Journal of Hydrology 569 (2019) 265–277

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Enhancing the standardized drought vulnerability index by integrating spatiotemporal information from satellite and in situ data

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ARTICLE INFO

This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of Bellie Sivakumar, Associate Editor

Keywords:
Drought
Drought vulnerability
Drought impacts
SDVI
Water resources
South platte

ABSTRACT

Drought is a complex natural hazard with its adverse multifaceted impacts cascading in every physical and human system. The vulnerability magnitude of various areas to drought mostly depends on their exposure to water deficiency, the existing water management policy framework and its implementation. The Standardized Drought Vulnerability Index (SDVI) is an integrated attempt towards characterizing drought vulnerability based on a comparative classification system, incorporating precipitation patterns, the supply and demand trends, and the socioeconomic background as the most crucial contributors to drought vulnerability. This work attempts to evolve the SDVI by presenting a more rigorous method of index parameters estimation and argues that the combination of in-situ and satellite data improve the index results in an effort to further minimize the paucity of drought related information. At the same time, it helps to surpass previous limitations in temporal and spatial propagation of the vulnerability concept. The new framework is applied in the South Platte Basin, within Colorado, on the 2012 summer drought (July-September). The proposed index modification may convey drought information in a more holistic manner to decision makers. SDVI could aid in advancing the understanding of each component contribution through in situ and remote sensing data integration and in avoiding existing practices of broken linkages and fragmentation of the reported impacts. Thus, it is believed that the SDVI could serve as an additional tool to guide decisions and target mitigation and adaptation actions, allowing for a more integrated management approach.

1. Introduction

Drought is a recurrent natural phenomenon aggressive in many areas around the world defying their normal climatic conditions (Kiem et al., 2016). It has diachronically manifested its existence in almost every place and culture by affecting social and economic welfare usually to a significant extent. Damages due to drought can be costlier than any other natural hazard (Loucks, 2006). Early on, Rosenberg (1980) stresses that vulnerability to drought in one water user group, has a ripple effect to the society at large. Further recent evidence on this is the increased prices of agricultural products due to shortages attributed to the drought of 2011–2012 in the US (Grigg, 2014). The combining effects of increased water demands and climate change impacts will further stress our ability to cope with droughts in the future (Mishra et al., 2015; Guo et al., 2018; Wang et al., 2017). The drought nature, characteristics and impacts have continuously drawn the attention of the scientific community, the state and federal entities, as well as the general public, resulting in the production of a rich menu of drought literature that mostly provides crucial information on its parameters and management strategies (Cancelliere et al., 2005; Fontane and Frevert, 1995; Grigg, 2014; Grigg and Vlachos, 1993; Hagman et al., 1984; Karavitis, 1992, 1998; Karavitis et al., 2012a, 2015a, 2015b; Loukas and Vasiliades, 2004; Playán et al., 2013; Pulwarty and Maia, 2015; Rosenberg, 1978, 1980; Traore and Fontane, 2007; Vasiliades and Loukas, 2009; Vlachos, 1982; Wilhite, 2004; Zarch et al., 2015; Oikonomou et al., 2018; Wang et al., 2016a).

Drought is a dynamic creeping phenomenon without a definition that may be widely accepted. As such, its holistic description is very demanding. Consequently, when a drought occurs is seemingly difficult to confront it, being a non-event, in other words the absence of enough water (Bordi et al., 2006; Eriyagama et al., 2009; Karavitis, 1999; Karavitis et al., 2014; Yevjevich et al., 1983). Since drought

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https://doi.org/10.1016/j.jhydrol.2018.11.058
Received 17 June 2018; Received in revised form 6 September 2018; Accepted 20 November 2018
Available online 27 November 2018
0022-1694/

characterization is a difficult task, numerous indices have been developed and some are used quite frequently. The Standardized Precipitation Index (SPI) developed by McKee et al. (1993) and the Palmer drought severity index (PDSI) (Palmer, 1965) serve as two of the most widely used ones. Furthermore, some more recently established indices focus on examining drought within a different context, such as the Reconnaissance Drought Index (Tsakiris et al., 2006; Tsakiris and Vangelis, 2005), the Standardized Precipitation Evapotranspiration Index (Vicente-Serrano et al., 2010), and the Multivariate Drought Index (Rajsekhar et al., 2015); whereas, other more complex ones are referring directly or indirectly to vulnerability and water scarcity concepts (Jain et al., 2015; Karavitis et al., 2014; Sullivan, 2002; Vargas and Paneque, 2017).

