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Handbook of Drought Indicators and Indices

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Integrated Drought Management Programme (IDMP)

Handbook of Drought Indicators and Indices

Integrated Drought Management Programme

WORLD METEOROLOGICAL ORGANIZATION

WMO-No. 1173

WEATHER CLIMATE WATER

Global Water Partnership

Towards a water secure world

The **World Meteorological Organization** (WMO) is a specialized agency of the United Nations. It is the United Nations system's authoritative voice on the state and behaviour of the Earth's atmosphere, its interaction with the land and oceans, the weather and climate it produces and the resulting distribution of water resources. WMO has a membership of 191 Member States and Territories.

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The **Integrated Drought Management Programme** (IDMP) was launched by WMO and GWP at the High Level Meeting on National Drought Policies in March 2013. IDMP works with a wide range of partners with the objective of supporting stakeholders at all levels. IDMP provides its partners with policy and management guidance through globally coordinated generation of scientific information and sharing best practices and knowledge for integrated drought management. It contributes to the Global Framework for Climate Services (GFCS), especially regarding the GFCS priority areas of disaster risk reduction, water, agriculture and food security, energy and health. It especially seeks to support regions and countries in developing more proactive drought policies and better predictive mechanisms. This handbook contributes to that objective.

www.droughtmanagement.info

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Note to the reader:
This publication is part of the ‘Integrated Drought Management Tools and Guidelines Series’, compiled by the Integrated Drought Management Programme (IDMP). This *Handbook of Drought Indicators and Indices* is based on available literature and draws findings from relevant works wherever possible. The handbook addresses the needs of practitioners and policymakers. The publication is considered as a resource guide/material for practitioners and not an academic paper.

This publication is a ‘living document’ and will be updated based on the experiences of its readers. The indicators and indices detailed in chapter 7 of the handbook are also available online at www.droughtmanagement.info. IDMP encourages water managers and related experts engaged in the management of drought around the globe to participate in the enrichment of this publication. For this purpose, comments and other inputs are cordially invited. Authorship and contributions will be appropriately acknowledged. Please kindly submit your inputs to: idmp@wmo.int under Subject: ‘Handbook of Drought Indicators and Indices’.

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1. INTRODUCTION

Why is it important to monitor droughts? Droughts are a normal part of the climate, and they can occur in any climate regime around the world, even deserts and rainforests. Droughts are one of the more costly natural hazards on a year-to-year basis; their impacts are significant and widespread, affecting many economic sectors and people at any one time. The hazard footprints of (areas affected by) droughts are typically larger than those for other hazards, which are usually constrained to floodplains, coastal regions, storm tracks or fault zones. Perhaps no other hazard lends itself quite so well to monitoring, because the slow onset of droughts allows time to observe changes in precipitation, temperature and the overall status of surface water and groundwater supplies in a region. Drought indicators or indices are often used to help track droughts, and these tools vary depending on the region and the season.

Like other hazards, droughts can be characterized in terms of their severity, location, duration and timing. Droughts can arise from a range of hydrometeorological processes that supress precipitation and/or limit surface water or groundwater availability, creating conditions that are significantly drier than normal or otherwise limiting moisture availability to a potentially damaging extent. The indicators and indices discussed in this *Handbook of Drought Indicators and Indices* provide options for identifying the severity, location, duration onset and cessation of such conditions. It is important to note that the impacts of droughts can be as varied as the causes of droughts. Droughts can adversely affect agriculture and food security, hydropower generation and industry, human and animal health, livelihood security, personal security (for example, women walking long distances to fetch water) and access to education (for example, girls not attending school because of increased time spent on fetching water). Such impacts depend on the socioeconomic contexts in which droughts occur, in terms of who or what are exposed to the droughts and the specific vulnerabilities of the exposed entities. Therefore, the type of impacts relevant in a particular drought monitoring and early warning context is often a crucial consideration in determining the selection of drought indicators.

A drought impact is **an observable loss or change at a specific time because of drought**. Drought risk management involves hazards, exposure, vulnerability and impact assessment, a drought early warning system (DEWS) (monitoring and forecasting, see Box below), and preparedness and mitigation (WMO, UNCCD and FAO, 2013). It is important that drought indicators or indices accurately reflect and represent the impacts being experienced during droughts. As droughts evolve, the impacts can vary by region and by season.

Monitoring different aspects of the hydrologic cycle may require a variety of indicators and indices. It is desirable to align these and their depiction with the impacts of emerging conditions on the ground and management decisions being taken by different individuals, groups and organizations. Although a DEWS is ultimately concerned with impacts, drought impact assessment is a large gap in many DEWSs used around the globe at this time. Assessment of impacts is complicated, as socioeconomic factors other than the physical nature of droughts influence the levels and types of impacts related to drought exposure and vulnerability. Understanding how droughts affect people, communities, businesses or economic sectors is key to taking steps towards mitigating the impacts of future droughts.

Drought early warning systems

Drought early warning systems typically aim to track, assess and deliver relevant information concerning climatic, hydrologic and water supply conditions and trends. Ideally, they have both a monitoring (including impacts) component and a forecasting component. The objective is to provide timely information in advance of, or during, the early onset of drought to prompt action (via threshold triggers) within a drought risk management plan as a means of reducing potential impacts. A diligent, integrated, approach is vital for monitoring such a slow-onset hazard.

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Following publication of the Intergovernmental Panel on Climate Change report on extreme events (IPCC, 2012), the issue of quantifying loss and damage from extreme climate events such as droughts has become important for policy implementation, especially with regard to the United Nations Framework Convention on Climate Change agenda. In addition, due to the magnitude of associated disaster losses, improved drought monitoring and management will be fundamental to implementing the Sendai Framework for Disaster Risk Reduction 2015–2030 and the Sustainable Development Goals. Effective and accurate monitoring of hydrometeorological indicators is a key input to risk identification, to DEWSs and for managing sector impacts. In light of this, the 17th World Meteorological Congress, held in June 2015, adopted Resolution 9: Identifiers for Cataloguing Extreme Weather, Water and Climate Events. This initiated a process of standardizing weather, water, climate, space weather and other related environmental hazards and risk information, and prioritized the development of identifiers for cataloguing extreme weather, water and climate events. This handbook will make an important contribution to these efforts.

The purpose of this handbook is to cover some of the most commonly used drought indicators/indices that are being applied across drought-prone regions, with the goal of advancing monitoring, early warning and information delivery systems in support of risk-based drought management policies and preparedness plans. These concepts and indicators/indices are outlined below in what is considered to be a living document that will evolve and integrate new indicators and indices as they come to light and are applied in the future. The handbook is aimed at those who want to generate indicators and indices themselves, as well as for those who simply want to obtain and use products that are generated elsewhere. It is intended for use by general drought practitioners (for example, meteorological/hydrological services and ministries, resource managers and other decision-makers at various levels) and aims to serve as a starting point, showing which indicators/indices are available and being put into practice around the world. In addition, the handbook has been designed with drought risk management processes in mind. However, this publication does not aim to recommend a 'best' set of indicators and indices. The choice of indicators/indices is based on the specific characteristics of droughts most closely associated with the impacts of concern to the stakeholders.

This handbook does not attempt to address the full complexities of impacts and the entire range of socioeconomic drought indicators and indices. The indicators and indices included describe the hydrometeorological characteristics of droughts and do not cover socioeconomic and environmental factors such as those that may be needed to assess and anticipate drought-related impacts and outcomes. The handbook is intended as a reference, providing an overview and guide to sources of further information. The Integrated Drought Management Programme (IDMP) is establishing a complementary help desk on integrated drought management.

2. DEFINITIONS: INDICATORS VERSUS INDICES

It is important to define what is meant by drought indicators and indices.

Indicators are variables or parameters used to describe drought conditions. Examples include precipitation, temperature, streamflow, groundwater and reservoir levels, soil moisture and snowpack.

Indices are typically computed numerical representations of drought severity, assessed using climatic or hydrometeorological inputs including the indicators listed above. They aim to measure the qualitative state of droughts on the landscape for a given time period. Indices are technically indicators as well. Monitoring the climate at various timescales allows identification of short-term wet periods within long-term droughts or short-term dry spells within long-term wet periods. Indices can simplify complex relationships and provide useful communication tools for diverse audiences and users, including the public. Indices are used to provide quantitative assessment of the severity, location, timing and duration of drought events. Severity refers to the departure from normal of an index. A threshold for severity may be set to determine when a drought has begun, when it ends and the geographic area affected. Location refers to the geographic area experiencing drought conditions. The timing and duration are determined by the approximate dates of onset and cessation. The interaction of the hazard event and the exposed elements (people, agricultural areas, reservoirs and water supplies), and the vulnerabilities of these elements to droughts, determines the impacts. Vulnerabilities may have been exacerbated by previous droughts, which, for example, might have triggered the sale of productive assets to meet immediate needs. The timing of droughts may be as significant as their severity in determining impacts and outcomes. A short, relatively low severity, intra-season drought, if it occurs during the moisture sensitive period of a stable crop, can have a more devastating impact on crop yield than a longer, more severe drought occurring at a less critical

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time during the agricultural cycle. Thus, drought indices – in combination with additional information on exposed assets and their vulnerability characteristics – are essential for tracking and anticipating drought-related impacts and outcomes. Indices may also play another critical role, depending on the index, in that they can provide a historical reference for planners or decision-makers. This provides users with a probability of occurrence, or recurrence, of droughts of varying severities. Importantly, however, climate change will begin to alter historical patterns.

Information derived from indicators and indices is useful in planning and designing applications (such as risk assessment, DEWSs and decision-support tools for managing risks in drought-affected sectors), provided that the climate regime and drought climatology is known for the location. In addition, various indictors and indices can be used to validate modelled, assimilated or remotely sensed indicators of drought.

3. APPROACHES FOR MONITORING DROUGHT AND GUIDING EARLY WARNING AND ASSESSMENT

There are three main methods for monitoring drought and guiding early warning and assessment:

1. Using a single indicator or index

2. Using multiple indicators or indices

3. Using composite or hybrid indicators

In the past, decision-makers and scientists employed one indicator or index because that was the only measurement available to them, or they had only limited time in which to acquire data and compute derivative indices or other deliverables. Over the past 20 years or so, there has been strong global interest and growth in the development of new indices based on various indicators that are suitable for different applications and scales, both spatial and temporal. These new tools have given decision-makers and policymakers more choices, but, until recently, they have still lacked a clear-cut method to synthesize results into a simple message that can be relayed to the public. The advent of geographic information systems and increasing computing and display capabilities has increased the capacity to overlay, map and compare various indicators or indices. For a more detailed discussion on mapping drought indices and indicators, see the chapter 9 of the Standardized Precipitation Index User Guide (WMO, 2012).

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Confusion can arise when trying to determine which indicators or indices to use, especially if they are linked to a comprehensive drought plan and used as a trigger for drought management actions. It takes time and a system of trial and error to determine the best fit for any given location, area, basin or region. In the past decade or so, a new type of composite (sometimes referred to as hybrid) indicator has emerged as a means to merge different indicators and indices, either weighted or not, or in a modelled fashion. The idea is to use the strengths of a variety of inputs, yet maintain a single, simple source of information for decision-makers, policymakers or the public. Given that drought severity is best evaluated on the basis of multiple indicators associated with water availability for a given area or region, the composite or hybrid approach allows an increased number of elements to be incorporated into the assessment process.

While this handbook does not aim to state exactly which indicators or indices to integrate or apply in terms of drought management guidance, it is important to note the role of indices and indicators in a DEWS within an overall drought risk management strategy. They provide useful triggers to help direct decision-makers and policymakers towards proactive risk management.

Triggers are specific values of an indicator or index that initiate and/or terminate each level of a drought plan and associated mitigation and emergency management responses. In other words, they trigger action and allow for accountability as to who is doing what and when they need to do it. This should ultimately tie in with a comprehensive drought management plan or policy (WMO and GWP, 2014). It is essential to have a complete list of triggers for indicators or indices, which should also be aligned with an action plan to guide a coordinated set of actions by individual agencies or ministries. Without this alignment, there is likely to be considerable delay in action at the onset of drought in an area or region.

4. SELECTING INDICATORS AND INDICES

Just as there is no 'one-size-fits-all' definition of drought, there is no single index or indicator that can account for and be applied to all types of droughts, climate regimes and sectors affected by droughts. This handbook is not intended to be prescriptive by telling readers which indices and indicators are best to use and when; in fact, many factors feed in to determining which indicator, index or trigger (or combination thereof) is the best to use for a particular need or application. The following questions may help users to decide which indicators and indices are most appropriate for their current situation:

- Do the indicators/indices allow for timely detection of drought in order to trigger appropriate communication and coordination of drought response or mitigation actions?
- Are the indicators/indices sensitive to climate, space and time in order to determine drought onset and termination?
- Are the indicators/indices and various severity levels responsive and reflective of the impacts occurring on the ground for a given location or region?
- Are the chosen indicators, indices and triggers the same, or different, for going into and coming out of drought? It is critical to account for both situations.
- Are composite (hybrid) indicators being used in order to take many factors and inputs into account?
- Are the data and resultant indices/indicators available and stable? In other words, is there a long period of record for the data source that can give planners and decision-makers a strong historical and statistical marker?
- Are the indicators/indices easy to implement? Do the users have the resources (time and human) to dedicate to efforts and will they be maintained diligently when not in a drought situation? This can be better justified if such a system is set up for monitoring all aspects of the hydrologic or climatic cycles, not just droughts.

