Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

SUNRISE: Drought Monitoring in China

A brief review

SUNRISE
Sustainable Use of Natural Resources to Improve Human Health and Support Economic Development

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Contents

1 Introduction

Drought is one of the most complex and costly natural hazards. It develops slowly and can affect a large area meaning it can be difficult to pinpoint the start and/or the end of an event. Drought is primarily driven by a deficit in precipitation but an additional level of complexity is introduced when these deficits in precipitation propagate to other parts of the hydrological cycle such as soil moisture, river flows and groundwater levels over different time scales.

Drought hazard has been well documented in China with a multitude of papers detailing the current, past and future drought risk and vulnerability (e.g. Dai, 2011; Piao et al., 2010; Zou et al., 2005). The widespread and costly nature of drought in China has naturally led to an interest in drought monitoring and forecasting. Both of which contribute to drought planning and preparedness and so reducing drought risk and vulnerability.

1.1 Purpose of this report

Given the need for drought monitoring in China, the aim of this report is to describe and outline the common themes and recent advances in the field.

1.2 Approach

Two approaches were used to compose this review of drought monitoring and forecasting in China, firstly, Web of Science was searched using appropriate search terms (see Section 2.1) followed by a brief review of the literature where key papers were summarised (see Section 2.2).

Acronyms are used throughout this report, see the Appendix a full list of acronyms used and their descriptions.

2 Drought Monitoring

There has been a proliferation of material coming out of China on the topic of drought monitoring and early warning over recent years. This section of the report outlines the trends in publications on the topic of drought monitoring in China and then reviews the common themes and most recent advances in the field.

2.1 Drought monitoring publication trends

In order to investigate the publication trends on the topic of drought monitoring in China, several Web of Science searches on publication topic were made using the following phrases:

- Drought monitoring China
- Drought indicators / index / indices China
- Drought early warning China

The search was conducted on publications in the Web of Science core collection between 1970 and 2018.

Table 1 shows the results in terms of numbers of publications of these search terms whilst Figure 1 shows the cumulative number of publications per year returned for each search term. Note that although publications published from 1970 onwards were searched, publications relating to these search terms were only found from 1997 onwards.

Table 1: Results from Web of Science for drought monitoring in China and associate search terms, search conducted on 22/01/2018

Search term	Total number of publications (topic)	Max. number of publications (topic)	Total number of publications (title)
Drought monitoring China	476	81 (2017)	60
Drought indicator / index / indices China	1575	268 (2017)	99
Drought early warning China	56	15 (2015)	4

A clear increase in the number of publications over time can be seen in Figure 1. Figure 2 shows the total numbers of publications for each search term peaking in 2015 ('Drought monitoring China' and 'Drought early warning China') and 2016 ('Drought indicators China').

However, an overview of the titles of publications do not necessarily specifically mention these phrases. Figure 2 shows that the number of publications reduces substantially when publication title is searched, rather than the topic. Although a much higher proportion of publications on the topic of 'Drought indicators / indices / index China' also included the phrase in the title than those on the topic of 'Drought monitoring China' or 'Drought early warning China'.

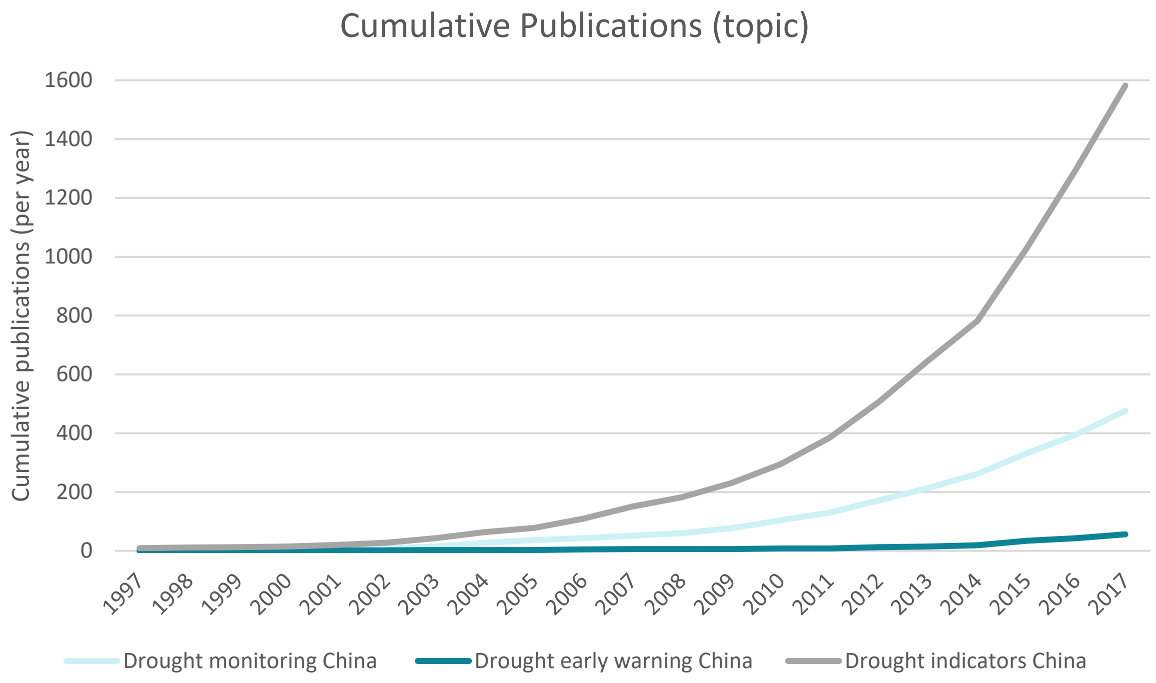

Figure 1: Cumulative number of publications returned for each search term (topic only), search up to the end of 2017 conducted 22/01/2018