The concept of vulnerability to drought is very challenging to be accurately presented due to a disciplinary and/or individually based series of interpretations (Gallopín, 2006). Thywissen (2006) and Manyena (2006) also provide extensive lists of various definitions of vulnerability. Nevertheless, the vulnerability concept mostly refers to the components affecting both a system's capacity to cope and its potential to be harmed, and it is strongly influenced by a plethora of factors (Cardona et al., 2012; Jain et al., 2015; Karavitis et al., 2014). Turner et al. (2003) defines vulnerability as the likelihood to experience harm due to exposure to hazard and encompasses exposure, sensitivity and resilience to the concept. According to IPCC, vulnerability is defined as "the propensity or the predisposition to be adversely affected", and is the result of "diverse historical, social, economic, political, cultural, institutional, natural resource, and environmental conditions and processes" (Lavell et al., 2012). Under this framework, vulnerability, the natural hazard, and the exposure to it, are related through the risk of an extreme event. The vulnerability term could also be expressed as a function of two variables, namely; hazard and impacts (Karavitis et al., 2014), which is adopted in the current effort. In this respect, without a disaster or a system in stress (hazard) there is no vulnerability. Furthermore, it is difficult to exactly estimate the magnitude and duration of the hazard in time and space, so as to exactly point out when a system's resilience threshold is exceeded or the ability of a system to cope with drought is collapsed (Karavitis et al., 2014; Vargas and Paneque, 2017). The vulnerability magnitude of various areas to that particular hazard depends on their exposure to water deficiency and to the existing water management policy framework/implementation (Karavitis, 2012).

Focusing on drought vulnerability, the most pivotal contributing factors, among others, are rainfall patterns, supply and demand trends both in the natural and anthropogenic scene, along with the socio-economic context. Societal drought vulnerability is affected by water demand. Therefore, socio-economic development in many parts of the world could be disrupted due to occurring supply deficits. Water demand deficits may increase due to supply failures, or sudden changes in land use patterns (i.e. increased irrigation requirements), or urgent population needs (DeFries and Eshleman, 2004). Also early on, it was pointed out that infrastructure status along with access to technology affect vulnerability levels (Rosenberg, 1980), for example efficient irrigation practices could counterbalance some of the effects of drought events. Under such conditions, some regions are more vulnerable than others and vulnerability is a fully dynamic phenomenon, complying with the changes that emerge in the various systems (Adger, 2006; Eakin and Luers, 2006; O'Brien et al., 2004; O'Brien and Leichenko, 2001).

Despite the abundance of environmental information, drought impacts and the factors contributing to systems vulnerability are scarcely reported (Bachmair et al., 2016; Blauhut et al., 2015, 2016), even in developed states. Grigg (2014) underlines the eluding nature of drought impacts since they could occur in different ways, times and places. Drought assessments are generally characterized by fragmentation and lack of synthesis, thus failing to give an integrated perspective of impacts (Dow, 2010; Grigg, 2014; Maia et al., 2015). At the same time, impact data gathered by the relevant authorities are usually not very detailed and have a coarse spatial scale since they are often aggregated. Duncan et al. (2015) argue that drought planning and management can be benefited by a high spatial resolution analysis, since climatic and morphological conditions (e.g. rainfall patterns, plains, mountainous chains) may not be spotted in a regional analysis. Likewise, factors affecting vulnerability to drought vary spatially, such as demand and supply patterns, infrastructure efficiency, etc. Therefore, drought vulnerability assessment in high spatial resolution could serve as an additional water resources management tool informing managers and planners on an area for priority actions.

