4

Drought Management and **DECISION-MAKING**

Animal tracks and footprints on a drying out indian lake, Andhra Pradesh, India | Photo Credit Tim Gainey, Alamy Stock Photo

DROUGHTS ARE HIGH impact natural disasters that affect populations around the world, and there is evidence of droughts becoming more severe. India is already a drought vulnerable country. With nearly half of the population employed in agriculture, drought events can have devastating impacts on society. A range of approaches to characterise, monitor and predict droughts to enhance resilience to the hazard are required. As in other regions, drought indicators have a vital role to play in enabling drought to be identified and declared, and the severity of drought conditions to be quantified. A corner-stone of drought mitigation in India is the 'Manual for Drought Management 2016', a framework which outlines the process by which welfare assistance is initiated according to a combination of drought indicators, severity level, and declarations. The Manual provides considerable flexibility for how the indicators should be applied in practice to support drought declaration. In this chapter, the current status of drought indicators, globally, is outlined, and the importance of having robust and validated drought indicators to enhance drought decision-making is demonstrated using a case study in Maharashtra.

4.1 Drought in a global context

Owing to its slow development and persistence of impacts, drought is often not considered to be as catastrophic as other natural disasters. Nevertheless, droughts are the most economically costly extreme events (UNDRR 2021; Wilhite 2000), owing to their wide-ranging impacts on the economy, agriculture, public water supply and environment. At their most extreme they are also deadly, and are associated with a range of accompanying phenomena that increase the costs to lives and livelihoods (e.g. wildfires, water quality issues, etc.). There is mounting evidence that droughts are becoming more severe due to climate change (e.g. Chiang et al 2021) in many

Using new tools to evaluate and improve drought response can support drought-vulnerable communities.

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Drought, outskirts Sami Town, Gujarat | Photo Credit REUTERS, Alamy Stock Photo

parts of the world, leading to dramatic increases in exposure of populations to severe drought (Pokhrel et al 2021).

Whilst recent advances have been made in understanding the drivers and propagation of drought, they are generally not sufficiently understood, creating a barrier to effective mitigation. Effective monitoring of developing drought is generally lacking internationally, and forecasting of drought is both highly complex and rarely available with sufficient lead time for water managers to act (e.g. Bachmair et al 2016a). The significant spatial footprint of drought events tends to exceed the scale of water management units, inhibiting effective drought mitigation actions even if accurate forecasts could be provided at sufficient lead time. Furthermore, in the Anthropocene, human activities are increasingly recognised as playing a significant role in exacerbating drought impacts (van Loon et al 2016), but information on the scale of these impacts is generally lacking. Taken together, this means that drought remains a damaging phenomenon, which is not sufficiently understood or anticipated, providing a strong rationale for advancing our understanding and management of these events globally.

4.2 Improving drought science for decision-making

Given these challenges, there is a critical need for tools to enable drought hazard to be quantified. The **three pillars of effective drought management**[1] are: monitoring and early warning; vulnerability and impact assessment; and mitigation and preparedness. In this context, drought indicators and indices can be seen as the cornerstone of drought management. They enable drought severity to be quantified, and as such are pivotal to monitoring and early warning, enabling drought onset, evolution and termination to be identified. They are also crucial to risk assessment, in enabling historical drought hazard (and future hazard using climate projections) to be quantified. Finally through both these applications, drought indicators support the implementation of appropriate and timely mitigation measures.

