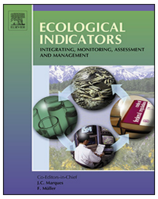
Ecological Indicators 94 (2018) 170–184

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



Original Articles

Investigating 'risk' of groundwater drought occurrences by using reliability analysis

Sina Sadeghfam[a,*], Ali Ehsanitabar[a], Rahman Khatibi[b], Rasoul Daneshfaraz[a]

[a] *Department of Civil Engineering, Faculty of Engineering, University of Maragheh, P.O. Box 55136-553, Maragheh, East Azerbaijan, Iran*
[b] *GTEV-ReX Limited, Swindon, UK*

ARTICLE INFO

Keywords:
Drought intensity
Frequency analysis
Groundwater drought
Reliability analysis
Environmental/Ecological Hazard Indicator

ABSTRACT

A novel methodology is introduced for the spatial indexing of groundwater drought 'risks' (GDRs). It combines reliability analysis and standardised water-level index (SWI), which is readily applicable to areas with sparse data on groundwater depth (GWD) measurements. In reliability analysis, GWDs are reformulated in terms of load, which accounts for external effects, e.g. withdrawals and recharge, as well as resistance, which accounts for system capacity with regard to drought intensities (mild, moderate, severe and extreme). Reliability analysis formulates a novel procedure by using loads and resistance to formulate a performance function, which can be treated by statistical techniques, and thereby derives values of GDR, defined as failure of an operational system but without considering consequences. GDRs at observation wells are spatially distributed by using an interpolation technique. The methodology allows for estimating time variability in GDR to derive an environmental/ecological hazard indicator (EHI), which can serve in the management and planning of predicting groundwater drought. A Graphical User Interface (GDR V.1.0) is developed to serve as a decision support system and to derive GDR and EHI values.

1. Introduction

A methodology is introduced to serve drought planning, particularly suiting the cases with sparse data. This is the case in the study area related to the Lake Urmia basin, where there is a serious need for water resource planning and drought planning and also where influencing by participatory practices offers a good potential. Participatory water resource planning is under continual development since the 1980s and it uses emerging modelling tools; see; Kallis et al. (2006), Pahl-Wostl et al. (2013), WBO (2007), TP2.5 (2010) and Coenen et al. (1998). Under modern management practices, water resource plans allocate resources for a time horizon of 40–60 years, e.g. see (NERA, 2016), but drought plans cater for management across time horizons that vary in 2–10 years or more; see Cook (2017). The present paper does not focus on any type of planning but on a methodology to create information for proactive identification of droughts.

Any mathematical formulation of groundwater drought is subject to uncertainties associated with natural variability (e.g. precipitation and evapotranspiration) and knowledge deficiency (e. g. groundwater overexploitation and lack of data). Droughts can occur when precipitation is either very low or very high (WMO, 1986), and droughts under high precipitations may occur when there is uneven distribution of temporal precipitation. Mishra and Singh (2010) provide the operational definition of droughts in terms of processes to identify onsets, severity and terminations of drought periods, and according to them, frequency analysis can be used to estimate the severity and duration of droughts for a specified return period of operational droughts. This study investigates the derivation of a probability-based index through reliability analysis to cope with uncertainties by using Monte Carlo Sampling (MCS) or Latin Hypercube Sampling (LHS). Using sparse data often includes missing data in time series, and the paper fills data gaps using artificial intelligence (AI), e.g. Sugeno fuzzy logic (SFL) (Tanaka and Sugeno, 1992).

The present study uses a drought index to identify probabilities of drought occurrence. Different drought indices are available in the literature; these indices are summarised in Table 1 and include those on groundwater droughts. Groundwater droughts refer to stored water that is depleted without being sufficiently recharged; they are of the hydrological drought type but at a slower rate. Mishra and Singh (2010) point out the stages in aquifer droughts as (i) groundwater recharge reduces with time and (ii) water table declines with time, with subsequent decreases in groundwater discharges. This type of drought is called groundwater droughts and their time scale is often for years (Van Lanen and Peters, 2000).

---

* Corresponding author.
E-mail address: s.sadeghfam@maragheh.ac.ir (S. Sadeghfam).

https://doi.org/10.1016/j.ecolind.2018.06.055
Received 6 April 2018; Received in revised form 22 June 2018; Accepted 25 June 2018

Table 1
Commonly used drought indices.