The employment of indicators and indices is a common practice for describing complex phenomena and concepts. The Standardized Drought Vulnerability Index (SDVI) was conceived as an integrated approach for assessing drought vulnerability (Karavitis et al., 2014), with a multi-component drought vulnerability characterization based on a classification system. It was produced during the Drought Management Centre in Southeastern Europe (DMCSEE) Project (Karavitis et al., 2011, 2012b, 2014). The present effort is attempting to surpass some of the SDVI's earlier application limitations and assess the information improvement provided by the integration of satellite data in the calculation of SDVI. This is accomplished by introducing a more transparent, data rigorous methodology that replaces qualitative information with more quantitative data. The enhancement of the SDVI to accurately depict occurring conditions in space and time is essential for the index utilization as an efficient, timely and effective decision making tool in water resources planning and management under drought conditions. Better understanding of the vulnerability to drought and its different contributing components could convey drought information for mitigation and adaptation strategies to decision makers in a more holistic manner. Hence, avoiding at the same time, existing practices of broken linkages and fragmentation of reported impacts. The 2012 summer drought affected a large portion of the US including a large part of the state of Colorado and it was one of the driest periods ever recorded (Grigg, 2014; NOAA Drought Task Force, 2013; Wang et al., 2016c). Thus, it was selected as the study event for this effort. By expansion, such a methodology may be introduced in less data rich environments.

2. Materials and methods

2.1. Study site

The South Platte River Basin, located at the northeast corner of Colorado (Fig. 1a), has total area of 49,000 km^2 (Dennehy et al., 1993), while its total population is estimated approximately at 3,700,000 inhabitants (70% of state's population) (Colorado Department of Local Affairs, 2016). It is a semi-arid basin with average annual precipitation of about 400 mm. According to McKee et al. (2000) the basin's climate in the mountainous region is wet during December-April and dry in June and August-October, while the lower section is dry from November-February and wet from April-July. The dependence on snow accumulation during the winter months is significant since it serves as a natural storage for the basin to meet the demands during the summer period, along with several manmade storage structures. The South Platte is a highly developed basin with various competing and conflicting water demands (Oikonomou et al., 2018). The agricultural sector is the largest water user and among the traditional water uses in the basin there is also relative high water demand for unconventional energy development (Oikonomou et al., 2015a,b, 2016). The 2010 irrigated parcels spatial extent is shown in Fig. 1a with dark green color and their estimated total area was 3426 km^2 (846,634 acres) (Colorado Decision Support Systems, 2016).

Colorado has faced the impacts of droughts several times during the 20th century (McKee et al., 2000), and most recently the 2002 and 2012 drought events. During the 2012drought, Colorado experienced