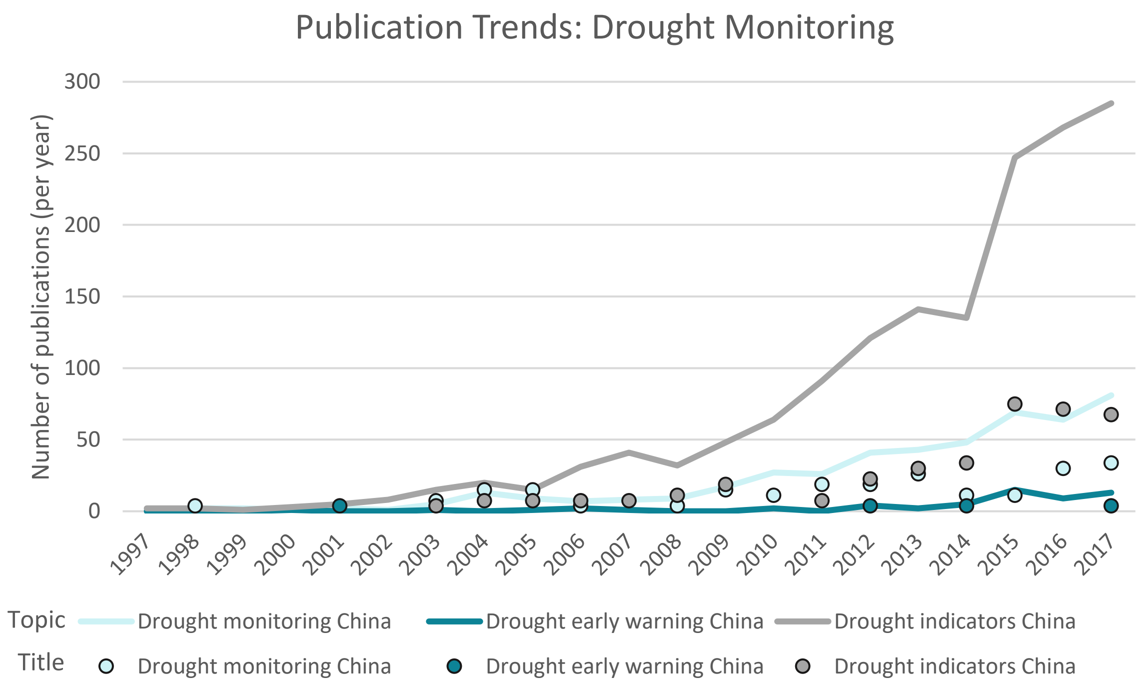

Figure 2: Number of publications each year for drought monitoring search terms by both topic (lines) and points (title), there were 7 publications published between 1989 and 1996 (inclusive) for the search term 'drought indicators China', search up to the end of 2017 conducted on 22/01/2018

2.2 Common themes & recent advances

A brief review of some of the most highly cited papers on drought monitoring in China as well as more recent publications are summarised in Table 2. The common themes and recent advances in drought monitoring techniques and methods are further discussed in Sections 2.2.1 and 2.2.2.

2.2.1 Common themes

Purpose and spatial scale

Although the papers reviewed in Table 2 aimed to improve drought monitoring through a better understanding of the drought risk (like a better understanding of the timing of drought propagation), the use of a new indicator or method, few/if any presented methods used operationally in China. This suggests that that either, there remains a step of translating drought monitoring research into operational practices and that this topic has been science rather than application driven or, operational Chinese drought monitoring processes have not be written up in the (English) academic literature.

Five papers of the 30 reviewed used data for the whole of China, whilst the remaining studies focussed on smaller regions (Figure 3). Eight papers considered large scale regions of China such as northern China and south-west China, five papers at the province level (Du et al., 2013a). One paper (Wu et al., 2001) researched the best indicator for monitoring moisture conditions in four cities (Urumqi, Fuzhou, Beijing and Wuhan). Others papers were concerned with drought monitoring at the catchment (river or lake) scale or geographical area such as the Loess Plateau or Guanzhong Plain.