One of the key challenges in drought science globally, is in determining which **drought indica-**

1 https://www.unccd.int/issues/land-and-drought

tors to use to support drought management, and in ensuring that indicators are fit for purpose, i.e. that they identify drought and/or capture drought events appropriately. More specifically, this means indicators that can identify drought conditions that will lead to impacts, and hence, can be used as triggers for mitigation responses. While there is a burgeoning international literature on drought indicators, with more than 100 identified by Lloyd-Hughes (2014), and the number grows annually, there remains little consensus, beyond a widespread adoption of the Standardized Precipitation Index (SPI), on how they should be applied. There is even less clarity on the extent to which widely-used indicators can robustly identify impacts to give confidence in their use in applied drought management (Bachmair et al 2016b). This is complicated by the multi-faceted nature of drought, with different indicators available for meteorological, hydrological and agricultural drought (and so on). Many studies have recently argued that selection of drought indicators depends on the impacts in question, and have tried to select indicators for monitoring and early warning, or risk assessment, based on their link with impacts in given sectors (e.g. Blauhut et al 2016; Bachmair et al 2017; Wang et al 2021). This is a challenging task given the lack of readily available information on impacts for 'ground-truth.'

Drought indicators are often developed for academic purposes and there remains a gulf between the indicators available through monitoring and early warning platforms, and the needs of water managers 'on the ground' concerned with drought management (e.g. Bachmair et al 2016a). Several recent studies have highlighted that ongoing **engagement with decision-makers**, in the context of their own drought management frameworks, is the most effective strategy for selecting drought indicators and designing drought monitoring systems (e.g. Steineman et al (2015) in the US; Hannaford et al (2019) in the UK; Collins et al (2016) in these countries and Australia).

4.3 Drought in India

India is a drought vulnerable country, with depleting groundwater, and access to only 4.2% of the world's freshwater supply whilst being home to a sixth of the world's population (Gautam & Bana 2014; Panda & Wahr 2016). To provide water needed for industry, agriculture and public consumption, the country relies on the southwest Monsoon (June to September). Failure of the southwest Monsoon has been linked to the historical prevalence of droughts across India, which in turn have been associated to the major famines that have occurred over the subcontinent (Mishra et al 2018 & Mishra, 2020). With nearly half of the Indian population (43%) employed in agriculture, drought events can be far-reaching and devastating for the country (UNDP 2018). While famines have decreased over time as drought resilience has improved, droughts remain a major threat to agriculture and rural livelihoods (Mishra et al 2019).

Recent notable drought events have occurred in 2015 and 2019. In 2015, a severe heatwave and resulting drought caused India's reservoir stocks to plummet to just 29% of their total capacity, with an estimated impact on a quarter of the population (BBC 2016). In 2019, India saw its lowest pre-monsoon rainfall in more than 60 years, resulting in the worst drought in Maharashtra for nearly half a century (Al Jazeera 2019). Water resources and drought management in India are challenging in the present, and the likely future combination of population growth, increasing water consumption that accompanies further development, and climate change, will only increase these challenges.

4.4 Current approach to drought declaration in India

The '**Manual for Drought Management 2016**' is a guide to drought monitoring, declaration and response in India. Since its inception in 2009, the Manual has been comprehensively updated in 2016, with subsequent amendments made in 2018, to ensure its relevance in effective monitoring and mitigating the impacts of drought in India. The Manual helps to inform State decision makers and water managers about drought, how to make early warnings and declare a drought, and in the event of drought, what responses and mitigation strategies to use. The chapter on 'Drought Declarations' sets-out five categories of indicators and indices to be used to assess drought severity: rainfall, crop area sown, vegetation cover, soil moisture, and hydrology. The causative indicator 'rainfall' is mandatory in all drought assessments, whereas one impact indicator must be chosen from three of the remaining four categories. Drought declarations are made for the main cropping seasons in India, i.e. August, October and March, which correspond to the Early-Kharif, Kharif and Rabi seasons, respectively. The declarations classify the drought event as either 'moderate' or 'severe.' A 'moderate' drought may unlock relief from the State Disaster Relief Fund (SDRF) or the State's own resources, whereas a declaration of 'severe' drought enables the State to seek assistance from the national government's National Disaster Relief Fund (NDRF; Sharma 2019).