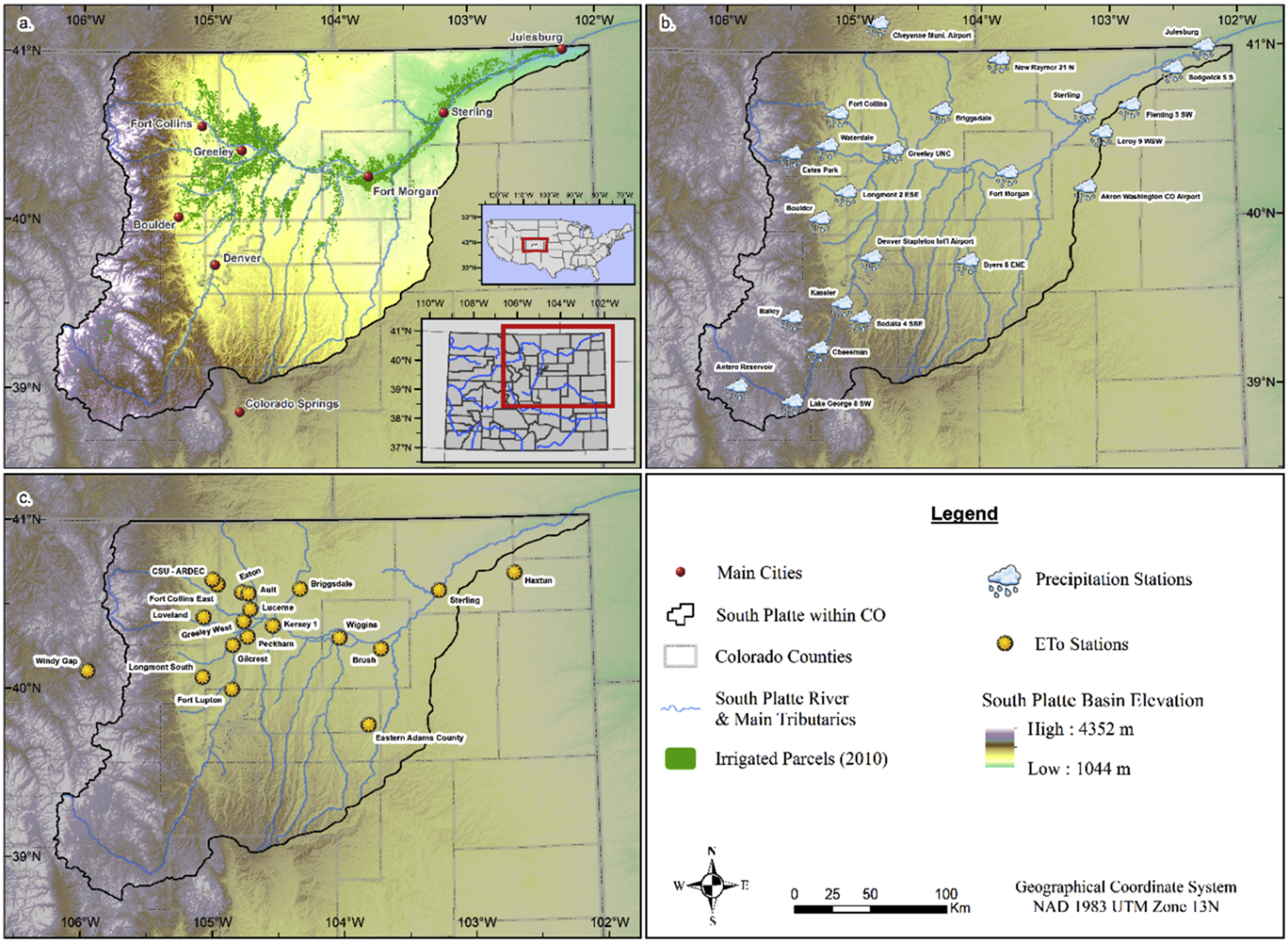

Fig. 1. (a) The South Platte Basin within the State of Colorado; (b) The precipitation stations and (c) reference evapotranspiration (ETo) stations used for the SDVI calculation.

severe impacts, resulting to damages of approximately $409 million in agricultural revenue (Pritchett et al., 2013). Thus, the July, August and September period of 2012 drought event was selected as a representative time frame for the application of vulnerability assessment in the South Platte basin, since it also includes the vegetation's growth season. In addition, the projected climate conditions in the basin suggest an increase in the severity of future droughts (Colorado Water Conservation Board et al., 2013), which makes well planned management strategies for coping with drought and mitigating its impacts even more imperative.