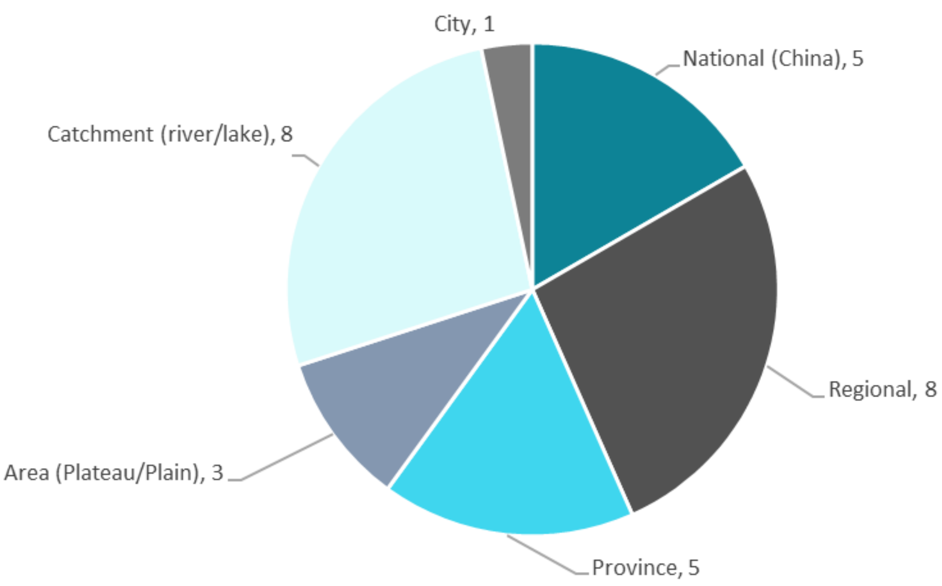

Figure 3 Spatial scale considered by reviewed papers on the topic of drought monitoring

Those considering that national scale were specifically investigating the effectiveness of indicators for real-time drought monitoring. Regional studies mostly aimed to develop and test a new indicator (Wu et al., 2013; Zhang and Jia, 2013; Hao et al., 2015), one regional and one area study aimed to analyse the performance of indicators for monitoring agricultural drought (Bai et al., 2017; Wang et al., 2016). Catchment scale studies were interested in the propagation of droughts from meteorological to hydrological (Ye et al., 2016; Wu et al., 2017), monitoring lake levels (Ding and Li, 2011), developing new indicators for identifying regional/aerial droughts (Fluixá-Sanmartín et al., 2018) or developing drought grades for management (Zhao et al., 2016).

Types of drought

The complexity of defining drought has led to the definition of 'types' of drought which relate to the compartment of the hydrological cycle in which deficits occur (Wilhite and Glantz, 1985). For example, deficits in precipitation are characterised as meteorological drought, soil moisture as agricultural drought and river flow as hydrological drought. It has been recommended that meteorological drought indicators should not be used to monitor hydrological droughts due to the non-linear responses of hydrological processes to climate inputs (Van Lanen et al., 2013; Van Loon and Van Lanen, 2012). This principle can be extended to other types of drought like agricultural drought. As such, drought type specific indicators should be used for operational monitoring (e.g. meteorological drought and precipitation; agricultural drought and soil moisture/vegetation condition; hydrological drought and streamflow/groundwater levels). The impacts of drought often occur after drought has propagated from meteorological drought to agricultural or hydrological drought, and so these drought types should be monitored for a full understanding of the drought hazard.

Understandably, many papers in this brief review (Table 2) focussed on monitoring agricultural drought with most using remotely sensed data such as MODIS or AVHRR NDVI and LST to calculate relevant drought indicators. Meteorological drought was the next most commonly monitored drought type using observed rainfall data with one study (Zhang and Jia, 2013) using microwave data to monitor precipitation.

Hydrological drought was not considered by many of the reviewed papers. Table 2 includes Ding and Li (2011) where satellite imagery was used to calculate lake water area, which was used with observed lake level data to calculate the water storage change. But few studies used observed hydrological (river flow/groundwater) data directly although Long et al. (2014)- not included in Table 2, developed a method whereby GRACE data could be used to monitor (and forecast) total water storage availability. Zhang et al. (2015) used a hydrological model to undertake water budget simulations for their SZI, but again, the SZI does not include streamflow data directly (although is used in the study to validate the SZI). The SZI was found to agree with observed streamflow better the SPI or SPEI, presumably due to this inclusion of water budget simulations.

There were also studies which compared the lag between meteorological (SPEI/SPI) and hydrological droughts (SRI/SSI: Wu et al., 2017; Ye et al., 2016) but did not discuss the use of the SSI directly for monitoring. These studies do however provide an indication over which precipitation should be monitored in these regions to reflect any deficits in streamflow where there may be a lack of easily available streamflow data for monitoring purposes. Wu et al. (2017) also illustrated how for the operation of a reservoir may impact the lag between meteorological and hydrological drought.

2.2.2 Recent advances

Data sources

Although many of the papers in Table 2 used observed point measurements of precipitation, temperature, soil moisture or river flows, many do so in order to validate results/indicators produced using remotely sensed data. The most commonly used remote sensing data were MODIS (NDVI and LST) and AVHRR (NDVI and LST), with other datasets including AMSR-E and GRACE. This perhaps reflects the wider availability and ease of accessing these data in comparison to point observations. Zhang and Jia (2013) used microwave sensors to improve meteorological drought monitoring when remote sensing techniques have more commonly been used to monitor agricultural drought.

Modelled data were used by Zhang et al. (2015) in order to calculate the SZI enabling water budget simulations are included in the indicator. This meant that the SZI agreed with observed streamflow better than meteorological drought indicators like the SPI and SPEI. Elsewhere, modelled data have been used to monitor regions with sparse observations, for example modelled hydrological data are used in the African Flood and Drought Monitor (http://stream.princeton.edu/AWCM/WEBPAGE/interface.php), including evapotranspiration, reference crop evapotranspiration, runoff, baseflow and streamflow.