The Manual is flexible by design, which is necessary for a procedure which applies to a hydro-climatologically and hydro-geologically diverse country such as India[1]. Though the Manual has provided a basis for declarations of drought and release of relief across India, the flexibility may have resulted in sensitivities in drought declarations (Sharma 2019). Understanding the complexities of drought declaration across spatially diverse regions is complicated, but new technologies, such as **interactive applications[2]**, can provide water managers with intuitive and accessible interfaces with which to investigate and interpret their decisions (see **Box 4.1**).

4.5 Drought science for decision-making in Maharashtra: a case study

The first step of developing new technologies and research that is applicable to a set of stakeholders, is to involve them in **defining the aims of the research**. In order to understand the experiences of applying the Manual guidance on the ground, two stakeholder events were held in Mumbai in late 2018 and 2019. The broad audience included representatives from water management, academia and consultancy. The general consensus was that with limited guidance being provided, subjective decisions are required of water managers in implementing the Manual procedures. In addition, it was suggested that further validation was required to improve confidence in the methods.

This feedback was used to develop an interactive application (**Box 4.1**), which was then used to validate the indicators and procedures implemented in the Manual. It is important that declared droughts align closely with droughts that have actually occurred and resulted in impacts. Given that the declaration process has changed over time, simply benchmarking observed drought to historical declarations cannot be done. Instead, the declarations have to be 'reconstructed' as if the current procedure has been in place throughout the historical record.

The **validation** of these reconstructed drought declarations was done using the Integrated Drought Index (IDI; Shah & Mishra 2020), which has been calculated for all Maharashtra districts for the period 2001 to 2015. The skill of the Manual was also assessed by computing a range of scores across districts, combinations of indicators, season, and drought severity.

This validation exercise highlighted variations across space, between reconstructed drought declarations and observed drought. For example, **Figure 4.1** highlights the difference in performance of the Manual between districts. The results show that for a given combination of indicators, the reconstructed drought events align poorly with IDI in Dhule district, whilst aligning well in Solapur district. This spatial variability in performance of the Manual may have negative impacts on communities dependent on drought relief assistance.

The results (see **Figure 4.1**) also suggested an **underestimation of drought occurrence**, which may be linked to the indicators and procedures prescribed in the Manual. In order to enhance drought decision-making, this aspect needs further investigation, as too stringent a procedure that results in actual droughts not being declared can lead to huge impacts for people in need of drought relief assistance.

An unexpected observation from validating the method using the interactive application was apparent **subjectivities in drought character-**

1 If interested, Chapter 6 contains more information on the nature of the diversity across geology, hydrology and climate in India.