2.2. The standardized drought vulnerability index

The SDVI is a composite index that aims at providing an integrated estimation of drought vulnerability based on four drought manifestations, namely: meteorological, hydrological, social and economic (Karavitis et al., 2014). The SDVI is comprised of six components (Eq. (1)), the 6 and 12-month Standardized Precipitation Index (SPI), demand, supply, infrastructure, and impacts, which capture the aforementioned drought manifestations and may complement each other. More specifically, the 6-month SPI and 12-month SPI, describing the precipitation anomaly from normal conditions, represent the hazard/risk element. The 6-month SPI is capturing more accurately the seasonal variation, thus may display water availability during the crop growing season, especially for rain fed crops (Karavitis et al., 2014). On the other hand, the 12-month SPI captures long-term drought periods and thus it may reflect the urban/tourism, industrial, reservoir storage and hydropower water availability (Karavitis et al., 2014). As it is also depicted in other studies (Sullivan et al., 2003, 2009; Sullivan, 2011; Sullivan and Meigh, 2007), a region with high positive SPI values may still display high drought vulnerability conditions if it lacks the necessary water infrastructure and the corresponding water resources management framework. The remaining four components (demand, supply, infrastructure and socio-economic inflicted drought damages) represent the impact description in the vulnerability concept, as described in the previous section. Hence, the index's components describe both the effects of the precipitation deficits or surplus and the response conditions within the regions of interest. Those six index parameters are classified into four vulnerability categories labelled 0 to 3 according to their performance (Table 1), which is the product of extensive pertinent literature review and expert opinion categorization (Karavitis et al., 2014; Tsesmelis, 2017).

Table 1
SDVI components vulnerability scale (Karavitis et al., 2014).

Vulnerability Level	Classification of SDVI Components Deficit/Deficiency	
	SPI-6 & SPI-12	Supply, Demand, Impact & Infrastructure
Less Vulnerable (0)	≥ 1.50	0%
Vulnerable (1)	1.49 to 0	$\leq 15\%$
Highly Vulnerable (2)	< 0 to -1.49	> 15 to50%
Extremely Vulnerable (3)	≤ -1.50	$> 50\%$

Table 2
SDVI scaled values (Karavitis et al., 2014).

SDVI	Vulnerability Scale	Signal
0.00 – 0.49	No or Least Vulnerable	
0.50 – 0.99	Low Vulnerability	
1.00 – 1.49	Medium Vulnerability	
1.50 – 1.99	High Vulnerability	
2.00 – 2.49	Very High Vulnerability	
2.50 – 3.00	Extreme Vulnerability	

$$\boldsymbol{SDVI} = \boldsymbol{F}(\boldsymbol{SPI}_6,\ \boldsymbol{SPI}_{12},\ \boldsymbol{Demand},\ \boldsymbol{Supply},\ \boldsymbol{Infrastructure},\ \boldsymbol{Impacts}) \tag{1}$$

The vulnerability to drought is calculated using Eq. (2) (Karavitis et al., 2014), which infers that the six SDVI components (C_i) are of equal importance. That particular technique has been chosen since it is most often applied in the development of composite indicators despite the pitfall for some components to be over or under estimated (OECD and European Commission, 2008). Furthermore, assigning weights on the components of a complex phenomenon could be misleading with unfounded premises. In addition, an effort to assess the uncertainty caused by different weighting methods on the SDVI (Tsesmelis, 2017), concluded that the equal weighting method is having similar results when compared to the more complex weighing forms of the SDVI. Finally, the computed SDVI values are categorized into six classes of vulnerability as demarcated in Table 2.

$$\mathrm{SDVI} = \frac{1}{\mathrm{N}}\sum_{\mathrm{i}=1}^{N} C_i\,,\quad where\ N = 6 \tag{2}$$

2.3. Index adjustment and data

The SDVI application in the South Platte basin is the first outside the geographical area of Southeast Europe (SEE), where it was developed and first tested. The fact that SEE has a variety of climatic conditions and levels of socio-economic development, makes it suitable for developing a non-geographically bounded index. At the same time, the various countries (11 in total) of the SEE region follow different data standards and thus detailed space and time information is lacking, which creates significant data challenges. Information for the index components at a basin or sub-basin scale (except from precipitation data), may not reveal local variations of drought vulnerability levels. Furthermore, a key limitation of previous applications is the static representation of the impacts component. Its estimation is based on the monetary yield loss (annual representation), which distorts the monthly calculation of the index. Lastly, the ecosystem as well as the secondary socio-economic impacts in SEE were not considered due to lack of dependable data.