The simplest indicator/index to use is typically one that is already being produced operationally and freely available, but this does not necessarily mean that it is the best or most applicable. Ultimately, the choice has to be determined by users at the regional, national or local levels. The preferred and recommended approach is for users to take a multiple or composite/hybrid indicator/index approach as part of a DEWS within the context of a comprehensive drought mitigation plan. Ideally, this requires thorough analyses and a research approach to determine which indicators work best in particular climate regimes, regions, basins and locations. Research is also required to determine which seasons the indicators are most relevant to, representing impacts occurring on the ground. Once identified, the indicators/indices can be recommended or implemented in a DEWS as potential triggers tied to emergency response or mitigation actions within a drought plan.

5. SUMMARY OF INDICATORS AND INDICES

As already stated, no single indicator or index can be used to determine appropriate actions for all types of droughts given the number and variety of sectors affected. The preferred approach is to use different thresholds with different combinations of inputs. Ideally, this will involve prior study to determine which indicators/indices are best suited to the timing, area and type of climate and drought. This takes time because it requires a trial-and-error approach. Decision-making based on quantitative index-based values is essential to the appropriate and accurate assessment of drought severity and as input into an operational DEWS or comprehensive drought plan.

The indicators and indices listed in Table 1 have been drawn from IDMP and partner literature and online searches. They are categorized by type and ease of use, and grouped into the following classifications: (a) meteorology, (b) soil moisture, (c) hydrology, (d) remote sensing and (e) composite or modelled. Although listed by ‘ease of use’, it is possible that any, all or none of the indicators may be suitable for a particular application, based on user knowledge, needs, data availability and computer resources available to implement them. The resource needs increase from green to yellow to red, as outlined below. Again, the simplest index/indicator is not necessarily the best one to use.

The ‘ease of use’ classification uses a ‘traffic-light’ approach for each indicator/index as follows:

Green: Indices are considered to be green if one or more of the following criteria apply:

- A code or program to run the index is readily and freely available
- Daily data are not required
- Missing data are allowed for
- Output of the index is already being produced operationally and is available online

Note: While a green ‘ease of use’ classification may imply that the indicator/index may be the easiest to obtain or use, it does not mean it is the best for any given region or locality. The decision as to which indicators/indices to use has to be determined by the user and depends on the given application(s).

Yellow: Indices are considered to be yellow if one or more of the following criteria apply:

- Multiple variables or inputs are needed for calculations
- A code or program to run the index is not available in a public domain
- Only a single input or variable may be needed, but no code is available
- The complexity of the calculations needed to produce the index is minimal

Red: Indices are considered to be red if one or more of the following criteria apply:

- A code would need to be developed to calculate the index based upon a methodology given in the literature
- The index or derivative products are not readily available
- The index is obscure index, and is not widely used, but may be applicable
- The index contains modelled input or is part of the calculations

Table 1. Indicators and indices listed in this handbook

Meteorology	*Page*	*Ease of use*	*Input parameters*	*Additional information*
Aridity Anomaly Index (AAI)	11	Green	P, T, PET, ET	Operationally available for India
Deciles	11	Green	P	Easy to calculate; examples from Australia are useful
Keetch–Byram Drought Index (KBDI)	12	Green	P, T	Calculations are based upon the climate of the area of interest
Percent of Normal Precipitation	12	Green	P	Simple calculations
Standardized Precipitation Index (SPI)	13	Green	P	Highlighted by the World Meteorological Organization as a starting point for meteorological drought monitoring
Weighted Anomaly Standardized Precipitation (WASP)	15	Green	P, T	Uses gridded data for monitoring drought in tropical regions
Aridity Index (AI)	15	Yellow	P, T	Can also be used in climate classifications
China Z Index (CZI)	16	Yellow	P	Intended to improve upon SPI data
Crop Moisture Index (CMI)	16	Yellow	P, T	Weekly values are required
Drought Area Index (DAI)	17	Yellow	P	Gives an indication of monsoon season performance
Drought Reconnaissance Index (DRI)	17	Yellow	P, T	Monthly temperature and precipitation are required
Effective Drought Index (EDI)	18	Yellow	P	Program available through direct contact with originator
Hydro-thermal Coefficient of Selyaninov (HTC)	19	Yellow	P, T	Easy calculations and several examples in the Russian Federation
NOAA Drought Index (NDI)	19	Yellow	P	Best used in agricultural applications
Palmer Drought Severity Index (PDSI)	20	Yellow	P, T, AWC	Not green due to complexity of calculations and the need for serially complete data
Palmer Z Index	20	Yellow	P, T, AWC	One of the many outputs of PDSI calculations
Rainfall Anomaly Index (RAI)	21	Yellow	P	Serially complete data required
Self-Calibrated Palmer Drought Severity Index (sc-PDSI)	22	Yellow	P, T, AWC	Not green due to complexity of calculations and serially complete data required
Standardized Anomaly Index (SAI)	22	Yellow	P	Point data used to describe regional conditions
Standardized Precipitation Evapotranspiration Index (SPEI)	23	Yellow	P, T	Serially complete data required; output similar to SPI but with a temperature component
Agricultural Reference Index for Drought (ARID)	23	Red	P, T, Mod	Produced in south-eastern United States of America and not tested widely outside the region
Crop-specific Drought Index (CSDI)	24	Red	P, T, Td, W, Rad, AWC, Mod, CD	Quality data of many variables needed, making it challenging to use
Reclamation Drought Index (RDI)	25	Red	P, T, S, RD, SF	Similar to the Surface Water Supply Index, but contains a temperature component

Soil moisture	*Page*	*Ease of use*	*Input parameters*	*Additional information*
Soil Moisture Anomaly (SMA)	25	Yellow	P, T, AWC	Intended to improve upon the water balance of PDSI
Evapotranspiration Deficit Index (ETDI)	26	Red	Mod	Complex calculations with multiple inputs required
Soil Moisture Deficit Index (SMDI)	26	Red	Mod	Weekly calculations at different soil depths; complicated to calculate
Soil Water Storage (SWS)	27	Red	AWC, RD, ST, SWD	Owing to variations in both soil and crop types, interpolation over large areas is challenging

Hydrology	*Page*	*Ease of use*	*Input parameters*	*Additional information*
Palmer Hydrological Drought Severity Index (PHDI)	27	Yellow	P, T, AWC	Serially complete data required
Standardized Reservoir Supply Index (SRSI)	28	Yellow	RD	Similar calculations to SPI using reservoir data
Standardized Streamflow Index (SSFI)	29	Yellow	SF	Uses the SPI program along with streamflow data
Standardized Water-level Index (SWI)	29	Yellow	GW	Similar calculations to SPI, but using groundwater or well-level data instead of precipitation
Streamflow Drought Index (SDI)	30	Yellow	SF	Similar calculations to SPI, but using streamflow data instead of precipitation
Surface Water Supply Index (SWSI)	30	Yellow	P, RD, SF, S	Many methodologies and derivative products are available, but comparisons between basins are subject to the method chosen
Aggregate Dryness Index (ADI)	31	Red	P, ET, SF, RD, AWC, S	No code, but mathematics explained in the literature
Standardized Snowmelt and Rain Index (SMRI)	32	Red	P, T, SF, Mod	Can be used with or without snowpack information

Remote sensing	*Page*	*Ease of use*	*Input parameters*	*Additional information*
Enhanced Vegetation Index (EVI)	32	Green	Sat	Does not separate drought stress from other stress
Evaporative Stress Index (ESI)	33	Green	Sat, PET	Does not have a long history as an operational product
Normalized Difference Vegetation Index (NDVI)	33	Green	Sat	Calculated for most locations
Temperature Condition Index (TCI)	34	Green	Sat	Usually found along with NDVI calculations
Vegetation Condition Index (VCI)	34	Green	Sat	Usually found along with NDVI calculations
Vegetation Drought Response Index (VegDRI)	35	Green	Sat, P, T, AWC, LC, ER	Takes into account many variables to separate drought stress from other vegetation stress
Vegetation Health Index (VHI)	35	Green	Sat	One of the first attempts to monitor drought using remotely sensed data

Water Requirement Satisfaction Index (WRSI and Geo-spatial WRSI)	36	Green	Sat, Mod, CC	Operational for many locations
Normalized Difference Water Index (NDWI) and Land Surface Water Index (LSWI)	37	Green	Sat	Produced operationally using Moderate Resolution Imaging Spectroradiometer data
Soil Adjusted Vegetation Index (SAVI)	37	Red	Sat	Not produced operationally

Composite or modelled	*Page*	*Ease of use*	*Input parameters*	*Additional information*
Combined Drought Indicator (CDI)	38	Green	Mod, P, Sat	Uses both surface and remotely sensed data
Global Integrated Drought Monitoring and Prediction System (GIDMaPS)	38	Green	Multiple, Mod	An operational product with global output for three drought indices: Standardized Soil Moisture Index, SPI and Multivariate Standardized Drought Index
Global Land Data Assimilation System (GLDAS)	39	Green	Multiple, Mod, Sat	Useful in data-poor regions due to global extent
Multivariate Standardized Drought Index (MSDI)	40	Green	Multiple, Mod	Available but interpretation is needed
United States Drought Monitor (USDM)	41	Green	Multiple	Available but interpretation is needed

Note: Indicators and indices are sorted by 'ease of use' and then alphabetically within each 'ease of use' category.

Key to variables:
AWC = available water content,
CC = crop coefficient,
CD = crop data,
ER = ecoregion,
ET = evapotranspiration,
GW = groundwater,
LC = land cover,
Mod = modelled,
Multiple = multiple indicators used,
P = precipitation,
PET = potential evapotranspiration,
Rad = solar radiation,
RD = reservoir,
S = snowpack,
Sat = satellite,
SF = streamflow,
ST = soil type,
SWD = soil water deficit,
T = temperature,
Td = dewpoint temperature,
W = wind data.

6. INDEX AND INDICATOR RESOURCES

There are several sources of information on the many indices and indicators being applied today around the world. Some of the more common indices are documented and explained by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, United States of America, which maintains a dedicated drought indices resource section, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro.aspx.

The World Meteorological Organization (WMO)/NDMC Inter-Regional Workshop on Indices and Early Warning Systems for Drought was held in 2009 at the University of Nebraska-Lincoln. One of the outcomes was to endorse the Standardized Precipitation Index (SPI) via the Lincoln Declaration on Drought Indices as the standard for determining the existence of meteorological drought (Hayes et al., 2011). WMO has developed a user guide to SPI, see http://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf.

As a follow-up, WMO and the United Nations Office for Disaster Risk Reduction in collaboration with the Segura Hydrographic Confederation and Spain’s Agencia Estatal de Meteorología (State Meteorological Agency) organized an expert group meeting on agricultural drought indices in Murcia, Spain, in 2010 (Sivakumar et al., 2011). A group of scientists from around the world represented WMO regions and reviewed 34 indices used for assessing drought impacts on agriculture, highlighting their strengths and weaknesses. The proceedings, Agricultural Drought Indices: Proceedings of an Expert Meeting, are documented in the form of 17 papers and can be found at http://www.wamis.org/agm/pubs/agm11/agm11.pdf.

See also the references listed at the end of this publication, for example, Heim (2002), Keyantash and Dracup (2002) and Zargar et al. (2011), which review drought indices in use, both today and in the past.

For additional help with the selection, interpretation and application of indicators and indices, contact IDMP at http://www.droughtmanagement.info/ or by e-mail at idmp@wmo.int.

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7. INDICATORS AND INDICES

7.1 Meteorology

Index name: Aridity Anomaly Index (AAI).

Ease of use: Green.

Origins: Developed in India by the India Meteorological Department.

Characteristics: A real-time drought index in which water balance is considered. The Aridity Index (AI) is computed for weekly or two-weekly periods. For each period, the actual aridity for the period is compared to the normal aridity for that period. Negative values indicate a surplus of moisture, while positive values indicate moisture stress.

Input parameters: Actual evapotranspiration and calculated potential evapotranspiration, which require temperature, wind and solar radiation values.

Applications: Impacts of drought in agriculture, especially in the tropics where defined wet and dry seasons are part of the climate regime. Both winter and summer cropping seasons can be assessed using this method.

Strengths: Specific to agriculture, calculations are simple, and descriptions of drought (mild, moderate or severe) are based on departure from normal. Responds quickly with a weekly time step.

Weaknesses: Not applicable to long-term or multiseasonal events.

Resource: http://imdpune.gov.in/hydrology/methodology.html.

Reference: http://www.wamis.org/agm/gamp/GAMP_Chap06.pdf.

Index name: Deciles.

Ease of use: Green.

Origins: A simple mathematical approach described by Gibbs and Maher in 1967 through their work with the Australian Bureau of Meteorology.

Characteristics: Using the entire period of record of precipitation data for a location, the frequency and distribution of precipitation are ranked. The first decile is composed of the rainfall amounts in which the lowest 10% of the values are not exceeded, and the fifth decile is the median. A wet scale is also available. Daily, weekly, monthly, seasonal and annual values can all be considered in the methodology, as it is flexible when current data are compared to the historical record for any given period.

Input parameters: Precipitation only, and the timescale considered is flexible.

Applications: With the ability to look at different timescales and time steps, deciles can be used in meteorological, agricultural and hydrological drought situations.

Strengths: With a single variable being considered, the methodology is simple and flexible for many situations. Using clearly defined thresholds, the current data are put into a historical context and drought status can be recognized. Useful in both wet and dry situations.