2 Chapter 3 also introduces another use for interactive applications, but this time for flood risk management.

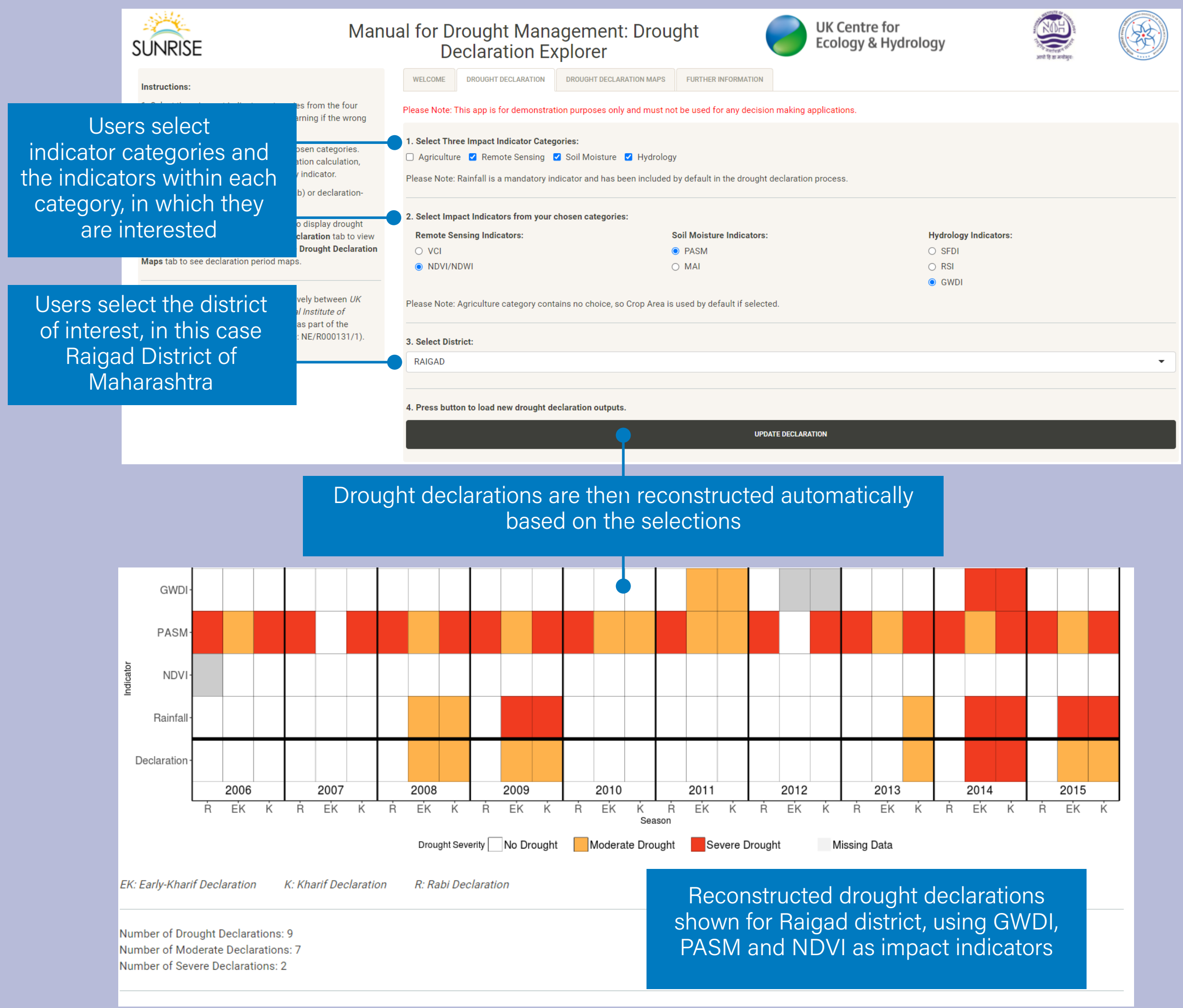
BOX 4.1 An interactive app for drought declarations in India

Interactive applications (apps) are powerful vehicles for the assessment of drought management and mitigation approaches. They have the flexibility to cater for the full range of combinations of drought indicators that need to be assessed; they can cope with the assimilation of a range of relevant datasets for validation; and they provide an intuitive interface for users to swiftly and clearly ask their own questions and interpret the output.

The '*Manual for Drought Management: Drought Declarations Explorer*'[1], an interactive app, was developed to validate the droughts identified and characterised using the procedure set out in the 'Manual for Drought Management 2016', and to help better understand how subjective decisions in the process can lead to sensitivities in drought declarations.

The demonstrator App can reconstruct drought declarations over a period of time where data are available, following the processes described in the Manual, as well as advice on best practice from implementers of the Manual. For the case study, the reconstructions were made for the period between 2006 and 2015 for 34 districts in Maharashtra State, for which data were available.

Within the App, users select which impact indicator categories and impact indicators to use in the reconstruction of drought events, which are then visualised as maps or time series for each district. This enables users to explore the impacts of changing drought indices on a spatial and temporal scale, respectively. The App could be extended nationally, dependent on data availability.