The input and calibration data needed to calculate the SZI and other modelled monitoring outputs, in addition to the computational effort of processing the data (an issue also applicable to the use of remotely sensing data for monitoring) should be considered for an operational monitoring system in need of reliable, regular updates. The simple calculation of SPI, requiring only one data input, for example, led to the WMO recommending the use of the SPI for monitoring meteorological droughts (Hayes et al., 2011).

Combined indicators

Of the papers reviewed here which proposed new indicators (five papers and six new indicators – marked with a * in Table 2), all proposed a combined indicator designed to monitor several aspects of the water cycle, or combine data and information to better characterise a particular type of drought. The optimised combined indicators developed by Hao et al. (2015) performed better than single remotely sensed indicators and were more highly correlated with SPI-1 and SPEI-3 based on point observations. The SZI developed by Zhang et al. (2015) was more comparable to streamflow and the NDVI as it included evapotranspiration, runoff and soil moisture changes in its combination of the PDSI and the SPEI. The aim of these combined indicators is valid, however, the added complexity and computational effort of calculating such combined indicators should be assessed for an operational drought monitoring system which requires fast, regular updates.

*Table 2: Key papers on the topic of drought monitoring in China, * indicates a new indicator was proposed/developed*

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
(Bai et al., 2017)	TVDI; CWSI; SPI	**Observed point measurements** surface observations of precipitation and soil moisture **Remote sensing** MODIS NDVI and LST	Guanzhong Plain	2003 (monthly)		✓		*Evaluate and compare the effectiveness of TVDI and CWSI for drought monitoring in the Guanzhong Plain.* SPI and 10cm/20cm soil moisture were better correlated with CWSI than TVDI. CWSI was a more reliable indicator of agricultural drought for the Guanzhong Plain.
Ding and Li (2011)	-	**Observed point measurements** Water level data at Chenglingji hydrologic station from the Hubei Hanjiang River Administration and Changjiang Yichang Waterway Engineering Bureau **Remote sensing** ENVISTAT ASAR	Lake Dongting (ASAR 150m)	2002-2009			✓	*Use independent in-situ water level data and water area from ASAR images to derive the relationship between water level and water area of Lake Dongting.* The water-area and water level of Lake Dongting have a strong linear correlation. This study shows remote sensing data can be used to complement scarce ground measurements.

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
Du et al. (2013a)	SPI	**Observed point measurements** rainfall from 21 stations from the National Climate Center of the China Meteorological Administration. Daily flow data from 5 gauging stations on the Xiang river from the Hunan Hydrographic Office.	Hunan Province	1951-2007	✓		✓	*To evaluate the spatio-temporal variability of dry/wet conditions, examine the relationship between SPI values at multiple time scales and river flow, and to assess the potential of SPI for drought/flood monitoring and management in Hunan Province.* River flow was most strongly correlated with short SPI accumulation periods. Whilst longer accumulation periods were more suitable for monitoring groundwater droughts. Results suggest that various time scales should be considered when monitoring droughts of different types.
Du et al. (2013b)	SDI*	**Observed point measurements** Total monthly precipitation and the monthly mean temperature (1961-2010) for	Shadong Province, northern China (MODIS 1km, TRMM 0.25°)	2000-2010	✓	✓		*To develop the SDI in order to represent the non-linear, correlated relationship between meteorology, temperature and vegetation.*

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
		15 stations from China Meteorological Data Sharing Service System of China Meteorological Administration **Remote sensing** MODIS NDVI and LST, TRMM						The SDI was found to be the principal component of the PCI, TCI and VCI and could monitor the onset, duration, extent and severity of droughts. SDI was well correlated with SPI-3, crop yield and drought affected crop area meaning it can monitor agricultural and meteorological drought well.
Fluixá-Sanmartín et al. (2018)	ODE*; ODI*	**Observed point measurements** The monthly precipitation data (1960-2014) for 29 meteorological stations within or around Jinsha River basin, recorded from the China Meteorological Data Service Center[1]. **Drought catalogue** A catalogue of 13 drought events occurring 1960-2014 was created from a range of sources cited in the paper.	Jinsha River basin, in the upper Yangtze	1960-2014	✓			*To evaluate and calibrate two new indicators capable of identifying and characterising droughts using a database of known drought events occurring since 1960.* The ODE and ODI were used to characterize the occurrence and intensity of an event. ODE over the 6 month timescale was found to be the best indicator to

[1] http://data.cma.cn/en

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
								identify the known drought events.
Guo et al. (2016)	SPI	**Remote sensing** NOAA PERSIANN-CDR multi-satellite high resolution rainfall data **Gridded observations** CPAP from the National Meteorological Information Center and China Meteorological Administration developed using 2000 rain gauge observations.	China	1983-2014	✓			*Assess whether the PERSIANN-CDR dataset can be used to monitor drought conditions. Provide data users and developers valuable information on its quality for drought monitoring applications.* There was good agreement between the PERSIANN data and CPAP where the gauged network was dense or terrain was particularly complex. PERSIANN was able to detect droughts well, although there was some spatial and temporal variability. PERSIANN-CDR was found to be useful applications, such as long-term hydrological and climate studies over most of China, especially for eastern parts of China.