Weaknesses: As with other indicators that use only precipitation, the impacts of temperatures and other variables are not considered during the development of drought. A long record period provides the best results because many wet and dry periods will be included in the distribution.

Resources: There is no specific software code for deciles, and several online tools can provide output. Thus, it is important to clarify the underlying methodology, as there are a number of statistical approaches to calculate deciles from meteorological data, http://drinc.ewra.net/.

Reference: Gibbs, W.J. and J.V. Maher, 1967: *Rainfall Deciles as Drought Indicators*. Bureau of Meteorology Bulletin No. 48, Melbourne, Australia.

Index name: Keetch–Byram Drought Index (KBDI).

Ease of use: Green.

Origins: Part of work done in the late 1960s by Keetch and Byram of the United States Department of Agriculture's Forest Service Division. It is mainly a fire index.

Characteristics: Developed to identify drought in the early stages using a uniform method specific to the climate of the region. It is the net effect of evapotranspiration and precipitation in producing a moisture deficiency in the upper layers of the soil and also gives an indication of how much precipitation is needed for saturation of the soil and eliminating drought stress.

Input parameters: Daily maximum temperature and daily precipitation. Tables are computed to relate KBDI to various precipitation regimes based upon the local climate.

Applications: Intended as a method of monitoring fire danger due to drought, KBDI was found to be useful in agricultural contexts because the measure of soil moisture was directly related to drought stress on crops.

Strengths: Expresses moisture deficiency for an area and can be scaled to indicate the characteristics of each particular location. Calculations are simple and the method is easy to use.

Weaknesses: Assumes a limit of available moisture and the necessity of certain climatic conditions for drought to develop, which may or may not be true for every location.

Resources: The method and calculation are available and well described in the literature. Many maps are available online for various locations, http://www.wfas.net/index.php/keetch-byram-index-moisture--drought-49.

Reference: Keetch, J.J. and G.M. Byram, 1968: *A Drought Index for Forest Fire Control*. United States Department of Agriculture Forest Service Research Paper SE-38, Southeastern Forest Experiment Station, Asheville, NC.

Index name: Percent of Normal Precipitation.

Ease of use: Green.

Origins: The percentage of any quantity is a simple statistical formulation. The exact origin or first use is not known in describing precipitation anomalies.

Characteristics: Simple calculation that can be used to compare any time period for any location. Can be computed on daily, weekly, monthly, seasonal and annual timescales, which will suit many user needs. Calculated by dividing actual precipitation by normal precipitation for the time being considered and multiplying by 100.

Input parameters: Precipitation values suitable for the timescale being calculated. It is ideal to have at least 30 years' worth of data for calculation of the normal period.

Applications: Can be used for identifying and monitoring various impacts of droughts.

Strengths: A popular method that is quick and easy to calculate with basic mathematics.

Weaknesses: Establishing the normal for an area is a calculation that some users could confuse with mean or average precipitation. It is hard to compare different climate regimes with each other, especially those with defined wet and dry seasons.

Reference: Hayes, M.J., 2006: *Drought Indices*. Van Nostrand's Scientific Encyclopedia, John Wiley & Sons, Inc., doi:10.1002/0471743984.vse8593, http://onlinelibrary.wiley.com/doi/10.1002/0471743984.vse8593/abstract;jsessionid=CA39E5A4F67AA81580F505CBB07D2424.f01t04.

Index name: Standardized Precipitation Index (SPI).

Ease of use: Green.

Origins: The result of research and work done in 1992 at Colorado State University, United States, by McKee et al. The outcome of their work was first presented at the 8th Conference on Applied Climatology, held in January 1993. The basis of the index is that it builds upon the relationships of drought to frequency, duration and timescales.

In 2009, WMO recommended SPI as the main meteorological drought index that countries should use to monitor and follow drought conditions (Hayes, 2011). By identifying SPI as an index for broad use, WMO provided direction for countries trying to establish a level of drought early warning.

Characteristics: Uses historical precipitation records for any location to develop a probability of precipitation that can be computed at any number of timescales, from 1 month to 48 months or longer. As with other climatic indicators, the time series of data used to calculate SPI does not need to be of a specific length. Guttman (1998, 1999) noted that if additional data are present in a long time series, the results of the probability distribution will be more robust because more samples of extreme wet and extreme dry events are included. SPI can be calculated on as little as 20 years' worth of data, but ideally the time series should have a minimum of 30 years of data, even when missing data are accounted for.

SPI has an intensity scale in which both positive and negative values are calculated, which correlate directly to wet and dry events. For drought, there is great interest in the 'tails' of the precipitation distribution, and especially in the extreme dry events, which are the events considered to be rare based upon the climate of the region being investigated.

Drought events are indicated when the results of SPI, for whichever timescale is being investigated, become continuously negative and reach a value of –1. The drought event is considered to be ongoing until SPI reaches a value of 0. McKee et al. (1993) stated that drought begins at an SPI of –1 or less, but there is no standard in place, as some researchers will choose a threshold that is less than 0, but not quite –1, while others will initially classify drought at values less than –1.

Owing to the utility and flexibility of SPI, it can be calculated with data missing from the period of record for a location. Ideally, the time series should be as complete as possible, but SPI calculations will provide a 'null' value if there are insufficient data to calculate a value, and SPI will begin calculating output again as data become available. SPI is typically calculated for timescales of up to 24 months, and the flexibility of the index allows for multiple applications addressing events that affect agriculture, water resources and other sectors.

Input parameters: Precipitation. Most users apply SPI using monthly datasets, but computer programs have the flexibility to produce results when using daily and weekly values. The methodology of SPI does not change based upon using daily, weekly or monthly data.

Applications: The ability of SPI to be calculated at various timescales allows for multiple applications. Depending on the drought impact in question, SPI values for 3 months or less might be useful for basic drought monitoring, values for 6 months or less for monitoring agricultural impacts and values for 12 months or longer for hydrological impacts. SPI can also be calculated on gridded precipitation datasets, which allows for a wider scope of users than those just working with station-based data.

Strengths: Using precipitation data only is the greatest strength of SPI, as it makes it very easy to use and calculate. SPI is applicable in all climate regimes, and SPI values for very different climates can be compared. The ability of SPI to be computed for short periods of record that contain missing data is also valuable for those regions that may be data poor or lacking long-term, cohesive datasets. The program used to calculate SPI is easy to use and readily available. NDMC provides a program for use on personal computers that has been distributed to more than 200 countries around the world. The ability to be calculated over multiple timescales also allows SPI to have a wide breadth of application. Many articles relating to SPI are available in the science literature, giving novice users a multitude of resources to rely on for assistance.

Weaknesses: With precipitation as the only input, SPI is deficient when accounting for the temperature component, which is important to the overall water balance and water use of a region. This drawback can make it more difficult to compare events of similar SPI values but different temperature scenarios. The flexibility of SPI to be calculated for short periods of record, or on data that contain many missing values, can also lead to misuse of the output, as the program will provide output for whatever input is provided. SPI assumes a prior distribution, which may not be appropriate in all environments, particularly when examining short-duration events or entry into, or exit out of, drought. There are many versions of SPI available, implemented within various computing software packages other than that found in the source code distributed by NDMC. It is important to check the integrity of these algorithms and the consistency of output with the published versions.

Resource: The SPI program can be run on Windows-based personal computers, http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx.

References:

Guttman, N.B., 1998: Comparing the Palmer Drought Index and the Standardized Precipitation Index. *Journal of the American Water Resources Association*, 34:113–121, doi:10.1111/j.1752-1688.1998.tb05964.

Guttman, N.B., 1999: Accepting the Standardized Precipitation Index: a calculation algorithm. *Journal of the American Water Resources Association*, 35:311–322, doi:10.1111/j.1752-1688.1999.tb03592.x.

Hayes, M., M. Svoboda, N. Wall and M. Widhalm, 2011: The Lincoln Declaration on Drought Indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, 92(4):485–488.

McKee, T.B., N.J. Doesken and J. Kleist, 1993: *The Relationship of Drought Frequency and Duration to Time Scales.* Proceedings of the 8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, CA. Boston, MA, American Meteorological Society.

World Meteorological Organization, 2012: *Standardized Precipitation Index User Guide* (WMO-No. 1090), Geneva.

Wu, H., M.J. Hayes, D.A. Wilhite and M.D. Svoboda, 2005: The effect of the length of record on the Standardized Precipitation Index calculation. *International Journal of Climatology*, 25(4):505–520.

Index name: Weighted Anomaly Standardized Precipitation Index (WASP).

Ease of use: Green.

Origins: Developed by Lyon to monitor precipitation in the tropical regions within 30° latitude of the Equator.

Characteristics: Uses gridded monthly precipitation data on a 0.5° × 0.5° resolution, and is based on 12-month overlapping sums of weighted, standardized monthly precipitation anomalies.

Input parameters: Monthly precipitation and annual precipitation values.

Applications: Used mainly in wet tropical regions to monitor developing drought, taking into account the defined wet and dry periods in the climate regime. Can be used to monitor droughts that affect agriculture and other sectors.

Strengths: Using precipitation as a single input allows for simpler computations.

Weaknesses: Does not work so well in desert regions. Gridded precipitation data may be a challenge to obtain in an operational capacity.

Resources: The methods and calculations are provided and explained in the literature, http://iridl.ldeo.columbia.edu/maproom/Global/Precipitation/WASP_Indices.html.

Reference: Lyon, B., 2004: The strength of El Niño and the spatial extent of tropical drought. *Geophysical Research Letters*, 31:L21204, doi:10.1029/2004GL020901.

Index name: Aridity Index (AI).

Ease of use: Yellow.

Origins: Developed from work done by De Martonne in 1925; aridity is defined as the ratio of precipitation to mean temperature.

Characteristics: Can be used to classify the climates of various regions, because the ratio of precipitation to temperature provides a method for determining an area's climate regime. Monthly calculation of AI can be used to determine the onset of drought, as the index takes into account temperature impacts as well as precipitation.

Input parameters: Monthly mean temperature and precipitation. For climate classification, annual values are used.

Applications: Mainly used to determine the development of drought over shorter timescales, which is helpful for identifying and monitoring agricultural and meteorological impacts.

Strengths: Easy to compute with just two inputs. Flexible in that various time steps can be analysed.

Weaknesses: Does not take into account carry-over of dryness from year to year. May be slow to react in certain climates.

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Baltas, E., 2007: Spatial distribution of climatic indices in northern Greece. *Meteorological Applications*, 14:69–78.

De Martonne, E., 1925: *Traité de Géographie Physique*. 11. Paris, Colin.

Index name: China Z Index (CZI).

Ease of use: Yellow.

Origins: Developed in China, CZI builds on the ease of calculation provided by SPI and improves on it by making the calculations even easier for the user. A statistical Z-score can be used to identify and monitor drought periods. The index was first used and developed in 1995 by the National Climate Centre of China.

Characteristics: CZI is similar to SPI because precipitation is used to determine wet and dry periods, assuming that the precipitation obeys a Pearson type III distribution. It uses monthly time steps from 1 to 72 months, giving it the ability to identify droughts of various durations.

Input parameters: Monthly precipitation.

Applications: Similar to SPI, in which both wet and dry events can be monitored over multiple timescales.

Strengths: Simple calculations, which can be computed for several time steps. Can be used for both wet and dry events. Allows for missing data, similar to SPI.

Weaknesses: The Z-score data do not require adjustment by fitting them to gamma or Pearson type II distributions, and it is speculated that because of this, shorter timescales may be less well represented compared with SPI.

Resources: All calculations and explanations of CZI can be found at: http://onlinelibrary.wiley.com/doi/10.1002/joc.658/pdf.

References:

Edwards, D.C. and T.B. McKee, 1997: Characteristics of 20th century drought in the United States at multiple time scales. *Atmospheric Science*, 634:1–30.

Wu, H., M.J. Hayes, A. Weiss and Q. Hu, 2001: An evaluation of the Standardized Precipitation Index, the China-Z Index and the statistical Z-score. *International Journal of Climatology*, 21:745–758.

Index name: Crop Moisture Index (CMI).

Ease of use: Yellow.

Origins: As part of original work done by Palmer in the early 1960s, CMI is usually calculated weekly along with the Palmer Drought Severity Index (PDSI) output as the short-term drought component in which the impact on agriculture is considered.

Characteristics: As some of the drawbacks associated with PDSI became apparent, Palmer responded to them with the development of CMI. It is intended to be a drought index especially suited to drought impacts on agriculture, in that it responds quickly to rapidly changing conditions. It is calculated by subtracting the difference between potential evapotranspiration and moisture, to determine any deficit.

Input parameters: Weekly precipitation, weekly mean temperature and the previous week's CMI value.

Applications: Used to monitor droughts in which agricultural impacts are a primary concern.

Strengths: The output is weighted, so it is possible to compare different climate regimes. Responds quickly to rapidly changing conditions.

Weaknesses: As it was developed specifically for grain-producing regions in the United States, CMI may show a false sense of recovery from long-term drought events, as improvements in the short term may be insufficient to offset long-term issues.

Resource: https://www.drought.gov/drought/content/products-current-drought-and-monitoring-drought-indicators/crop-moisture-index.

Reference: Palmer, W.C., 1968: Keeping track of crop moisture conditions, nationwide: the Crop Moisture Index. *Weatherwise*, 21:156–161.

Index name: Drought Area Index (DAI).

Ease of use: Yellow.

Origins: Developed in the late 1970s by Bhalme and Mooley at the Indian Institute of Tropical Meteorology.