1 https://shiny-apps.ceh.ac.uk/manual_drought_management_explorer/

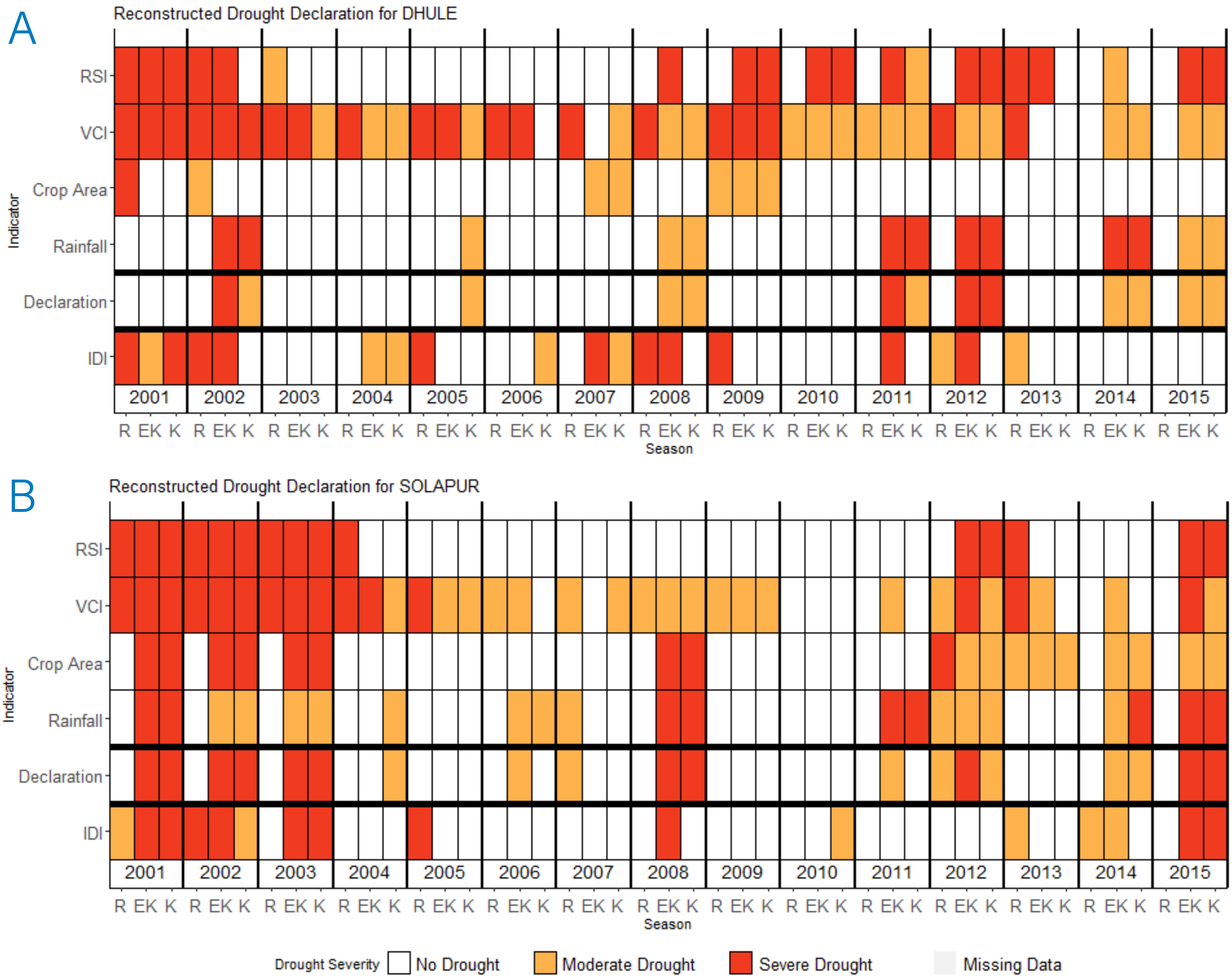


FIGURE 4.1 Reconstructed drought declarations for Dhule (A) and Solapur (B) districts using Reservoir Storage Index (RSI), Vegetation Condition Index (VCI) and Crop Area as indicators. The 'declaration' is shown between the bold horizontal lines, and compared to the Integrated Drought Index (IDI) in the bottom row.