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
Hao et al. (2015)	OMDI*; OVDI*	**Observed point measurements** Monthly precipitation data and mean temperature data from 1981 to 2010 were obtained from China Meteorological Data Service for 42 stations over the study area **Remote sensing** MODIS NDVI and LST, TRMM, AMSR-E soil moisture and brightness temperature, CLSMAS soil moisture	South-west China (MODIS 1km; TRMM 0.25°; AMSR-E 25km, CLSMAS 0.1°)	2005-2009	✓	✓		*To establish optimized meteorological and vegetation drought indices (OMDI and OVDI) from multi-sensor remote sensing data for monitoring drought over complex landforms* The combined drought indices performed better than single remotely sensed indicators and the constrained optimization method derived higher correlations with SPEI-1 and SPEI-3.
Jiang et al. (2017)	SPI	**Remote sensing** TMPA 3B42 – processed precipitation data from TRMM	Weihe River basin (northwest China – largest tributary of the Yellow River)	1998-2013	✓			*To evaluate the accuracy of the gridded data product; to test effect of short/long reference period on SPI derivation. Investigate spatial and temporal patterns in SPI.* The monthly TMPA 3B42V7 precipitation agreed with rain gauge observations and could accurately capture the

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								temporal and spatial characteristics of rainfall within the Weihe River Basin and so can be used to monitor droughts in the basin.
Li et al. (2015)	MDI*; SPI; scPDSI	**Modelled data** The Xin'anjiang model (Zhao, 1992) was applied to simulate daily evapotranspiration, soil moisture and runoff processes in the Huaihe River basin according to its rainfall-runoff mechanism. **Observed point measurements** The daily 1988–2005 time series of rainfall from sixty-three rainfall gauges in the study area, and discharge and evaporation from the Xixian hydrology station were collected for daily simulation	Eastern China using Huaihe River Basin (central China, highest population density) as a case study	1998, 1999-2000, 2001 drought events	✓	✓	✓	*To develop a multivariate drought index by incorporating multiple variables to better depict drought evolution in the upper Huaihe River basin, China.* The MDI was able to characterise meteorological, hydrological and agricultural droughts. The MDI was calculated using PCA to monthly evapotranspiration, soil moisture, runoff and precipitation. The MDI and the SPI were applicable in the Huaihe river basin with the MDI performing best. The scPDSI failed to monitor the three typical droughts.

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
Lu et al. (2014)	SWAP; SPI	**Observed point measurements** Daily precipitation data from 2205 stations over the 61 years from 1951 to 2011 are used in this study.	Yangtze River basin	1951-2011	✓			*The SWAP is applied to monitor the severe 2011 drought in China and performance is compared with SPI.* SWAP can be calculated each day so is useful for identifying short periods of drought (it can also be used to monitor floods). It successfully monitored the emergence of the spring drought in the Yangtze and changes in the affected area.
Meng et al. (2016)	IDCI*; SPEI; Pa	**Observed point measurements** monthly precipitation and mean temperature data from 1961 to 2012 for 135 stations were acquired from China Meteorological Data Sharing Service System. **Remote sensing** MODIS LST and NDVI, TRMM precipitation	Northern China (including Hebei, Shandong, Shanxi, and Liaoning provinces)	1961-2012	✓	✓		*To establish IDCI, which considers precipitation, vegetation growth condition, and land surface temperature comprehensively. These factors are weighted differently for each month of the growing season.* The IDCI and SPEIs were highly correlated during the growing season, and all the

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								correlations were statistically significant. ICDI agreed well with SPEI-6.
Su et al. (2003)	DSI	**Observed point measurements** Lysimeter measurements, a dataset from an intensive field campaigns and (c) a study area from the North China Plain with regular meteorological data. **Remote sensing** NOAA/AVHRR satellite data	North China Plain	1998	✓	✓		*To derive relative evaporation by means of the SEBS (surface energy balance system) and to compare the proposed DSI and the actual measurements of soil moisture in the North China Plain to confirm the validity and robustness of the proposed theory.* The relationship derived between the relative soil moisture and relative evapotranspiration was confirmed by the observed data and can be used to derive a DSI for drought monitoring using remote sensing data
Tao et al. (2016)	SPI	**Observed point measurements** 65 meteorological stations from Jiangsu province 1998-2014	Jiangsu Province	1998-2014	✓			*To perform an initial qualitative and quantitative comparison between monthly precipitation from*

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
		from the National Climate Center of China **Remote Sensing** monthly precipitation data of TMPA Version 7 of; the TRMM 3B43						*TRMM 3B43 and ground observations, and to investigate the suitability of applying TRMM 3B43 for drought monitoring in Jiangsu Province and to determine whether the it is suitable for future drought monitoring at a provincial level in East China.* The performance of the SPI time series from TRMM 3B43 decreases with longer accumulation periods (the correlation coefficients between TRMM 3B43 and observations when longer time scales are used reduce). However, the TRMM 3B43 product shows reliable results for drought monitoring in the central regions of Jiangsu Province (although further investigation is necessary) and it might be a cost-