Characteristics: Developed as a method to improve understanding of monsoon rainfall in India, determining both flood and drought episodes using monthly precipitation. By comparing monthly precipitation during the critical monsoon period, the intensities of wet and dry periods are obtained, and the significance of the dryness can be derived based upon the contribution of each month's precipitation to the total monsoon season.

Input parameters: Monthly precipitation during the monsoon season.

Applications: Used to identify when the monsoon season has been adequate or dry, or there is potential for flooding. The drought prediction is a good early warning for the potential of famine development.

Strengths: Very focused on Indian monsoon seasons in the tropics.

Weaknesses: Lack of applicability to other areas or climate regimes.

Resource: The mathematics and associated explanation of this index are in the original paper, http://moeseprints.incois.gov.in/1351/1/large%20scale.pdf.

Reference: Bhalme, H.N. and D.A. Mooley, 1980: Large-scale droughts/floods and monsoon circulation. *Monthly Weather Review*, 108:1197–1211.

Index name: Drought Reconnaissance Index (DRI).

Ease of use: Yellow.

Origins: Work was initiated by Tsakiris and Vangelis at the National Technical University of Athens, Greece.

Characteristics: Consists of a drought index that contains a simplified water balance equation considering precipitation and potential evapotranspiration. It has three outputs: the initial value, the normalized value and the standardized value. The standardized DRI value is similar in nature to SPI and can be compared to it directly. DRI is more representative than SPI, however, as it considers the full water balance instead of precipitation alone.

Input parameters: Monthly temperature and precipitation values.

Applications: Cases where impacts on agriculture or water resources are a primary concern.

Strengths: The use of potential evapotranspiration gives a better representation of the full water balance of the region than SPI provides, which will give a better indication of the drought severity. Can be calculated for many time steps, as with SPI. All the required mathematics are available in the literature.

Weaknesses: Potential evapotranspiration calculations can be subject to errors when using temperature alone to create the estimate. Monthly timescales may not react quickly enough for rapidly developing droughts.

Resource: DRI software is available at http://drinc.ewra.net/.

Reference: Tsakiris, G. and H. Vangelis, 2005: Establishing a drought index incorporating evapotranspiration. *European Water*, 9/10:3–11.

Index name: Effective Drought Index (EDI).

Ease of use: Yellow.

Origins: Developed through work done by Byun and Wilhite, along with staff at NDMC.

Characteristics: Uses daily precipitation data to develop and compute several parameters: effective precipitation (EP), daily mean EP, deviation of EP (DEP) and the standardized value of DEP. These parameters can identify the onset and end of water deficit periods. Using the input parameters, EDI calculations can be performed for any location in the world in which the results are standardized for comparison, giving a clear definition of the onset, end and duration of drought. At the time of EDI development, most drought indices were being calculated using monthly data, so the switch to daily data was unique and important to the utility of the index.

Input parameters: Daily precipitation.

Applications: A good index for operational monitoring of both meteorological and agricultural drought situations because calculations are updated daily.

Strengths: With a single input required for calculations, it is possible to calculate EDI for any location where precipitation is recorded. Supporting documents explaining the processes are available for the program. EDI is standardized so that outputs from all climate regimes can be compared. It is effective for identifying the beginning, end and duration of drought events.

Weaknesses: With precipitation alone accounted for, the impact of temperature on drought situations is not directly integrated. Using daily data may make it difficult to use EDI in an operational situation, as daily updates to input data may not be possible.

Resources: The authors state that the code is available by contacting them directly. The calculations are available and described in the original paper referenced below. EDI calculations are part of a suite of indices calculated as part of the Spatial and Time Series Information Modeling (SPATSIM) software package, http://www.preventionweb.net/files/1869_VL102136.pdf.

Reference: Byun, H.R. and D.A. Wilhite, 1996: Daily quantification of drought severity and duration. *Journal of Climate*, 5:1181–1201.

Index name: Hydro-thermal Coefficient of Selyaninov (HTC).

Ease of use: Yellow.

Origins: Developed by Selyaninov in the Russia Federation and based on the Russian climate.

Characteristics: Uses temperature and precipitation values and is sensitive to dry conditions specific to the climate regime being monitored. It is flexible enough to be used in both monthly and decadal applications.

Input parameters: Monthly temperature and precipitation values.

Applications: Useful in the monitoring of agricultural drought conditions and has also been used in climate classifications.

Strengths: Simple to calculate, and the values can be applied to agricultural conditions during the growing season.

Weaknesses: The calculations do not take into account soil moisture.

Resources: Information can be found at the website of the Russian National Institute on Agricultural Meteorology, http://cxm.obninsk.ru/index.php?id=154, and at the website of the Interactive Agricultural Ecological Atlas of Russia and Neighboring Countries, http://www.agroatlas.ru/en/content/Climatic_maps/GTK/GTK/index.html.

Reference: Selyaninov, G.T., 1928: About climate agricultural estimation. *Proceedings on Agricultural Meteorology*, 20:165–177.

Index name: NOAA Drought Index (NDI).

Ease of use: Yellow.

Origins: Developed in the early 1980s at the Joint Agricultural Weather Facility as part of the United States Department of Agriculture's attempt to use weather and climate data for crop production estimates around the world.

Characteristics: A precipitation-based index in which the actual precipitation measured is compared with normal values during the growing season. Mean precipitation for each week is calculated and a running eight-week average of measured average precipitation is summed and compared. If the actual precipitation is greater than 60% of the normal precipitation for the eight-week period, then the current week is assumed to have little or no water stress. If stress is detected, it remains until the actual precipitation is at 60% or more of normal.

Input parameters: Monthly precipitation converted to weekly precipitation values.

Applications: Used as an indicator of drought conditions affecting agriculture.

Strengths: The only input is precipitation, in a monthly time step. The calculations and explanation of use are simple.

Weaknesses: At least 30 years' worth of data are required to compute normalized monthly values that are used in the computation of the weekly values. It has very specific applications related to agriculture and crop progression and development.

Reference: Strommen, N.D. and R.P. Motha, 1987: An operational early warning agricultural weather system. In: *Planning for Drought: Toward a Reduction of Societal* Vulnerability (D.A. Wilhite, W.E. Easterling and D.A. Wood, eds.). Boulder, CO, Westview Press.

Index name: Palmer Drought Severity Index (PDSI).

Ease of use: Yellow.

Origins: Developed in the 1960s as one of the first attempts to identify droughts using more than just precipitation data. Palmer was tasked with developing a method to incorporate temperature and precipitation data with water balance information to identify droughts in crop-producing regions of the United States. For many years, PDSI was the only operational drought index, and it is still very popular around the world.

Characteristics: Calculated using monthly temperature and precipitation data along with information on the water-holding capacity of soils. It takes into account moisture received (precipitation) as well as moisture stored in the soil, accounting for the potential loss of moisture due to temperature influences.

Input parameters: Monthly temperature and precipitation data. Information on the water-holding capacity of soils can be used, but defaults are also available. A serially complete record of temperature and precipitation is required.

Applications: Developed mainly as a way to identify droughts affecting agriculture, it has also been used for identifying and monitoring droughts associated with other types of impacts. With the longevity of PDSI, there are numerous examples of its use over the years.

Strengths: Used around the world, and the code and output are widely available. Scientific literature contains numerous papers related to PDSI. The use of soil data and a total water balance methodology makes it quite robust for identifying drought.

Weaknesses: The need for serially complete data may cause problems. PDSI has a timescale of approximately nine months, which leads to a lag in identifying drought conditions based upon simplification of the soil moisture component within the calculations. This lag may be up to several months, which is a drawback when trying to identify a rapidly emerging drought situation. Seasonal issues also exist, as PDSI does not handle frozen precipitation or frozen soils well.

Resource: http://hydrology.princeton.edu/data.pdsi.php.

References:

Alley, W.M., 1984: The Palmer Drought Severity Index: limitations and assumptions. *Journal of Applied Meteorology*, 23:1100–1109.

Palmer, W.C., 1965: *Meteorological Drought*. Research Paper No. 45, US Weather Bureau, Washington, DC.

Index name: Palmer Z Index.

Ease of use: Yellow.

Origins: The Palmer Z Index responds to short-term conditions better than PDSI and is typically calculated for much shorter timescales, enabling it to identify rapidly developing drought conditions. As part of the original work done by Palmer in the early 1960s, the Palmer Z Index is usually calculated on a monthly basis along with PDSI output as the moisture anomaly.

Characteristics: Sometimes referred to as the 'Moisture Anomaly Index', and the derived values provide a comparable measure of the relative anomalies of a region for both dryness and wetness when compared to the entire record for that location.

Input parameters: The Palmer Z Index is a derivative of PDSI, and the Z values are part of the PDSI output.

Applications: Useful for comparing current periods to other known drought periods. It can also be used to determine the end of a drought period, when it is used to determine how much moisture is needed to reach the near normal category, as defined by Palmer.

Strengths: Same as for PDSI. The scientific literature contains a number of relevant papers. The use of soil data and a total water balance methodology makes the Palmer Z Index quite robust for identifying drought.

Weaknesses: Same as for PDSI, with the need for serially complete data possibly causing problems. It has a timescale of approximately nine months, which leads to a lag in identifying drought conditions based upon simplification of the soil moisture component within the calculations. This lag may be up to several months, which is a drawback when trying to identify a rapidly emerging drought situation. Seasonal issues also exist, as the Palmer Z Index does not handle frozen precipitation or frozen soils well.

Resource: Contact NDMC to access the code for the Palmer suite, http://drought.unl.edu/.

Reference: Palmer, W.C., 1965: *Meteorological Drought*. Research Paper No. 45, US Weather Bureau, Washington, DC.

Index name: Rainfall Anomaly Index (RAI).

Ease of use: Yellow.

Origins: Work began in the early 1960s by van Rooy.

Characteristics: Uses normalized precipitation values based upon the station history of a particular location. Comparison to the current period puts the output into a historical perspective.

Input parameters: Precipitation.

Applications: Addresses droughts that affect agriculture, water resources and other sectors, as RAI is flexible in that it can be analysed at various timescales.

Strengths: Easy to calculate, with a single input (precipitation) that can be analysed on monthly, seasonal and annual timescales.

Weaknesses: Requires a serially complete dataset with estimates of missing values. Variations within the year need to be small compared to temporal variations.

Resources: No resources available.

References:

Kraus, E.B., 1977: Subtropical droughts and cross-equatorial energy transports. *Monthly Weather Review*, 105(8):1009–1018.

van Rooy, M.P., 1965: A Rainfall Anomaly Index independent of time and space. *Notos*, 14:43–48.

Index name: Self-Calibrated Palmer Drought Severity Index (sc-PDSI).

Ease of use: Yellow.

Origins: Initial work was conducted at the University of Nebraska-Lincoln by Wells et al. in the early 2000s.

Characteristics: Accounts for all the constants contained in PDSI, and includes a methodology in which the constants are calculated dynamically based upon the characteristics present at each station location. The self-calibrating nature of sc-PDSI is developed for each station and changes based upon the climate regime of the location. It has wet and dry scales.

Input parameters: Monthly temperature and precipitation. Information on the water-holding capacity of soils can be used, but defaults are also available. A serially complete record of temperature and precipitation data is required.

Applications: Can be applied to meteorological, agricultural and hydrological drought situations. With the results being tied directly to station location, extreme events are rare, as they are related directly to that station's information and not a constant.

Strengths: With the calculations for sc-PDSI accounting for each individual location, the index reflects what is happening at each site and allows for more accurate comparisons between regions. Different time steps can be calculated.

Weaknesses: As the methodology is not significantly different from PDSI, it has the same issues in terms of time lag and frozen precipitation and frozen soils.

Resources: The code can be obtained from http://drought.unl.edu/ and https://climatedataguide.ucar.edu/climate-data/cru-sc-pdsi-self-calibrating-pdsi-over-europe-north-america.

Reference: Wells, N., S. Goddard and M.J. Hayes, 2004: A self-calibrating Palmer Drought Severity Index. *Journal of Climate*, 17:2335–2351.

Index name: Standardized Anomaly Index (SAI).

Ease of use: Yellow.

Origins: Introduced by Kraus in the mid-1970s and was examined closely by Katz and Glantz at the National Center for Atmospheric Research, United States, in the early 1980s. SAI was developed based on RAI, and RAI is a component of SAI. They are similar, but both are unique.

Characteristics: Based upon the results of RAI, and was developed to help identify droughts in susceptible regions, such as the West African Sahel and north-east Brazil. RAI accounts for station-based precipitation in a region and standardizes annual amounts. Deviations are then averaged over all stations in the region to obtain a single SAI value.

Input parameters: Precipitation at monthly, seasonal or annual time steps.

Applications: Identifying drought events, especially in areas frequented by drought.

Strengths: Single input, which can be calculated for any defined period.

Weaknesses: Only uses precipitation, and calculations are dependent on quality data.

Resources: Equations for the calculations are provided in the literature.

References:

Katz, R.W. and M.H. Glantz, 1986: Anatomy of a rainfall index. *Monthly Weather Review*, 114:764–771.

Kraus, E.B., 1977: Subtropical droughts and cross-equatorial energy transports. *Monthly Weather Review*, 105(8):1009–1018.

Index name: Standardized Precipitation Evapotranspiration Index (SPEI).

Ease of use: Yellow.

Origins: Developed by Vicente-Serrano et al. at the Instituto Pirenaico de Ecologia in Zaragoza, Spain.