isation, based on the combination of indicators used. For instance, as they both assess impact on vegetation it would be expected that Normal-ised Difference Vegetation Index/ Water Index (NDVI/NDWI) and Vegetation Condition Index (VCI) would show a similar number of drought events. However, as illustrated in **Figure 4.2**, VCI regularly falls below the Moderate (solid) and Severe (dashed) thresholds, whereas NDVI/NDWI rarely crosses these thresholds. This results in a far greater number of drought declarations when VCI is used in the drought declaration process compared to NDVI/NDWI.

This result needs further research, to deter-mine why these differences arise and under what circumstances one or the other vegetation indicator should be used, so that the Manual can offer the relevant guidance to water managers. At present, it appears that the choice of indicator in this instance can have an impact on whether or not drought relief assistance is unlocked.

4.6 Towards enhanced drought management

A robust assessment of measures to quantify drought is an essential component of any drought compensation scheme. If indicators misrepresent the duration, severity or spatio-temporal evolution of drought, they cannot provide water managers with adequate information on the hazard, and as a result prevent the timely implementation of appropriate measures to mitigate the worst of the impacts.

The approaches described above are one such mechanism to validate the metrics underpinning a drought compensation scheme. The case study of Maharashtra State was selected because of its significant population and drought vulnerability, and any extrapolation of the findings for this location must be considered with caution. Nevertheless, the approaches provide a framework for validating the drought characterisation underpinning compensation schemes more widely for other States, river basins or countries. The only requirement is a sufficient amount of observed data against which to compare declarations of drought. Of course, validation of existing procedures is only the first step in the process of providing enhanced resilience to drought. The findings of this validation must be integrated into practice, perhaps through the inclusion of alternative metrics, parameters of these indicators, or different approaches to combining data across different components of the hydrological cycle.

4.7 References

Al Jazeera 2019. India reels under worst drought in decades, heat kills dozens https://www.aljazeera.com/news/2019/6/17/india-reels-under-worst-drought-in-decades-heat-kills-dozens (Accessed 24 02 2021)

Bachmair S, Stahl K, Collins K, Hannaford J, Acreman M, Svoboda M, Knutson C, Helm Smith K, Wall N, Fuchs B, Crossman ND & Overton IC 2016a. Drought indicators revisited: the need for a wider consideration of environment and society. *WIREs Water* 3:516–536 doi: 10.1002-wat2.1154

Bachmair S, Svensson C, Hannaford J, Barker LJ & Stahl K 2016b. A quantitative analysis to objectively appraise drought indicators and model drought impacts. *Hydrology and Earth System Sciences* 20, 2589–2609 doi: 10.5194-hess-20-2589-2016

Bachmair S, Svensson C, Prosdocimi I, Hannaford J & Stahl K 2017. Developing drought impact functions for drought risk management. *Natural Hazards and Earth System Sciences* 17, 1947-1960 doi: 10.5194-nhess-17-1947-201

BBC 2016. India drought: '330 million people affected' https://www.bbc.co.uk/news/world-asia-india-36089377 (Accessed 24 02 2021)

Blauhut V, Stahl K, Stagge JH, Tallaksen, LM, De Stefano L & Vogt J 2016. Estimating drought risk across Europe from reported drought impacts, drought indices, and vulnerability factors. *Hydrology and Earth System Sciences* 20, 2779–2800 doi: 10.5194-hess-20-2779-2016

Chiang F, Mazdiyasni O, & AghaKouchak A 2021. Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. *Nature Communications* 12, 2754 doi:10.1038/s41467-021-22314-w