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								effective solution for drought monitoring here.
Wang et al. (2004)	TVDI; NDVI; CWSI	**Remote sensing** AVHRR NDVI and LST	China	March-May 2000	✓	✓		*To evaluate the drought status in all of China using the TVDI; and to compare TVDI with the measured topsoil moisture, with NDVI and the CWSI to verify their efficiency in drought monitoring with AVHRR data* TVDI combined with NDVI and LST information is more accurate than the CWSI for evaluating soil moisture.
Wang et al. (2015)	SPEI; SPI; scPDSI; PDSI; Z index	**Observed point measurements** soil moisture data from 40 stations and climatic data from 756 stations from China's meteorological sharing service system[2] - paired weather stations with soil moisture leading to 32 pairs across northern China.	Northern China	1982-1999		✓		*To enhance agricultural drought monitoring by understanding the relationship between indicator time scales and soil moisture, finding which indicator best characterises soil moisture.* The mulitscalar indices better characterise soil

[2] http://cdc.cma.gov.cn/

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								moisture – with the SPEI being best as it includes temperature, wind, and humidity etc. in calculation of PET. The PDSI works best for monitoring over long time scales and for deeper soil depths. The Z index outperforms PDSI at shallow depths.
Wang et al. (2016)	SPI; SPEI; PDSI; Palmer Z index; scPDSI	**Observed point measurements** Observed meteorological data from 752 weather stations. Soil moisture and winter wheat yield observations (2000-2013) from 27 agrometeorological stations run by the Chinese Meteorological Agency	North-eastern China	1981-2013		✓		*To analyse the performance of five climate-based drought indices and soil moisture measurements for monitoring winter wheat (agricultural) drought threat in China.* Over Northern China, the SPI and SPEI calculated at shorter timescales (i.e., 1–5 months) in the previous year of harvest showed stronger influence on winter wheat yield than the other indicators tested.
Wang et al. (2017)	Pa; Z index; M	**Observed point measurements China**	Henan Province	1953-2012	✓			*To test 3 three indexes, Pa, Z and M in assessing the*

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
		Meteorological Data haring Network[3] and Hydrology Handbook of Henan Province[4], including weather data collected from 18 typical weather stations in Henan Province						*drought in Henan Province and systematically analyse the characteristics of past drought events between 1953 and 2012, to provide reference for regional drought assessment.* The Z index better captures past droughts and is easier to calculate, however it assumes rainfall follows Pe3 distribution and doesn't include temperature, evaporation, human activities etc.
Wu et al. (2013)	ISDI*	**Observed point measurements** Daily precipitation and temperature data (1960–2009) from 130 stations, and agro-meteorological disaster 10-day interval observation dataset (2000–2009) for 298	Mid-eastern China – 11 provinces (MODIS 1km, land cover 1km, irrigation 10km)	2000-2009 (2006 used to validate ISDI)				*To establish the ISDI based on the concept of VegDRI.* The ISDI was found to be suitable for local to large-scale (larger than provincial or national area) drought monitoring and can monitor

[3] http://www.cma.gov.cn/2011qxfw/2011qsjgx
[4] Yang et al., 2009

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
		agro-meteorological stations, both from the China Meteorological Data Sharing Service[5] **Remote sensing** MODIS NDVI & LST **Land cover** Ecological zoning (Zheng & Li, 2008), available water holding capacity (International Geosphere-Biosphere Programme), Global Irrigation Area Map						the drought onset, extension, and evolution.
Wu et al. (2001)	SPI; CZI; z-Score	**Observed point measurements** Monthly precipitation totals (1951-1998) for the four locations from the NMCC	Urumqi, Fuzhou, Beijing & Wuhan	1951-1998 (1, 3, 6, 9, 12 month accumulation periods)	✓			*To compare and evaluated the SPI, CZI and Z-Score for multiple time scales in two climate regions in China to find the best indicator for monitoring moisture conditions.* The CZI was more responsive to precipitation deficits in extremely dry conditions (whilst the z-Score has a wet bias), however the z-Score and CZI

[5] http://cdc.cma.gov.cn/

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
								are much easier to calculate than the SPI so could be considered more appropriate to monitor droughts than the SPI.
Wu et al. (2015)	ISDI; PDSI; SPI	**Remote sensing** MODIS data to calculate ISDI 2001-2013 **Observed point measurements** Meteorological observations for 1961-2013 from 497 stations throughout China	China (1km)	2009-2013 (16-day ISDI)	✓			*ISDI is evaluated its capability for near real-time drought monitoring.* The ISDI had strong correlation with PDSI in spring, summer and autumn. It had good performance in south west China 2009-2010, during the high temperatures and droughts in southern China in 2013, and floods in north-eastern China in 2013.
Wu et al. (2016)	SPEI; SMAPI; SRI	**Observed point measurements** temperature and precipitation for 142 stations from China meteorological data sharing service network. **Modelled data** daily soil moisture and runoff grids from 1951 to 2012 were	Southwest China (including Yunnan, Guizhou, Guangxi, Sichuan Provinces, and Chongqing City)	1951-2012	✓	✓	✓	*To evaluate three drought indices in relation to the drought process and the spatiotemporal relationships between types of drought in south west China.* There was good temporal correlation among the