Characteristics: As a relatively new drought index, SPEI uses the basis of SPI but includes a temperature component, allowing the index to account for the effect of temperature on drought development through a basic water balance calculation. SPEI has an intensity scale in which both positive and negative values are calculated, identifying wet and dry events. It can be calculated for time steps of as little as 1 month up to 48 months or more. Monthly updates allow it to be used operationally, and the longer the time series of data available, the more robust the results will be.

Input parameters: Monthly precipitation and temperature data. A serially complete record of data is required with no missing months.

Applications: With the same versatility as that of SPI, SPEI can be used to identify and monitor conditions associated with a variety of drought impacts.

Strengths: The inclusion of temperature along with precipitation data allows SPEI to account for the impact of temperature on a drought situation. The output is applicable for all climate regimes, with the results being comparable because they are standardized. With the use of temperature data, SPEI is an ideal index when looking at the impact of climate change in model output under various future scenarios.

Weaknesses: The requirement for a serially complete dataset for both temperature and precipitation may limit its use due to insufficient data being available. Being a monthly index, rapidly developing drought situations may not be identified quickly.

Resources: SPEI code is freely available and the calculations are also described in the literature, http://sac.csic.es/spei/.

Reference: Vicente-Serrano, S.M., S. Begueria and J.I. Lopez-Moreno, 2010: A multi-scalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. *Journal of Climate*, 23:1696–1718.

Index name: Agricultural Reference Index for Drought (ARID).

Ease of use: Red.

Origins: Based upon research done in the south-east United States by Woli at Mississippi State University and Jones et al. at the University of Florida in 2011.

Characteristics: Predicts the status of moisture availability in the soil. It uses a combination of water stress approximations and crop models to identify the impact of water stress on plant growth, development and yield for specific crops.

Input parameters: Daily temperature and precipitation data. The CERES-Maize model is also used, but other crop simulations models can be used.

Applications: Used for identifying and predicting drought in contexts where agricultural impacts are the primary concern.

Strengths: Crop models and water balance methods prove to be useful in predicting soil moisture and subsequent stress to crops. Can be computed daily so reaction times to drought will be fast.

Weaknesses: Designed and tested in the south-east United States for only a few cropping systems. Not easily transferable.

Resources: The equations and the methodology used are explained in the referenced article below. No source code is publicly available.

Reference: Woli, P., J.W. Jones, K.T. Ingram and C.W. Fraisse, 2012: Agricultural Reference Index for Drought (ARID). *Agronomy Journal*, 104:287–300.

Index name: Crop-specific Drought Index (CSDI).

Ease of use: Red.

Origins: Developed by Meyer et al. in the early 1990s at the University of Nebraska-Lincoln to examine the impact of drought on actual crop yield.

Characteristics: By calculating a basic soil water balance, it takes into account the impact of drought, but identifies when the drought stress occurred within the development of the crop and what the overall impact to the final yield will be. PDSI and CMI can identify drought conditions affecting a crop, but do not indicate the likely impact on yields.

Input parameters: Daily maximum temperature, daily minimum temperature, precipitation, dewpoint temperature, wind speed and global solar radiation are the climatic inputs. Characteristics of the soil profile are also needed for model development. Yield and phenology data are required for proper correlations to growing days, crop progress and final yield.

Applications: Developed mainly to help identify the impact of drought on crop yields in the grain-producing regions of the United States, and is very specific to the type of crop being monitored.

Strengths: Very specific to a particular crop and based upon the development of the plant. The model takes into account when the drought stress occurred during plant growth and estimates the overall impact on yield.

Weaknesses: The inputs are quite complex, and many locations will lack the required instruments or period of record needed to properly assess conditions.

Resources: The methodology and calculations are all described thoroughly in the literature, see references below.

References:

Meyer, S.J., K.G. Hubbard and D.A. Wilhite, 1993: A Crop-specific Drought Index for corn. I. Model development and validation. *Agronomy Journal*, 85:388–395.

Meyer, S.J., K.G. Hubbard and D.A. Wilhite, 1993: A Crop-specific Drought Index for corn. II. Application in drought monitoring and assessment. *Agronomy Journal*, 85:396–399.

Index name: Reclamation Drought Index (RDI).

Ease of use: Red.

Origins: The United States Bureau of Reclamation developed this drought index in the mid-1990s as a method to trigger drought emergency relief funds associated with public lands.

Characteristics: Developed to define drought severity as well as duration and can also be used to predict the onset and end of drought periods. It has both wet and dry scales and is calculated at the river basin level, in a similar way to the Surface Water Supply Index (SWSI). RDI has water-demand and temperature components, which allow for the inclusion of evaporation into the index.

Input parameters: Monthly precipitation, snowpack, reservoir levels, streamflow and temperature.

Applications: Used mainly to monitor water supply for river basins.

Strengths: Very specific to each basin. Unlike SWSI, it accounts for temperature effects on climate. Wet and dry scales allow for monitoring of wet and dry conditions.

Weaknesses: Calculations are made for individual basins, so comparisons are hard to make. Having all the inputs in an operational setting may cause delays in the production of data.

Resources: The characteristics and mathematics are provided in the reference below.

Reference: Weghorst, K., 1996: *The Reclamation Drought Index: Guidelines and Practical Applications*. Bureau of Reclamation, Denver, CO.

7.2 Soil moisture

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Index name: Soil Moisture Anomaly (SMA).

Ease of use: Yellow.

Origins: Developed by Bergman et al. at the National Weather Service in the United States during the mid-1980s as a way to assess global drought conditions.

Characteristics: Can use weekly or monthly precipitation and potential evapotranspiration values in a simple water balance equation. It is intended to reflect the degree of dryness or saturation of the soil compared with normal conditions and to show how soil moisture stress influences crop production around the world.

Input parameters: Weekly or monthly temperature and precipitation data along with date and latitude. Values for soil moisture holding capacity and site-specific data can be used, although defaults are included.

Applications: Developed and used extensively for monitoring drought impacts on agriculture and crop production around the world.

Strengths: By taking into account the effects of both temperature and precipitation, the water balance aspects that make PDSI so popular are included with the ability to change constants with site-specific data. It considers moisture at different layers of the soil and is more adaptable than PDSI to different locations.

Weaknesses: The data requirements make it challenging to calculate. Potential evapotranspiration estimates can vary quite substantially by region.

Resources: The inputs and calculations are described thoroughly in the literature. No program exists at this time to provide the calculations.

Reference: Bergman, K.H., P. Sabol and D. Miskus, 1988: *Experimental Indices for Monitoring Global Drought Conditions*. Proceedings of 13th Annual Climate Diagnostics Workshop, United States Department of Commerce, Cambridge, MA.

Index name: Evapotranspiration Deficit Index (ETDI).

Ease of use: Red.

Origins: Developed from research at the Texas Agricultural Experiment Station, United States, by Narasimhan and Srinivasan in 2004.

Characteristics: A weekly product that is helpful for identifying water stress for crops. ETDI is calculated along with the Soil Moisture Deficit Index (SMDI), in which a water stress ratio is calculated that compares actual evapotranspiration with reference crop evapotranspiration. The water stress ratio is then compared with the median calculated over a long-term period.

Input parameters: Modelled data from a hydrologic model with the Soil and Water Assessment Tool (SWAT) model are used initially to compute soil water in the root zone on a weekly basis.

Applications: Useful for identifying and monitoring short-term drought affecting agriculture.

Strengths: Analyses both actual and potential evapotranspiration and can identify wet and dry periods.

Weaknesses: Calculations are based upon output from the SWAT model, but could be calculated if the appropriate inputs were available. The spatial variability of ETDI increases in the summer months during the period of greatest evapotranspiration and highly variable precipitation.

Resources: Calculations are provided and explained thoroughly in the reference below, along with correlation studies to other drought indices. Information on the SWAT model can be found at http://swat.tamu.edu/software/swat-executables/.

Reference: Narasimhan, B. and R. Srinivasan, 2005: Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, 133(1):69–88.

Index name: Soil Moisture Deficit Index (SMDI).

Ease of use: Red.

Origins: Developed from research at the Texas Agricultural Experiment Station, United States, by Narasimhan and Srinivasan in 2004.

Characteristics: A weekly soil moisture product calculated at four different soil depths, including the total soil column, at 0.61, 1.23 and 1.83 m, and can be used as an indicator of short-term drought, especially using the results from the 0.61 m layer.

Input parameters: Modelled data from a hydrologic model with the SWAT model are used initially to compute soil water in the root zone on a weekly basis.

Applications: Useful for identifying and monitoring drought affecting agriculture.

Strengths: Takes into account the full profile as well as different depths, which makes it adaptable to different crop types.

Weaknesses: The information needed to calculate SMDI is based upon output from the SWAT model. There are auto-correlation concerns when all the depths are being used.

Resources: The calculations are provided and explained thoroughly in the reference below. Information on the SWAT model can be found at http://swat.tamu.edu/software/swat-executables/.

Reference: Narasimhan, B. and R. Srinivasan, 2005: Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agricultural and Forest Meteorology*, 133(1):69–88.

Index name: Soil Water Storage (SWS).

Ease of use: Red.

Origins: Unknown – producers have been trying to measure soil moisture accurately since the beginning of agriculture.

Characteristics: Identifies the amount of available moisture within a plant's root zone, which depends upon the type of plant and the type of soil. Precipitation and irrigation both affect the results.

Input parameters: Rooting depth, available water storage capacity of the soil type and maximum soil water deficit.

Applications: Used mainly for monitoring drought in agricultural contexts, but can also be a component in drought conditions affecting water availability.

Strengths: Calculations are well known and simple to follow, even using defaults. Many soils and crops have been analysed using this method.

Weaknesses: In areas where soils are not homogeneous, there may be large changes over small distances.

Resources: Calculations and examples are provided in the reference below.

Reference: British Columbia Ministry of Agriculture, 2015: *Soil Water Storage Capacity and Available Soil Moisture*. Water Conservation Fact Sheet, http://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/agriculture-and-seafood/agricultural-land-and-environment/soil-nutrients/600-series/619000-1_soil_water_storage_capacity.pdf.

7.3 Hydrology

Index name: Palmer Hydrological Drought Index (PHDI).

Ease of use: Yellow.

Origins: Part of the suite of indices developed by Palmer in the 1960s with the United States Weather Bureau.

Characteristics: Based on the original PDSI and modified to take into account longer-term dryness that will affect water storage, streamflow and groundwater. PHDI has the ability to calculate when a drought will end based on precipitation needed by using a ratio of moisture received to moisture required to end a drought. There are four drought categories: near normal, which occurs approximately 28%–50% of the time; mild to moderate, which occurs approximately 11%–27% of the time; severe, which occurs approximately 5%–10% of the time; and extreme, which occurs approximately 4% of the time.

Input parameters: Monthly temperature and precipitation. Information on the water-holding capacity of soils can be used, but defaults are also available. A serially complete record of temperature and precipitation data is required.

Applications: Most useful for taking into account drought affecting water resources on longer timescales.

Strengths: Its water balance approach allows the total water system to be considered.

Weaknesses: Frequencies will vary by region and time of year, where extreme drought may not be a rare event during some months of the year. The impact of human influences, such as management decisions and irrigation, are not considered in the calculations.

Resources: The code can be found in the original Palmer paper in the reference below, http://onlinelibrary.wiley.com/doi/10.1002/wrcr.20342/pdf.

Reference: Palmer, W.C., 1965: *Meteorological Drought*. Research Paper No. 45. United States Weather Bureau, Washington, DC.

Index name: Standardized Reservoir Supply Index (SRSI).

Ease of use: Yellow.

Origins: Developed by Gusyev et al. in Japan as a systematic way to analyse reservoir data in drought conditions.

Characteristics: Similar to SPI in that monthly data are used to compute a probability distribution function of reservoir storage data, to provide information on water supply for a region or basin within a range of –3 (extremely dry) to +3 (extremely wet).

Input parameters: Monthly reservoir inflows and average reservoir storage volumes.

Applications: Takes into account the total inflow and storage associated with any particular reservoir system, and provides information for municipal water supply managers and local irrigation providers.

Strengths: Easy to compute, as it mimics SPI calculations using a standard gamma distribution of the probability distribution function.

Weaknesses: Does not take into account changes due to management of the reservoir and losses due to evaporation.

Resource: The International Centre for Water Hazard and Risk Management has applied the SRSI methodology to several Asian river basins, http://www.icharm.pwri.go.jp/.

Reference: Gusyev, M.A., A. Hasegawa, J. Magome, D. Kuribayashi, H. Sawano and S. Lee, 2015: *Drought Assessment in the Pampanga River Basin, the Philippines. Part 1: A Role of Dam Infrastructure in Historical Droughts*. Proceedings of the 21st International Congress on Modelling and Simulation (MODSIM 2015), Broadbeach, Queensland, Australia.

Index name: Standardized Streamflow Index (SSFI).

Ease of use: Yellow.

Origins: Modarres introduced SSFI in 2007, and Telesca et al. investigated it further in 2012. In the original work, Modarres described how SSFI was similar to SPI in that SSFI for a given period was defined as the difference in streamflow from mean to standard deviation.

Characteristics: Developed using monthly streamflow values and the methods of normalization associated with SPI. Can be calculated for both observed and forecasted data, providing a perspective on high and low flow periods associated with drought and flood.

Input parameters: Streamflow data on a daily or monthly timescale.

Applications: Monitoring of hydrological conditions at multiple timescales.

Strengths: Easy to calculate using the SPI program. A single variable input that allows for missing data makes it easy to use.