Collins K, Hannaford J, Svoboda M, Knutson C, Wall N, Bernadt T, Crossman N, Overton I, Acreman M, Bachmair S & Stahl K 2016. Stakeholder Coinquiries on Drought Impacts, Monitoring, and Early Warning Systems. *Bulleting of the American Meteorological Society* 97(11), ES217-ES220 doi: 10.1175-BAMS-D-16-0185.1

Gautam RC & Bana RS 2014. Drought in India: Its impact and mitigation strategies - A review. *Indian*

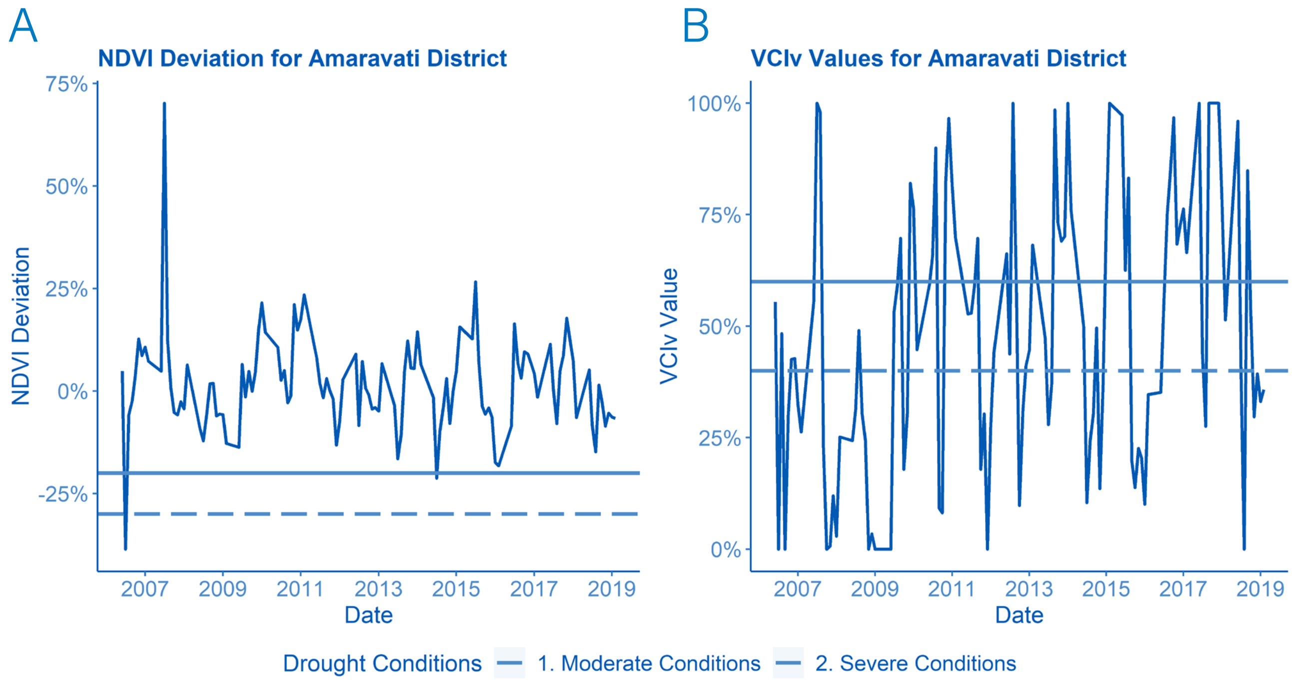


FIGURE 4.2 Comparison of the two indicators within the 'Remote Sensing' category, and the influence of their thresholds on the identification and characterisation of drought within the declaration process for Amaravati District: (A) Normalised Difference Vegetation Index/ Water Index (NDVI/NDWI); (B) Vegetation Condition Index (VCI).