Groups		Drought index	Abbreviation	Input Parameters	Developer
Meteorological Indices		Rainfall Anomaly Index	RAI	Precipitation	Van Rooy (1965)
		Palmer Drought Severity Index	PDSI	Precipitation, temperature, available water content	Palmer (1965)
		Deciles	–	Precipitation	Gibbs (1967)
		Crop Moisture Index	CMI	Precipitation, temperature	Palmer, 1968
		Standardised Precipitation Index	SPI	Precipitation	McKee et al. (1993)
		Reclamation Drought Index	RDI	Precipitation, temperature, snowpack, reservoir, streamflow	Weghorst (1996)
Stream/reservoir	Hydrological indices	Surface Water Supply Index	SWSI	Precipitation, reservoir, streamflow, snowpack	Shafer and Dezman (1982)
		Standardised Streamflow Index	SSFI	Streamflow	Modarres (2007)
		Streamflow Drought Index	SDI	Streamflow	Nalbantis and Tsakiris (2009)
		Standardised Reservoir Supply Index	SRSI	Reservoir	Gusyev et al. (2015)
	Groundwater Indices	Standardised Water-level Index	SWI	Groundwater depth/level	Bhuiyan (2004)
		Groundwater Resources Index	GRI	Water balance model	Mendicino et al. (2008)
		Groundwater Recharge Drought Index	GRDI	Recharge	Goodarzi et al. (2016)
		Standardised Groundwater-level Index	SGI	Groundwater depth/level	Bloomfield and Marchant (2013)
Agricultural Ecological Indices		Soil Moisture Drought Index	SMDI	Modelled	Narasimhan and Srinivasan (2005)
		Evapotranspiration Deficit Index	ETDI	Modelled	Narasimhan and Srinivasan (2005)
		Normalized Difference Vegetation Index – Standardised Precipitation Index	NDVI-SPI	Satellite, precipitation	Dutta et al. (2013)
		Drought Effect of Habitat Loss on Invertebrates	DEHLI	Average of the component Drought Intolerance Scores	Chadd et al. (2017)
		Integrated Agricultural Drought Index	IADI	Drought rarity, evapotranspiration	Zhao et al. (2017)
Combined Indices		Global Integrated Drought Monitoring/ Prediction System	GIDMaPS	Multiple indicators used, modelled	Hao et al. (2014)
		Global Land Data Assimilation System	GLDAS	multiple indicators used, modelled, satellite	Rodell et al. (2004)
		Combined Drought Indicator	CDI	modelled, precipitation, satellite	Sepulcre-Canto et al. (2012)
		Aggregate Drought Index	ADI	Precipitation, evapotranspiration, gross primary production, potential evapotranspiration, satellite	Wang et al. (2018)

Similar to the other drought types, groundwater droughts are initiated by low precipitation and thereby groundwater recharging is reduced. Driven by lack of planning, overexploitation of aquifer resources accelerates groundwater droughts, and these together amplify their impacts (Acreman et al., 2000; van Lanen and Peters, 2000). There are several groundwater drought indices (GDIs) derived using satellite imagery, and these are shown in Table 1. The table indicates that research on aquifer droughts remains topical. Standardised water-level index (SWI) developed by Bhuiyan (2004) serves the basis to the present paper to assess groundwater deficit. He states that unlike meteorological droughts, hydrological droughts follow some patterns in a study area. He prepared maps of SWI by analysing time series for monsoon and pre-monsoon seasons and observed alternate shifts in droughts and drought patterns with time. Bhuiyan (2004) and Bhuiyan et al. (2006) state that the negative standardised precipitation index (SPI) anomalies do not always correspond to real droughts, as these take no account of impacts, but SWI presents better insight into droughts.

The challenges for the study area include the following: (i) the onset of a drought episode is not obvious; (ii) site-specific data are sparse; (iii) participatory management plans are yet to be adopted, (iv) over-abstraction of rivers and aquifers are widespread and (v) water demand is increasing. The present paper takes up challenges on the sparsity of data and targets drought planning for increased resilience.

The present paper uses groundwater depth (GWD) to formulate reliability analysis. In spite of some confusion on terminology between reliability analysis, reliability theory and reliability engineering, it has a long history and often goes back to the late 19th century, but research in these areas has become topical since the 1960s. The presentation in the present paper is based on that by Tung et al. (2005) to hydrosystems, but other applications include risk analysis for dam overtopping (Kuo et al., 2007), drought risk in water supply system (Cancelliere et al., 2009), reliability of soil slope (e.g. Low et al., 2011) and risk aggregation problems (Sadeghfam et al., 2018).

Reliability analysis is framed in such a way that it accounts for safe operations of a system and also its failure as a function of (i) load, which accounts for external actions, and (ii) resistance, which accounts for system capacity (Tung et al., 2005). Load and resistance are of the same dimension, and a function of their differences provides an approach to measure safety or failure of the system, as elaborated later. Another approach includes the use of reliability and resistance to evaluate and compare management policies (e.g. Loucks, 1997; Bocchini et al., 2013).

The present paper uses reliability analysis to develop a new GDI, to be referred to as groundwater drought risk (GDR) as an extension of SWI. Its data requirements are based on commonly available GWD time series data. Unlike existing indices, GDR is derived using the probability theory; hence, it is a probability-based index and capable of stochastic inferences. GDR can also provide an insight into hazards of environmental problems such as subsidence induced by groundwater droughts under a long-term decline in water table. A Graphical User Interface (GUI)-based module is developed in MATLAB to implement the introduced methodology to calculate the above two indices. They are derived for the Maragheh-Bonab plain aquifer, which suffers from groundwater drought with impending environmental impacts including land subsidence.