Weaknesses: Only accounts for the streamflow in the context of monitoring drought, with no other influences being investigated.

Resources: It is described well in the literature, with mathematics and case studies available. The SPI program is available at http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx.

References:

Modarres, R., 2007: Streamflow drought time series forecasting. *Stochastic Environmental Research and Risk Assessment*, 21:223–233.

Telesca, L., M. Lovallo, I. Lopez-Moreno and S. Vicente-Serrano, 2012: Investigation of scaling properties in monthly streamflow and Standardized Streamflow Index time series in the Ebro basin (Spain). *Physica A: Statistical Mechanics and its Applications*, 391(4):1662–1678.

Index name: Standardized Water-level Index (SWI).

Ease of use: Yellow.

Origins: Developed by Bhuiyan at the Indian Institute of Technology, India, as a way to assess groundwater recharge deficits.

Characteristics: As a hydrology-based drought indicator, it uses data from wells to investigate the impact of drought on groundwater recharge. Results can be interpolated between points.

Input parameters: Groundwater well levels.

Applications: For areas with frequent seasonal low flows on main rivers and streams.

Strengths: The impact of drought on groundwater is a key component in agricultural and municipal water supplies.

Weaknesses: Only takes groundwater into account, and interpolation between points may not be representative of the region or climate regime.

Reference: Bhuiyan, C., 2004: *Various Drought Indices for Monitoring Drought Condition in Aravalli Terrain of India*. Proceedings of the XXth ISPRS Conference. International Society for

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Photogrammetry and Remote Sensing, Istanbul, Turkey, http://www.isprs.org/proceedings/XXXV/congress/comm7/papers/243.pdf.

Index name: Streamflow Drought Index (SDI).

Ease of use: Yellow.

Origins: Developed by Nalbantis and Tsakiris using the methodology and calculations of SPI as the basis.

Characteristics: Uses monthly streamflow values and the methods of normalization associated with SPI for developing a drought index based upon streamflow data. With an output similar to that of SPI, both wet and dry periods can be investigated, as well as the severity of these occurrences.

Input parameters: Monthly streamflow values and a historical time series for the streamflow gauge.

Applications: Used to monitor and identify drought events with reference to a particular gauge, which may or may not represent larger basins.

Strengths: The program is widely available and easy to use. Missing data are allowed, and the longer the streamflow record, the more accurate the results. As with SPI, various timescales can be examined.

Weaknesses: A single input (streamflow) does not take into account management decisions, and periods of no flow can skew the results.

Resources: It is described in the literature with mathematical examples provided. The SPI code is available at http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx. See http://drinc.ewra.net/ for information on SDI.

Reference: Nalbantis, I. and G. Tsakiris, 2008: Assessment of hydrological drought revisited. *Water Resources Management*, 23(5):881–897.

Index name: Surface Water Supply Index (SWSI).

Ease of use: Yellow.

Origins: Developed by Shafer and Dezman in 1982 to directly address some of the limitations identified in PDSI.

Characteristics: Takes into account the work done by Palmer with PDSI but adds additional information including water supply data (snow accumulation, snowmelt and runoff, and reservoir data), and is calculated at the basin level. SWSI identifies the approximate frequency of mild drought occurrence at 26%–50%, moderate drought occurrence at 14%–26% and severe drought occurrence at 2%–14%. Extreme drought occurs approximately less than 2% of the time.

Input parameters: Reservoir storage, streamflow, snowpack and precipitation.

Applications: Used to identify drought conditions associated with hydrological fluctuations.

Strengths: Taking into account the full water resources of a basin provides a good indication of the overall hydrological health of a particular basin or region.

Weaknesses: As data sources change or additional data are included, the entire index has to undergo recalculation to account for these changes in the inputs, making it difficult to construct a homogeneous time series. As calculations may vary between basins, it is difficult to compare basins or homogeneous regions.

Resources: Calculations and an explanation of the methodology are provided in the references below.

References:

Doesken, N.J. and D. Garen, 1991: *Drought Monitoring in the Western United States using a Surface Water Supply Index.* Preprints, Seventh Conference on Applied Climatology, Salt Lake City, UT. American Meteorology Society, 266–269.

Doesken, N.J., T.B. McKee and J. Kleist, 1991: *Development of a Surface Water Supply Index for the Western United States*. Climatology Report 91-3, Colorado Climate Center, http://climate.colostate.edu/pdfs/climo_rpt_91-3.pdf.

Shafer, B.A. and L.E. Dezman, 1982: *Development of a Surface Water Supply Index (SWSI) to Assess the Severity of Drought Conditions in Snowpack Runoff Areas*. Proceedings of the Western Snow Conference, Colorado State University, Fort Collins, CO, 164–175.

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Index name: Aggregate Dryness Index (ADI).

Ease of use: Red.

Origins: The result of work done at California State University, United States, by Keyantash and at the University of California-Berkeley, United States, by Dracup in 2003.

Characteristics: A multivariate regional drought index that looks at all water resources across many timescales and impacts. It was developed to be used across uniform climate regimes.

Input parameters: Precipitation, evapotranspiration, streamflow, reservoir storage, soil moisture content and snow water content. The inputs are only used if the region for which ADI is being calculated contains the variable.

Applications: Can be used in the context of multiple types of drought impacts. Looking at the total amount of water in a climate regime allows a better understanding of water availability to be made.

Strengths: Takes into account water stored as well as moisture that comes from precipitation.

Weaknesses: Does not take into account temperatures or groundwater, which are accounted for in the description of ADI.

Resources: The methodology and mathematics are explained in the literature, with examples provided. No code was found for this index.

Reference: Keyantash, J.A. and J.A. Dracup, 2004: An aggregate drought index: assessing drought severity based on fluctuations in the hydrologic cycle and surface water storage. *Water Resources Research*, 40:W09304, doi:10.1029/2003WR002610, http://www.geo.oregonstate.edu/classes/ecosys_info/readings/2003WR002610.pdf.

Index name: Standardized Snowmelt and Rain Index (SMRI).

Ease of use: Red.

Origins: Developed to account for frozen precipitation and how it contributes to runoff into streams as snowmelt. The work was conducted by Staudinger et al., and tested over several Swiss basins.

Characteristics: With methods similar to SPI, SMRI takes into account both rain and snow deficits and the associated impact to streamflow, including precipitation stored as snow. It is most widely used as a complement to SPI.

Input parameters: Streamflow data, daily precipitation and daily temperature data. Gridded data were used in the initial study of SMRI.

Applications: Focuses on the impact of frozen precipitation and the contribution of this stored water to future streamflows, this index is associated with the monitoring of drought situations.

Strengths: Accounting for snow and future contributions to streamflow, it captures all the inputs into a basin. With the ability to use temperature and precipitation to model snow, actual snow amounts are not needed.

Weaknesses: The use of gridded data and the fact that the data used go back only to 1971 is a drawback when investigating performance using point data and longer periods of record. Not using actual snow depths and associated snow water equivalency can lead to errors in runoff projections.

Resources: Background to the methods and calculations is provided in the literature.

Reference: Staudinger, M., K. Stahl and J. Seibert, 2014: A drought index accounting for snow. *Water Resources Research*, 50:7861–7872, doi:10.1002/2013WR015143.

7.4 Remote sensing

Index name: Enhanced Vegetation Index (EVI).

Ease of use: Green.

Origins: Originated from work done by Huete and a team from Brazil and the University of Arizona, United States, who developed a Moderate Resolution Imaging Spectroradiometer (MODIS)-based tool for assessing vegetation conditions.

Characteristics: Vegetation monitoring from satellite platforms using the Advanced Very High Resolution Radiometer (AVHRR) to compute the Normalized Difference Vegetation Index (NDVI) is quite useful. EVI uses some of the same techniques as NDVI, but with the input data from a MODIS-based satellite. Both EVI and NDVI are calculated using the MODIS platform and analysed on how they perform compared to AVHRR platforms. EVI is more responsive to canopy variations, canopy type and architecture, and plant physiognomy. EVI can be associated with stress and changes related to drought.

Input parameters: MODIS-based satellite information.

Applications: Used to identify stress related to drought over different landscapes. Mainly associated with the development of droughts affecting agriculture.

Strengths: High resolution and good spatial coverage over all terrains.

Weaknesses: Stress to plant canopies could be caused by impacts other than drought, and it is difficult to discern them using only EVI. The period of record for satellite data is short, with climatic studies being difficult.

Resources: Methodology and calculations are provided in the literature, and online resources of products exist, http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php.

Reference: Huete, A., K. Didan, T. Miura, E.P. Rodriguez, X. Gao and L.G. Ferreira, 2002: Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83(1):195–213.

Index name: Evaporative Stress Index (ESI).

Ease of use: Green.

Origins: Developed by a team led by Anderson, in which remotely sensed data were used to compute evapotranspiration over the United States. The team was composed of scientists from the United States Department of Agriculture, the University of Alabama-Huntsville and the University of Nebraska-Lincoln.

Characteristics: Established as a new drought index in which evapotranspiration is compared to potential evapotranspiration using geostationary satellites. Analyses suggest that it performs similarly to short-term precipitation-based indices, but can be produced at a much higher resolution and without the need for precipitation data.

Input parameters: Remotely sensed potential evapotranspiration.

Applications: Especially useful for identifying and monitoring droughts that have multiple impacts.

Strengths: Very high resolution with a spatial coverage of any area.

Weaknesses: Cloud cover can contaminate and affect results. There is not a long period of record for climatological studies.

Resources: Calculations of the index are provided in the literature, http://hrsl.arsusda.gov/drought/.

Reference: Anderson, M.C., C. Hain, B. Wardlow, A. Pimstein, J.R. Mecikalski and W.P. Kustas, 2011: Evaluation of drought indices based on thermal remote sensing of evapotranspiration over the continental United States. *Journal of Climate*, 24(8):2025–2044.

Index name: Normalized Difference Vegetation Index (NDVI).

Ease of use: Green.

Origins: Developed from work done by Tarpley et al. and Kogan with the National Oceanic and Atmospheric Administration (NOAA) in the United States.

Characteristics: Uses the global vegetation index data, which are produced by mapping 4 km daily radiance. Radiance values measured in both the visible and near-infrared channels are used to calculate NDVI. It measures greenness and vigour of vegetation over a seven-day period as a way of reducing cloud contamination and can identify drought-related stress to vegetation.

Input parameters: NOAA AVHRR satellite data.

Applications: Used for identifying and monitoring droughts affecting agriculture.

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Strengths: Innovative in the use of satellite data to monitor the health of vegetation in relation to drought episodes. Very high resolution and great spatial coverage.

Weaknesses: Data processing is vital to NDVI, and a robust system is needed for this step. Satellite data do not have a long history.

Resources: The literature describes the methodology and calculations. NDVI products are available online, http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php.

References:

Kogan, F.N., 1995: Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorology Society*, 76(5):655–668.

Tarpley, J.D., S.R. Schneider and R.L. Money, 1984: Global vegetation indices from the NOAA-7 meteorological satellite. *Journal of Climate and Applied Meteorology*, 23:491–494.

Index name: Temperature Condition Index (TCI).

Ease of use: Green.

Origins: Developed from work done by Kogan with NOAA in the United States.

Characteristics: Using AVHRR thermal bands, TCI is used to determine stress on vegetation caused by temperatures and excessive wetness. Conditions are estimated relative to the maximum and minimum temperatures and modified to reflect different vegetation responses to temperature.

Input parameters: AVHRR satellite data.

Applications: Used in conjunction with NDVI and the Vegetation Condition Index (VCI) for drought assessment of vegetation in situations where agricultural impacts are the primary concern.

Strengths: High resolution and good spatial coverage.

Weaknesses: Potential for cloud contamination as well as a short period of record.

Resources: Methodology and calculations are provided in the literature, and online resources of products exist, http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php.

Reference: Kogan, F.N., 1995: Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*, 15(11):91–100.

Index name: Vegetation Condition Index (VCI).

Ease of use: Green.

Origins: Developed from work done by Kogan with NOAA in the United States.

Characteristics: Using AVHRR thermal bands, VCI is used to identify drought situations and determine the onset, especially in areas where drought episodes are localized and ill defined. It focuses on the impact of drought on vegetation and can provide information on the onset, duration and severity of drought by noting vegetation changes and comparing them with historical values.

Input parameters: AVHRR satellite data.

Applications: Used in conjunction with NDVI and TCI for assessment of vegetation in drought situations affecting agriculture.

Strengths: High resolution and good spatial coverage.

Weaknesses: Potential for cloud contamination as well as a short period of record.

Resources: Methodology and calculations are provided in the literature, and online resources of products exist, http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php.

References:

Kogan, F.N., 1995: Application of vegetation index and brightness temperature for drought detection. *Advances in Space Research*, 15(11):91–100.

Liu, W.T. and F.N. Kogan, 1996: Monitoring regional drought using the Vegetation Condition Index. *International Journal of Remote Sensing*, 17(14):2761–2782.

Index name: Vegetation Drought Response Index (VegDRI).

Ease of use: Green.

Origins: Developed by a team of scientists from NDMC, the United States Geological Survey's Earth Resources Observation and Science Center, and the United States Geological Survey Flagstaff Field Center.

Characteristics: Developed as a drought index that was intended to monitor drought-induced vegetation stress using a combination of remote sensing, climate-based indicators, and other biophysical information and land-use data.

Input parameters: SPI, PDSI, percentage annual seasonal greenness, start of season anomaly, land cover, soil available water capacity, irrigated agriculture and defined ecological regions. As some of the inputs are derived variables, additional inputs are needed.