Journal of Agronomy 59, 179-190. Accessed via ResearchGate

Hannaford J, Collins K, Haines S & Barker LJ 2019. Enhancing Drought Monitoring and Early Warning for the United Kingdom through Stakeholder Coinquiries. *Weather, Climate and Society* 11(1), 49-63 doi: 10.1175/WCAS-D-18-0042.1

Lloyd-Hughes B 2014. The impracticality of a universal drought definition. *Theoretical and Applied Climatology* 117, 607-611 doi: 10.1007/s00704-013-1025-7

Mishra V 2020. Long-term (1870–2018) drought reconstruction in context of surface water security in India. *Journal of Hydrology* 580, 124228 doi: 10.1016-j.jhydrol.2019.124228

Mishra V, Tiwari AD, Aadhar S, Shah R, Xiao M, Pai DS & Lettenmaier D 2019. Drought and Famine in India, 1870–2016. *Geophysical Research Letters* 46(4), 2075-2083 doi: 10.1029-2018GL081477

Mishra V, Shah R, Azhar S, Shah H, Modi P & Kumar R 2018. Reconstruction of droughts in India using multiple land surface models (1951-2015). *Hydrology and Earth System Sciences* 22, 2269-2284 doi: 10.5194-hess-22-2269-2018

Panda DK & Wahr J 2016. Spatiotemporal evolution of water storage changes in India from the updated GRACE-derived gravity records. *Water Resources Research* 52, 135–149 doi:10.1002/2015WR017797.

Pokhrel Y, Felfelani F, Satoh Y, Boulange J, Burek P, Gädeke A, Gerten D, Gosling SN, Grillakis M, Gudmundsson L, Hanasaki N, Kim H, Koutroulis A, Liu J, Papadimitriou L, Schewe J, Müller Schmied H, Stacke T, Telteu C, Thiery W, Veldkamp T, Zhao F & Wada Y 2021. Global terrestrial water storage and drought severity under climate change. *Nature Climate Change* 11, 226–233 doi:10.1038-s41558-020-00972-w

Shah D & Mishra V 2020. Integrated Drought Index (IDI) for drought monitoring and assessment in India. *Water Resources Research* 56 e2019WR026284. doi: 10.1029/2019WR026284.

Sharma A 2019. Drought Management Policy of India: An Overview. *Disaster Advances* 12(11), 51-62 Accessed via ResearchGate

Steinemann A, Iacobellis SF & Cayan DR 2015. Developing and Evaluating Drought Indicators for Decision-Making. *Journal of Hydrometeorology* 16(4), 1793-1803 doi: 10.1175-JHM-D-14-0234.1

UNDP (United Nations Development Programme) 2018 Statistical Update: Human Development Indices and Indicators New York.

UNDRR (United Nations Office for Disaster Risk Reduction) 2021. GAR Special Report on Drought 2021. Geneva. Accessed via UNDP Human Development Reports

Van Loon A, Gleeson T, Clark J, Van Dijk AIJM, Stahl K, Hannaford J, Di Badldassarre G, Teuling AJ, Tallaksen LM, Uijlenhoet R, Hannah DM, Sheffield J, Svoboda M, Verbeiren B, Wagener T, Rangecroft S, Wander N, & Van Lanen HAJ 2016. Drought in the Anthropocene. *Nature Geoscience* 9, 89–91 doi: 10.1038/ngeo2646

Wang,Y, Lv J, Hannaford J, Wang Y, Sun H, Barker LJ, Ma M, Su Z & Eastman M 2020. Linking drought indices to impacts to support drought risk assessment in Liaoning province, China. *Natural Hazards and Earth System Sciences* 20, 889-906 doi: 10.5194-nhess-20-889-2020

Wilhite DA 2000. Drought as a Natural Hazard: Concepts and Definitions. In *Drought: A Global Assessment Wilhite* DA (Ed.) Vol 1 Routledge, London pp 3–18.

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Khadakwasla Dam, Maharashtra. Photo credit: Scarabea, Shutterstock.