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
		constructed based on the variable infiltration capacity (VIC) model (Liang et al. 1994, 1996) reported in the literature (Wu et al. 2007). Verified against observations.						meteorological, agricultural, and hydrological drought indices, with the best correlations at 3 months. The strength of correlation between SMAPI and SPEI is a factor of elevation but is more complex for SPEI and SRI.
Wu et al. (2017)	SPI; SSI	**Observed point measurements** Monthly precipitation and streamflow data (1960-2010) from the Meteorology Agency and Water Conservation Agency of Fujian Province, respectively. Daily inflow and outflow records for the Shanmei reservoir (January 2001-December 2010) from the Shanmei Reservoir Management Office, Quanzhou City.	Jinjiang River basin, Fujian Province	1960-2010			✓	*To examine the relationship between hydrological and meteorological droughts for both regulated and unregulated river basins. To assist in monitoring, prediction and management of hydrological droughts.* The regulation of reservoirs significantly modified hydrological drought duration and magnitude (and therefore the relationship between hydrological and meteorological droughts). Both the hydrological drought duration and

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
								magnitude were decreased due to operational management of the reservoir.
Wu and Lu (2016)	VWSI; RNDVI*; RLST*; MVWSI*; RPI	**Observed point measurements** meteorological data from the National Metrological Information Center for 185 stations **Remote Sensing** NDVI and LST data from the National Satellite Metrological Center	Sichuan Province and Chongqing municipality		✓	✓		*To propose the MVWSI (based on the RNDVI and RLST). The RPI was used to evaluate the effectiveness and monitoring capabilities of the MVWSI.* MVWSI effectively characterised the 2006 drought event as it developed and compared well to the RPI. The MVWSI can eliminate regional and seasonal features at a large scale, so it is applicable in monitoring the drought that happens in both the north and the south of China.
Yan et al. (2016)	SPI; VCI; TCI; VHI	**Remote Sensing** MODIS NDVI, VCI, TCI and VHI **Observed point measurements** rainfall data for 34 meteorological stations 1979-2009	Hai River Basin, north China	2000-2008	✓	✓		*To design and evaluate the performance of a drought monitoring system, DroughtWatch, developed for monitoring drought conditions in China.*

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								The VHI had a strong relationship with SPI-3 in rain-fed areas, the relationship was weaker in irrigated areas. The drought monitoring system could explain about 60% of the variance in the winter wheat yields. The system was found to be suitable for accurately monitoring drought at a national level.
Ye et al. (2016)	SPEI; SRI	**Observed point measurements** Daily precipitation and temperature data (1960-2010) from 14 standard national weather stations in the catchment from the National Centre of China Meteorological Administration (CMA). Daily river flows (1960-2010) for five gauging stations from the Hydrological Bureau of Jiangxi Province.	Poyang Lake catchment (flows into the Yangtze)	1960-2010	✓		✓	*To investigate the variability and correlation of hydrological and meteorological drought in a humid climate region.* Hydrological and meteorological droughts occur at different times, both seasonally and annually. The two indicators are more strongly correlated when longer accumulation periods are considered. SRI was less variable than SPEI

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								at shorter accumulation periods and had a delay of 1–2 months in response to SPEI with accumulation periods of more than 12 months. A 2-month accumulation of SPEI was found to be most appropriate for runoff monitoring, especially for those rivers with similar drainage area, climate and geographical conditions as in this study region
Zhang and Jia (2013)	MIDI*	**Observed point measurements** Monthly precipitation records for all available stations across northern China (1960-2010) **Remote sensing** MODIS NDVI and LST, TRMM, AMSR-E soil moisture and land surface temperature	Northern China	2003-2010	✓			*To propose the MIDI for monitoring short-term drought, especially the meteorological drought over semi-arid regions.* The remote sensing indicators were well correlated with SPI but the MIDI performed better for monitoring short-term drought. MIDI combines (TCI, PCI and SMCI) and

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
								outperformed the constituent parts for monitoring meteorological droughts over crop/grassland areas of northern China.
Zhang et al. (2015)	SZI*; SPEI; PDSI	**Observed point measurements** Daily meteorological data from 73 stations in the Loess Plateau (1971-2012) from the Data and Information Center of the China Meteorological Administration[6]. Monthly streamflow data from 11 gauging stations on the Yellow River from the Hydrology Bureau of the Yellow River Conservancy Commission of China[7] **VIC input** Soil parameters from the global 10 km soil profile dataset provided by the NOAA hydrology office. Vegetation parameters from	Loess Plateau, northern China (VIC soil data 10km, VIC vegetation data 1km, DEM 30m)	Loess Plateau	✓	✓		*To develop the SZI, a multiscalar drought indicator which combines the benefits of the PDSI and SPEI.* The SZI is more consistent with observed streamflow and NDVI than SPI or SPEI because it includes evapotranspiration, runoff, and any change in soil moisture storage. As such, it provides better information for drought monitoring and drought identification

[6] http://data.cma.gov.cn/site/index.html
[7] http://www.hwswj.gov.cn/swjcms/index.jsp