Applications: Used mainly as a short-term indicator of drought for agricultural applications.

Strengths: An innovative and integrated technique using both surface and remotely sensed data and technological advances in data mining.

Weaknesses: Short period of record due to remotely sensed data. Not useful out of season or during periods of little or no vegetation.

Resources: The methods used and a description of the calculations can be found in the reference given below. See also http://vegdri.unl.edu/.

Reference: Brown, J.F., B.D. Wardlow, T. Tadesse, M.J. Hayes and B.C. Reed, 2008: The Vegetation Drought Response Index (VegDRI): a new integrated approach for monitoring drought stress in vegetation. *GIScience & Remote Sensing*, 45:16–46.

Index name: Vegetation Health Index (VHI).

Ease of use: Green.

Origins: The result of work done by Kogan with NOAA in the United States.

Characteristics: One of the first attempts to monitor and identify drought-related agricultural impacts using remotely sensed data. AVHRR data in the visible, infrared and near-infrared channels are all used to identify and classify stress to vegetation due to drought.

Input parameters: AVHRR satellite data.

Applications: Used to identify and monitor droughts affecting agriculture around the world.

Strengths: Coverage over the entire globe at a high resolution.

Weaknesses: The period of record for satellite data is short.

Resources: The calculations and sample case studies are given in the literature. VHI maps can be found online at http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/vh_browse.php.

References:

Kogan, F.N., 1990: Remote sensing of weather impacts on vegetation in non-homogeneous areas. *International Journal of Remote Sensing*, 11:1405–1419.

Kogan, F.N., 1997: Global drought watch from space. *Bulletin of the American Meteorological Society*, 78:621–636.

Kogan, F.N., 2001: Operational space technology for global vegetation assessments. *Bulletin of the American Meteorological Society*, 82(9):1949–1964.

Index name: Water Requirement Satisfaction Index (WRSI) and Geo-spatial WRSI.

REMOTE SENSING

Ease of use: Green.

Origins: Developed by the Food and Agriculture Organization of the United Nations to monitor and investigate crop production in famine-prone parts of the world. Additional work was done by the Famine Early Warning Systems Network.

Characteristics: Used to monitor crop performance during the growing season and based upon how much water is available for the crop. It is a ratio of actual to potential evapotranspiration. These ratios are crop specific, and are based upon crop development and known relationships between yields and drought stress.

Input parameters: Crop development models, crop coefficients and satellite data.

Applications: Used to monitor crop development progress and stress related to agriculture.

Strengths: High resolution and good spatial coverage over all terrains.

Weaknesses: Stress related to factors other than available water can affect the results. Satellite-based rainfall estimates have a degree of error that will affect the results of the crop models used and the balance of evapotranspiration.

Resources:

http://chg.geog.ucsb.edu/tools/geowrsi/index.html

http://iridl.ldeo.columbia.edu/documentation/usgs/adds/wrsi/WRSI_readme.pdf

Reference: Verdin, J. and R. Klaver, 2002: Grid-cell-based crop water accounting for the famine early warning system. *Hydrological Processes,* 16(8):1617–1630.

Index name: Normalized Difference Water Index (NDWI) and Land Surface Water Index (LSWI).

Ease of use: Green.

Origins: Developed from work done by Gao in the mid-1990s at the National Aeronautics and Space Administration (NASA) Goddard Space Center in the United States.

Characteristics: Very similar to the NDVI methodology, but uses the near-infrared channel to monitor the water content of the vegetation canopy. Changes in the vegetation canopy are used to identify periods of drought stress.

Input parameters: Satellite information in the various channels of the near-infrared spectrum.

Applications: Used for monitoring of drought affecting agriculture as a method of stress detection.

Strengths: High resolution and good spatial coverage over all terrains. Different to NDVI, as the two indices look at different signals.

Weaknesses: Stress to plant canopies can be caused by impacts other than drought, and it is difficult to discern them using only NDWI. The period of record for satellite data is short, with climatic studies being difficult.

Resources: The methodology is described in the literature as are the calculations based on the MODIS data being used, http://www.eomf.ou.edu/modis/visualization/.

References:

Chandrasekar, K., M.V.R. Sesha Sai, P.S. Roy and R.S. Dwevedi, 2010: Land Surface Water index (LSWI) response to rainfall and NDVI using the MODIS vegetation index product. *International Journal of Remote Sensing*, 31:3987–4005.

Gao, B.C., 1996: NDWI—a Normalized Difference Water Index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment*, 58(3):257–266.

Note: The NDWI concept and calculations are very similar to those of the Land Surface Water Index (LSWI).

Index name: Soil Adjusted Vegetation Index (SAVI).

Ease of use: Red.

Origins: Developed by Huete at the University of Arizona, United States, in the late 1980s. The idea was to have a global model for monitoring soil and vegetation from remotely sensed data.

Characteristics: SAVI is similar to NDVI – spectral indices may be calibrated in such a way that the variations of soils are normalized and do not influence measurements of the vegetation canopy. These enhancements to NDVI are useful because SAVI accounts for variations in soils.

Input parameters: Remotely sensed data, which are then compared to known surface plots of various vegetation.

Applications: Useful for the monitoring of soils and vegetation.

Strengths: High-resolution and high-density data associated with remotely sensed data allow for very good spatial coverage.

Weaknesses: Calculations are complex, as is obtaining data to run operationally. A short period of record associated with the satellite data can hamper climate analyses.

Resources: The methodology and associated calculations are explained well in the literature.

Reference: Huete, A.R., 1988: A Soil-adjusted Vegetation Index (SAVI). *Remote Sensing of Environment*, 25(3):295–309.

7.5 Composite or modelled

Index name: Combined Drought Indicator (CDI).

Ease of use: Green.

Origins: Developed by Sepulcre-Canto et al. at the European Drought Observatory as a drought index for Europe in which SPI, SMA and fraction of Absorbed Photosynthetically Active Radiation (fAPAR) are combined as an indicator for droughts affecting agriculture.

Characteristics: Composed of three warning levels (watch, warning and alert) by integrating three drought indicators: SPI, soil moisture and remotely sensed vegetation data. A watch is indicated when there is a precipitation shortage, a warning level is reached when the precipitation shortage translates into a soil moisture shortage, and a warning occurs when the precipitation and soil moisture deficits translate into an impact to the vegetation.

Input parameters: SPI computed from station-based precipitation data throughout Europe; in this case, the three-month SPI is used. Soil moisture data are obtained using the LISFLOOD model, and fAPAR comes from the European Space Agency.

Applications: Used as an indicator of droughts with agricultural impacts.

Strengths: The spatial coverage is good and at a high resolution using a combination of remotely sensed and surface data.

Weaknesses: Using a single SPI value may not be the best option in all situations and does not represent conditions that may carry over from season to season. Hard to replicate and currently not available for areas outside Europe.

Resources: Housed and maintained at the European Drought Observatory within the European Commission's Joint Research Centre, http://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000.

Reference: Sepulcre-Canto, G., S. Horion, A. Singleton, H. Carrao and J. Vogt, 2012: Development of a Combined Drought Indicator to detect agricultural drought in Europe. *Natural Hazards and Earth Systems Sciences*, 12:3519–3531.

Index name: Global Integrated Drought Monitoring and Prediction System (GIDMaPS).

Ease of use: Green.

Origins: Developed from work done by Hao et al. at the University of California in Irvine, United States, as a system to monitor and predict drought over the globe.

Characteristics: Provides drought information for SPI, soil moisture and the Multivariate Standardized Drought Index (MSDI). GIDMaPS also uses satellite data combined with data assimilation tools. The product is produced on a gridded basis in near real time, and combines monitoring and prediction as a way to monitor, assess and anticipate droughts with multiple impacts.

Input parameters: Uses an algorithm in which remotely sensed data are combined with the Global Land Data Assimilation System (GLDAS) index to produce output for three drought indices as well as seasonal predictions.

Applications: Used for monitoring and predicting by producing values for SPI, MSDI and Standardized Soil Moisture Index. Can be used for agriculture and other sectors.

Strengths: The gridded and global data represent all areas well. With both a wet and a dry scale, GIDMaPS can be used to monitor more than just drought. It is excellent for areas lacking good surface observations with long periods of record. It is relatively easy to use in that it is computed without the need for input from users.

Weaknesses: Grid sizes may not represent all areas and climate regimes equally. A period of record going back to 1980 is very short when considering climatic applications. To modify it, the code and inputs would need to be obtained.

Resources: The literature explains the process well, and online resources and maps are readily available, http://drought.eng.uci.edu/.

Reference: Hao, Z., A. AghaKouchak, N. Nakhjiri and A. Farahmand, 2014: Global integrated drought monitoring and prediction system. *Scientific Data*, 1:1–10.

Index name: Global Land Data Assimilation System (GLDAS).

Ease of use: Green.

Origins: Rodell led the work, which involved scientists from NASA and NOAA in the United States.

Characteristics: Uses a system of surface and remotely sensed data along with land surface models and data assimilation techniques to provide data on terrestrial conditions. Output includes soil moisture characteristics, which are a good drought indicator.

Input parameters: Land surface models, surface-based meteorological observations, vegetation classifications and satellite data.

Applications: Useful for determining river and streamflow projections as well as runoff components based on current conditions; ideal for monitoring droughts that have multiple impacts.

Strengths: As it is global in nature and available at a high resolution, it can represent most areas. Useful for monitoring developing drought in areas that are data poor.

Weaknesses: The grid size is not sufficiently fine for island nations. Only areas that lack near-real-time surface observations are represented by the data assimilation process.

Resources: The methodology and inputs are described well in the literature. Output is available online.

https://climatedataguide.ucar.edu/climate-data/nldas-north-american-land-data-assimilation-system-monthly-climatologies

http://ldas.gsfc.nasa.gov/nldas/

http://disc.sci.gsfc.nasa.gov/services/grads-gds/gldas

References:

Mitchell, K., D. Lohman, P. Houser, E. Wood, J. Schaake, A. Robock, B. Cosgrove, J. Sheffield, Q. Duan, L. Luo, R. Higgins, R. Pinker, J. Tarpley, D. Lettenmaier, C. Marshall, J. Entin, M. Pan, W. Shi, V. Koren, J. Meng, B. Ramsay and A. Bailey, 2004: The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modelling system. *Journal of Geophysical Research*, 109:D07S90, doi:10.1029/2003JD003823.

Rodell, M., P. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosogrove, J. Radakovich, M. Bosilovich, J. Entin, J. Walker, D. Lohmann and D. Toll, 2004: The Global Land Data Assimilation System. *Bulletin of the American Meteorological Society*, 85(3):381–394.

Xia, Y., K. Mitchell, M. Ek, J. Sheffield, B. Cosgrove, E. Wood, L. Luo, C. Alonge, H. Wei, J. Meng, B. Livneh, D. Lettenmaier, V. Koren, Q. Duan, K. Mo, Y. Fan and D. Mocko, 2012: Continental-scale water and energy flux analysis and validation for the North American Land Data Assimilation System project phase 2 (NLDAS-2): 1. Intercomparison and application of model products. *Journal of Geophysical Research*, 117:D03109, doi:10.1029/2011JD016048.

Index name: Multivariate Standardized Drought Index (MSDI).

Ease of use: Green.

Origins: Developed by Hao and AghaKouchak at the University of California at Irvine, United States.

Characteristics: Uses information on both precipitation and soil moisture to identify and classify drought episodes by investigating precipitation and soil moisture deficits. It is helpful for identifying drought episodes where typical precipitation-based indicators or soil-moisture-based indicators may not indicate the presence of drought.

Input parameters: Monthly precipitation and soil moisture data are needed from the Modern Era Retrospective Analysis (MERRA)-Land systems. MERRA-Land data are generated by a 0.66° × 0.50° grid from 1980 onwards.

Applications: Useful for the identification and monitoring of drought in cases where precipitation and soil moisture are important contributors to impacts.

Strengths: The gridded and global data represent all areas well. With both a wet and a dry scale, it can be used to monitor more than just drought. It is excellent for areas lacking good surface observations with long periods of record. It is relatively easy to use in that it is computed without the need for input from users. Individual indices can be obtained from MSDI output.

Weaknesses: Grid size may not represent all areas and climate regimes equally. A period of record going back to 1980 is very short when considering climatic applications. To modify, the code and inputs would need to be obtained. Not all timescales are produced for SPI and Standardized Soil Moisture Index outputs.

Resources: The literature explains the process well, and online resources and maps are readily available, http://drought.eng.uci.edu/.

Reference: Hao, Z. and A. AghaKouchak, 2013: Multivariate Standardized Drought Index: a multi-index parametric approach for drought analysis. *Advances in Water Resources*, 57:12–18.

Index name: United States Drought Monitor (USDM).

Ease of use: Green.

Origins: Developed by Svoboda et al. in the late 1990s as an analysis of drought conditions using the results of many indicators and inputs and based on comparing current data with historical conditions. The work was the first operational 'composite' approach applied in the United States.

Characteristics: Uses a method of percentile ranking in which indices and indicators from various periods of record can be compared equivalently. It has a scale of five intensity levels, from abnormally dry conditions that will occur about every three to five years, to exceptional drought conditions that will occur about once every fifty years. It is flexible in that any number of inputs can be used, and it has a level of subjectivity that allows for the inclusion of drought-related impacts in the analysis.

