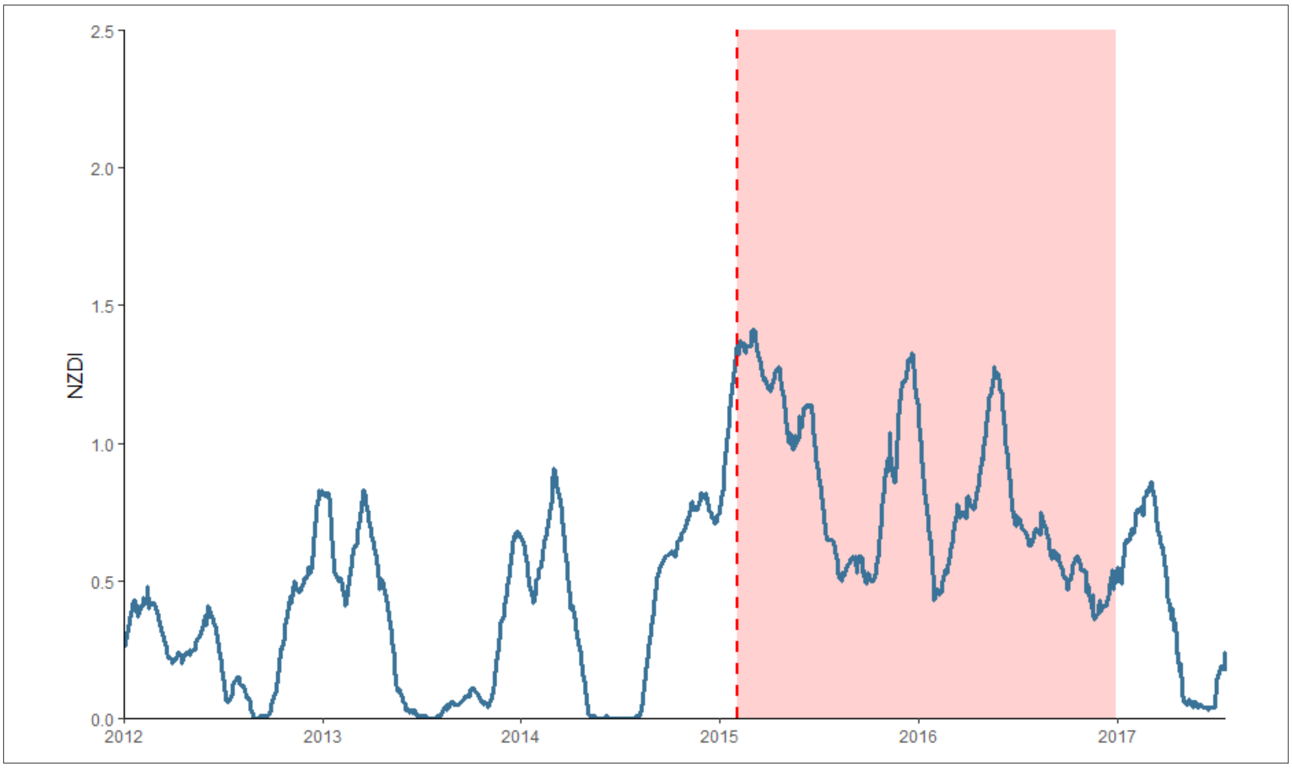

Figure 8: NZDI for Hurunui-East from January 2012-July 2017. The vertical dashed line indicates the official start of the adverse event and the shaded area indicates the duration of the declared event.

interesting because it lasted through two winters and winter droughts are extremely rare in New Zealand. In this case the winter dryness is definitely noticeable in the NZDI. Generally, NZDI values across the country fall to near zero during winter months, with the nationwide average being about 0.1 for July through to September. Here they remain well above 0.4 during both winters, indicating a sustained dry period. Without the usual winter soil moisture recharge, droughts in the following spring and summer have a greater impact on farmers, as late-winter and spring grass growth is severely reduced often meaning drastic mitigation measures (such as complete or near-complete destocking) are required. Figure 8 suggests that a combination of summer- and winter-time NZDI thresholds could be used to identify prolonged dry periods.

4. Discussion and next steps

Drought is a complex phenomenon that cannot be completely captured in a single number. However, for many purposes it is very desirable to have a single drought index that can be used to indicate the severity, extent and duration of a dry spell. The NZDI has been developed with that particular aim. It is a combined index with five meteorological/agricultural drought categories, from 'dry' to 'severe drought'.

The main users of the New Zealand Drought Monitor are representatives of the primary sector, at all levels. Importantly, several stakeholders from the primary sector were consulted and asked for their feedback once demonstration products were available. Feedback was excellent, with participants very happy with the depiction of previous drought events using the NZDI, and also offering good suggestions for improvement – some of which have already been implemented.

Qualitatively, the NZDI agrees well with known drought related adverse events declared in the recent past. In particular, test cases using the 2013 drought, which extended over a large proportion of New Zealand, and smaller-scale droughts in the Northland and North Canterbury regions, confirm the occurrences of severe dry spells known from adverse event declarations. From the 'Hurunui drought' it appears the NZDI might decrease during winter even in dry conditions due to the transformation used (Eq. (1)), where the maximum values for SMD or PED might only be approached during summer. This can be adjusted by either using a variable maximum, depending on time of year or by lowering the thresholds during colder months. In the first case, caution will have to be taken as the transformation is not defined when the parameter in question reaches the maximum value. Nevertheless, the NZDI during this event was still anomalously high during the winters of 2015 and 2016, which combined with high summer values in these years is highly indicative that this drought was indeed a multi-year event.

A full quantitative assessment of the NZDI in comparison with other drought indices, including some not included as base indices for the NZDI, has not yet been undertaken but could be the topic of future research. However, it is unlikely that any single index, or even combination of indices, will capture all the intricacies of drought. This is because drought is highly location- and context-specific, and managing drought is as much about risk-based decision-making as it is about how dry the conditions are and for how long. It is for this reason that the New Zealand Drought Monitor is best described as a decision support system, with the particular use of the NZDI maps and charts wholly dependent upon the users' needs. Future research should focus on whether and how these needs are being met through the practical use of the NZDI products.

The next step to produce a fully-functional CREWS for drought risk management in New Zealand is currently being developed through a new research project with two inter-related research aims: 1) Drought monitoring and forecast development; and 2) Use of drought information for risk management. The first research aim will focus on producing, validating and operationalising objective regional 1- to 3-month drought forecasts for all New Zealand. The second research aim will assess methods for better managing drought risk by New Zealand's agricultural sector using up-to-date drought monitoring and forecast information combined with good practice drought risk management strategies. Working with end-users throughout the entire project period will ensure that the results of this research are not only understandable and straightforward to use but are tailored to their specific requirements.

Acknowledgements

The authors would like to thank Vijay Paul for the spatial visualisations, the Ministry for Primary Industries (MPI), in particular Tony Schischka, and members of the stakeholder review group for their input. This work was co-funded by NIWA core research funds and MPI.

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