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought Met.	Agr.	Hyd.	*Aim* & Results
		the Land Data Assimilation System at 1 km resolution. **DEM** Advanced space borne thermal emission and reflection radiometer global digital elevation model[8] **Remote sensing** AVHRR NDVI						
Zhao et al. (2015)	SPEI; scPDSI	**Observed point measurements** Monthly average air temperature and precipitation data from 589 meteorological stations of China's National Meteorological Information Center	China	1961-2011 (monthly)	✓			*To compare the effects of applying a self-calibrating PDSI (scPDSI) and SPEI to monitor drought events with a focus on differences of event timescale* SPEI-3 was found to best monitor the evolution of the fall 2009-spring 2010 Southwest China drought and the spring 2000 Huang-Huai drought.
Zhao et al. (2016)	-	**Weather forecasts** TIGGE data (2006-2010) from China Meteorological Associating, ECMWF, UK Met Office and	Huaihe catchment, eastern China (DEM 30m)	2006-2010			✓	*To downscale TIGEE forecast ensemble to drive a distributed hydrological model which simulates soil water deficit. The*

[8] http://gdem.ersdac.jspacesystems.or.jp/

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
		US National Centres for Environmental Prediction **Observed point measurements** precipitation, evaporation, runoff, soil relative humidity, 10 cm soil moisture data etc. from China Meteorological Association **DEM** International Science Data Services Platform[9]						*relationship between observed and simulated soil moisture deficit depth are used to establish drought grades for drought monitoring in the Huaihe catchment.* Although the simulated soil water deficit depth and actual soil moisture were strongly correlated but the drought grades derived from each data source were not consistent and may be due to the different variables considered. But the combination of the TIGGE data and the hydrological model can help monitor droughts (as well as contributing to drought forecasting efforts).

[9] http://datamirror.csdb.cn/

Reference	Indicators	Data Sources	Spatial Scale (Resolution)	Temporal Coverage (Resolution)	Type of Drought			*Aim* & Results
					Met.	Agr.	Hyd.	
Zhou et al. (2017)	scPDSI; SPEI	**Observed point measurements** Monthly average temperature and precipitation observations from 756 stations from the China National Meteorological Information Center	China	1961-2011	✓		✓	*To compare the scPDSI and timescales of SPEI and their differences in characterising drought severity in different regions.* The scPDSI was insensitive to short-term drought and had the strongest correlations with SPEI of 9-19 months. This indicates that the scPDSI is suitable as a mid- and long timescale drought monitoring index, and can be used to monitor changes of river runoff, streamflow and groundwater levels. The SPEI (as it includes both precipitation and evapotranspiration and its flexible timescales) can conveniently monitor short- and long-term droughts. Consequently, this index has substantial application prospects in China.

3 Conclusions

It is clear that there is a wealth of publications on the subject of drought monitoring in China in the English academic literature. However, in order to fully assess the state-of-the-art in Chinese drought monitoring research and practice, a comparable review of the Chinese literature should be undertaken. Drought forecasting is a crucial part of drought planning, preparation and management. Here, we only consider monitoring, however this monitoring information are key products in order to inform and provide the context for forecasts. Future work will also assess the state-of-the-art in terms of drought forecasting in China. In addition, we plan to hold a workshop with Chinese partners and stakeholders to share knowledge on the state-of-the-art drought monitoring and forecasting practices in the UK and in China in November 2018. The outcomes of these activities will enable us, with our Chinese partners, to provide recommendations for future iterations of drought monitoring and forecasting products and tools in China.

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Appendix: List of acronyms used

Acronym	Description
AMSR-E	Advanced Microwave Scanning Radiometer-Earth Observing System
AVHRR	Advanced Very High Resolution Radiometer
CLSMAS	China Land Soil Moisture Assimilation System
CPAP	China monthly Precipitation Analysis Product
CWSI	Crop Water Stress Index
CZI	China-Z Index
DEM	Digital Elevation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
GRACE	Gravity Recovery and Climate Experiment
IDCI	Integrated Drought Condition Index
ISDI	Integrated Surface Drought Index (ISDI)
LST	Land Surface Temperature
M	Soil Moisture Index
MIDI	Microwave Integrated Drought Index
MODIS	MODerate-resolution Imaging Spectroradiometer
MVWSI	Modified Vegetation Water Supply Index
NDVI	Normalize Difference Vegetation Index
ODE	Overall Drought Extension
ODI	Overall Drought Indicator
OMDI	Optimized Meteorological Drought Index
OVDI	Optimized Vegetation Drought Index
Pa	Precipitation anomalies
PCI	Precipitation Condition Index
PDSI	Palmer Drought Severity Index
RLST	Relative Land Surface Temperature
RNDVI	Relative Normalized Difference Vegetation Index
RPI	Relative Precipitation Index
scPDSI	Self-calibrating Palmer Drought Severity Index
SDI	Synthesised Drought Index
SMAPI	Soil Moisture Anomaly Percentile Index
SMCI	Soil Moisture Condition Index
SPEI	Standardised Precipitation Evapotranspiration Index
SPI	Standardised Precipitation Index
SRI	Standardised Runoff Index
SWAP	Standardised weighted average of precipitation
SZI	Standardised Moisture Anomaly Index
TCI	Temperature Condition Index
TRMM	Tropical Rainfall Measuring Mission
TVDI	Temperature Vegetation Dryness Index
TWSA	Total Water Storage Anomalies
VCI	Vegetation Condition Index
VIC	Variable Infiltration Capacity (model)
VWSI	Vegetation Water Supply Index

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