Input parameters: Flexible, as there are no set numbers of indicators. Originally, only a few inputs were used; currently, the construction of USDM involves analysis of 40–50 inputs. Drought indices, soil moisture, hydrological inputs, climatological inputs, modelled inputs and remotely sensed inputs are all included in the analysis. As new indicators are developed, USDM is flexible enough to also include them.

Applications: Ideal for monitoring droughts that have many impacts especially on agriculture and water resources during all seasons over all climate regimes. It is a weekly product, but can also be adapted for monthly analyses.

Strengths: Uses many indices and indicators, which makes the final results more robust. It is flexible to meet the needs of various users. It was innovative in the way it identified drought and classified intensities, and has the ability to analyse data from various timescales using the percentile ranking methodology.

Weaknesses: Operational data are needed, as most current inputs will provide the best results when the analysis is done. If only a few inputs are available, USDM analysis becomes weaker, but it remains applicable.

Resources: The methodology is explained well in the literature and online, http://droughtmonitor.unl.edu/.

Reference: Svoboda, M., D. Lecomte, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, R. Tinker, M. Palecki, D. Stooksbury, D. Miskus and S. Stephens, 2002: The drought monitor. *Bulletin of the American Meteorological Society*, 83(8):1181–1190.

APPENDIX: SURVEY RESULTS

Every four years, the WMO Commission for Agricultural Meteorology sends out a request to National Meteorological and Hydrological Services (NMHSs) to fill out a survey on National Progress Reports in Agricultural Meteorology. In the most recent survey (2010–2014), one of the questions requested NMHSs to list their current drought indices in use in the service and/or country/territory. Table 2 provides a preliminary list of drought indices based on the survey. Please note that this is not an all-inclusive list of all drought indices in use, but it provides a good representation of what is currently being used and/or available. The exact instruction of the survey was: "Please list the five most-used drought indices in your service".

Table 2. Preliminary list of drought indices based on the survey

Country/territory	*Drought indices*
Argentina	Standardized Precipitation Index; quintiles; soil hydric balance; probability of occurrence; maximum period of days without precipitation
Austria	Standardized Precipitation Index; rainfall deciles
Belarus	Models of productivity of agricultural crops; Shashko moisture index; Protserova moisture measurement; moisture reserves in soil; number of days in month with relative humidity ≤ 30%
Belgium	Meteorological drought; precipitation deficit
Belize	Standard Precipitation Index
Bosnia and Herzegovina	Standardized Precipitation Index; Hydro-thermal Coefficient (Selyaninov); Aridity Index; Palmer Drought Severity Index; precipitation percentage of normal; reference evapotranspiration; water balance in soil
Brazil	Standardized Precipitation Index; Palmer Drought Severity Index; Standardized Evapotranspiration Index; Crop Moisture Index; deciles and quintiles; crop-specific drought indices
Bulgaria	Soil Moisture Index; Aridity Index; Thornthwaite Index; Standardized Precipitation Index; Palmer Drought Severity Index; Selyaninov's Hydro-thermal Coefficient
Canada	Standardized Precipitation Index; Vegetation Drought Response Index; precipitation departure; Palmer Drought Severity Index; blended indices used in test model
Chile	Standardized Precipitation Index; Normalized Difference Vegetation Index; percentage of normal precipitation
China	Crop Water Deficit Index; Soil Moisture Index; Precipitation Abnormal Index
Côte d'Ivoire	Water Satisfaction Requirements Index; water balance
Croatia	Standardized Precipitation Index; monitoring of dry/wet conditions and prediction seven days ahead; cumulative precipitation; Walter diagram; monthly temperature and precipitation anomalies
Cyprus	Standardized Precipitation Index; Bhalme–Mooley Drought Intensity Index
Czech Republic	Agro-meteorological drought; actual and potential evapotranspiration and soil moisture modelling with operational water balance model; climatic water balance; percentage of precipitation compared with normal value; hydrological measures (for example, streamflow and reservoir levels)
Democratic Republic of the Congo	Percentage of normal precipitation
Dominican Republic	Standard Precipitation Index
Germany	Standardized Precipitation Index; Standardized Temperature Index; Climatic Water Balance; soil humidity expressed as plant-available water of field capacity at different depths

Greece	Standardized Precipitation Index; Palmer Drought Severity Index; Reclamation Drought Index; Palfai Drought Index
Hong Kong, China	Standardized Precipitation Index
Iran, Islamic Republic of	Calculated daily: Effective Drought Index, Aridity Index, deciles, Percent of Normal Precipitation; calculated weekly: Temperature Condition Index, Vegetation Condition Index, Vegetation Health Index; calculated monthly: Standardized Precipitation Index, Reclamation Drought Index
Israel	Standardized Precipitation Index; ratio of precipitation averages
Jamaica	Standardized Precipitation Index; percentage of 30-year mean over two months
Jordan	Standardized Precipitation Index; Aridity Index
Kazakhstan	Hydro-thermal Coefficient of Selyaninov, Standardized Precipitation Index
Libya	Standardized Precipitation Index
Lithuania	Selyaninov’s Hydro-thermal Coefficient; Standardized Precipitation Index
New Zealand	Days of soil moisture deficit; Standardized Precipitation Index; depth of potential evapotranspiration deficit; rainfall deciles and anomalies; drought spatial assessments
Pakistan	Standardized Precipitation Index; Percent of Normal; percentage departure; Normalized Difference Vegetation Index; land surface temperature
Peru	Palmer Drought Severity Index; Standardized Precipitation Index; Standardized Runoff Index; Standardized Precipitation Evapotranspiration Index
Russian Federation	Ratio of monthly precipitation to sum of temperatures; ratio of precipitation to annual mean air humidity deficit; ratio of oil water storage for the period to air moisture deficit sum for the same period (multiplied by 0.375); number of days with relative air humidity below 30%; number of days with maximum air temperature above 25 °C; soil moisture water reserves at 0–20, 0–50 and 0–100 cm soil layers; sum of anomalous weather conditions; deviations of the mean air temperature; precipitation sum and water reserves in 1 m soil layer from the norm
Slovenia	Precipitation anomaly; Standardized Precipitation Index; cumulative meteorological water balance; decadal drought stress index, consecutive dry days
Spain	Standardized Precipitation Index; soil water content (available water calculated as percentage of soil water capacity from a soil water balance model)
Sri Lanka	Standardized Precipitation Index
Switzerland	Standardized Precipitation Index; Standardized Precipitation Evapotranspiration Index; precipitation anomaly; Agricultural Reference Index for Drought
Thailand	Moisture Available Index; Standardized Precipitation Index
The former Yugoslav Republic of Macedonia	Standardized Precipitation Index; deciles; Palmer Drought Severity Index; Aridity Index; Lang Index
Trinidad and Tobago	Standardized Precipitation Index; Palmer drought indices
Turkey	Standardized Precipitation Index; Percent of Normal Index; Palmer Drought Severity Index
Ukraine	Selyaninov’s Hydro-thermal Coefficient; Protserov’s humidity supply coefficient; Aridity Index by Ped; Meteorological Productivity Index by Bagrov; Standardized Precipitation Index
United Republic of Tanzania	Standardized Precipitation Index; Percent of Normal Precipitation
United States of America	Standardized Precipitation Index; Palmer Drought Severity Index; Crop Moisture Index; Surface Water Supply Index; Percent of Normal Precipitation
Uzbekistan	Number of days with temperatures above 40 °C; Aridity Index (annual amount of precipitation, mm/year); provision of water runoff during the growing season (April–September); accumulation of snow; reduction in soil moisture up to 4 mm or less

BIBLIOGRAPHY

This section includes all publications that were cited in chapters 1–6 or that were used in developing the framework of this handbook. Specific publications for each index/indicator can be found in the Reference(s) section of each index/indicator summary in chapter 7.

Eriyagama, N., V. Smakhtin and N. Gamage, 2009: *Mapping Drought Patterns and Impacts: a Global Perspective*. IWMI Research Report No. 133. Colombo, International Water Management Institute, http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB133/RR133.pdf.

Hayes, M.J., 2011: *Comparison of Major Drought Indices: Introduction*. National Drought Mitigation Center, http://drought.unl.edu/Planning/Monitoring/ComparisonofIndicesIntro.aspx.

Hayes, M., M. Svoboda, N. Wall and M. Widhalm, 2011: The Lincoln Declaration on Drought Indices: universal meteorological drought index recommended. *Bulletin of the American Meteorological Society*, 92:485–488.

Heim, R.R., 2002: A review of twentieth-century drought indices used in the United States. *Bulletin of the American Meteorological Society*, 83:1149–1165.

Hisdal, H. and L.M. Tallaksen (eds.), 2000: *Drought Event Definition*. Technical Report 6 of the ARIDE Project, Assessment of the Regional Impact of Droughts in Europe, Department of Geophysics, University of Oslo, Norway.

Intergovernmental Panel on Climate Change (IPCC), 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Special Report of Working Groups I and II of the IPCC (C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor and P.M. Midgley, eds.). Cambridge and New York, Cambridge University Press.

Keyantash, J. and J.A. Dracup, 2002: The quantification of drought: an evaluation of drought indices. *Bulletin of the American Meteorological Society*, 83:1167–1180.

Lawrimore, J., R.R. Heim, M. Svoboda, V. Swail and P.J. Englehart, 2002: Beginning a new era of drought monitoring across North America. *Bulletin of the American Meteorological Society*, 83:1191–1192.

Lloyd-Hughes, B., 2014: The impracticality of a universal drought definition. *Theoretical and Applied Climatology*, 117(3):607–611, doi:10.1007/s00704-013-1025-7.

McKee, T.B., N.J. Doesken and J. Kleist, 1993: *The Relationship of Drought Frequency and Duration to Time Scales*. Proceedings of the 8th Conference on Applied Climatology, 17–23 January 1993, Anaheim, CA. Boston, MA, American Meteorological Society.

Mishra, A.K. and V.P. Singh, 2010: A review of drought concepts. *Journal of Hydrology,* 391:202–216.

Mishra, A.K. and V.P. Singh, 2011: Drought modeling. A review. *Journal of Hydrology,* 403:157–175.

Pulwarty, R.S. and M. Sivakumar, 2014: Information systems in a changing climate: early warnings and drought risk management. *Weather and Climate Extremes*, 3:14–21.

Sivakumar, M.V.K., R.P. Motha, D.A. Wilhite and D.A. Wood (eds.), 2011: *Agricultural Drought Indices.* Proceedings of a WMO/UNISDR Expert Group Meeting on Agricultural Drought Indices, Murcia, Spain, 2–4 June 2010 (AGM-11, WMO/TD No. 1572; WAOB-2011). Geneva, http://www.droughtmanagement.info/literature/WMO_agricultural_drought_indices_proceedings_2010.pdf.

Svoboda, M., B.A. Fuchs, C. Poulsen and J.R. Nothwehr, 2015: The drought risk atlas: enhancing decision support for drought risk management in the United States. *Journal of Hydrology*, 526:274–286, doi:10.1016/j.jhydrol.2015.01.006.

Svoboda, M., D. LeComte, M. Hayes, R. Heim, K. Gleason, J. Angel, B. Rippey, R. Tinker, M. Palecki, D. Stooksbury, D. Miskus and S. Stephens, 2002: The drought monitor. *Bulletin of the American Meteorological Society*, 83(8):1181–1190.

Wardlow, B.D., M.C. Anderson and J.P. Verdin (eds.), 2012: *Remote Sensing of Drought: Innovative Monitoring Approaches*. Boca Raton, FL, CRC Press.

Wilhite, D. and M. Glantz, 1985: Understanding the drought phenomenon: the role of definitions. *Water International*, 10:111–120.

World Meteorological Organization, 2006: *Drought Monitoring and Early Warning: Concepts, Progress and Future Challenges* (WMO-No. 1006), Geneva, http://www.droughtmanagement.info/literature/WMO_drought_monitoring_early_warning_2006.pdf.

———, 2012: *Standardized Precipitation Index User Guide* (WMO-No.1090), Geneva, http://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf.

World Meteorological Organization (WMO) and Global Water Partnership (GWP), 2014: *National Drought Management Policy Guidelines: A Template for Action* (D.A. Wilhite). Integrated Drought Management Programme (IDMP) Tools and Guidelines Series 1. WMO, Geneva, and GWP, Stockholm, http://www.droughtmanagement.info/literature/IDMP_NDMPG_en.pdf.

World Meteorological Organization (WMO), United Nations Convention to Combat Desertification (UNCCD) and Food and Agriculture Organization of the United Nations (FAO), 2013: *High Level Meeting on National Drought Policy*, Geneva, 11–15 March 2013. Policy Document: National Drought Management Policy. Geneva, http://www.wmo.int/pages/prog/wcp/drought/hmndp/documents/PolicyDocumentRev_12-2013_En.pdf.

Zargar, A., R. Sadiq, B. Naser and F.I. Khan, 2011: A review of drought indices. *Environmental Reviews*, 19:333–349.

The Integrated Drought Management Programme (IDMP) was launched by the World Meteorological Organization and the Global Water Partnership at the High Level Meeting on National Drought Policy in March 2013. IDMP works with a wide range of partners with the objective of supporting stakeholders at all levels. IDMP provides its partners with policy and management guidance through globally coordinated generation of scientific information and sharing best practices and knowledge for integrated drought management. It contributes to the Global Framework for Climate Services (GFCS), especially regarding the GFCS priority areas of disaster risk reduction, water, agriculture and food security, energy and health. It especially seeks to support regions and countries in developing more proactive drought policies and better predictive mechanisms. This handbook contributes to that objective.

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