The increasing amount of available in-situ datasets, especially in North America, along with the employment of good quality remote sensing information gives the opportunity to reconsider the way the index was applied (Karavitis et al., 2015a). In this context, the revision of the SDVI for the South Platte Basin application is an effort to overcome the most of the aforementioned limitations and establish a framework of index calculation transparency (Karavitis et al., 2015a; Oikonomou, 2017; Oikonomou and Waskom, 2018). Fig. 2 outlines data integration procedure for the index space-time calculation. The datasets used for each SDVI component are shown in Table 3 and described in detail below. Information from the datasets used was not available for a long enough common period. Although that might introduce some bias, it was chosen to utilize the longest available period

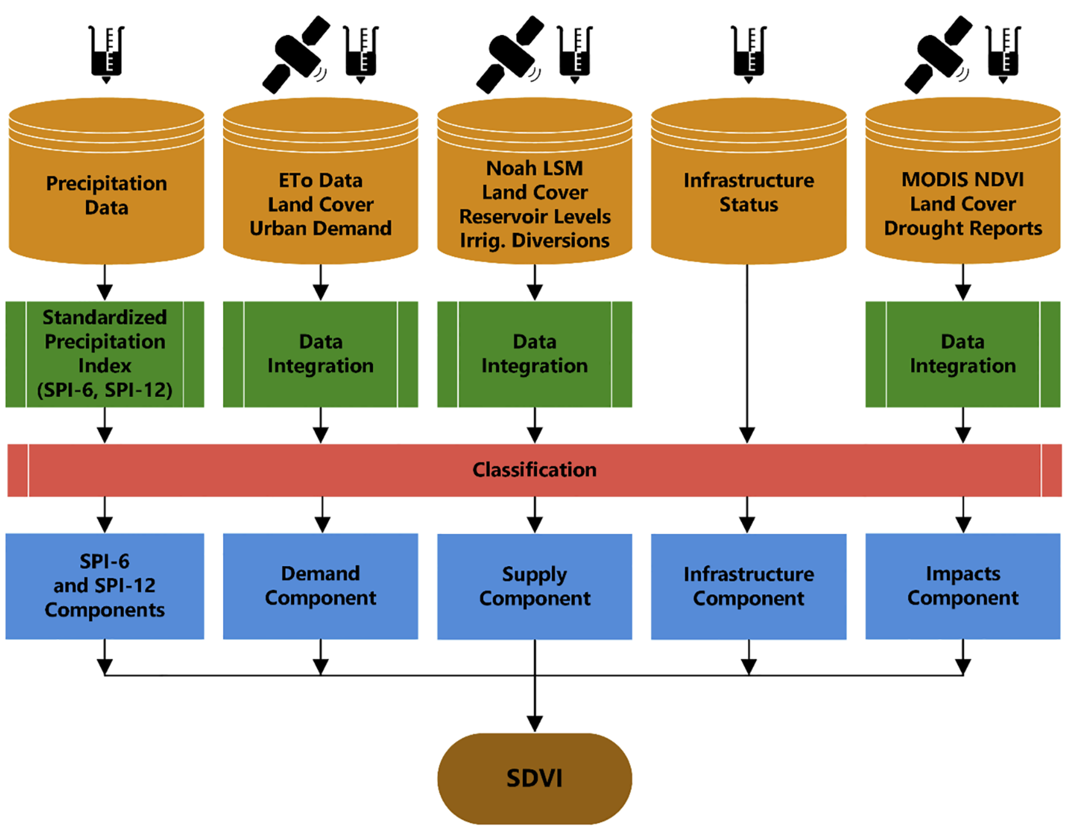

Fig. 2. Process and datasets (satellite and in situ) used for calculating each SDVI component.

Table 3
Details of the temporal and spatial resolutions of datasets used.

Data set	Time Period	Long-Term Average Period	Temporal Resolution	Spatial Resolution
Precipitation	1963–2012	–	Month	–
Reference Evapotranspiration	2000–2016	2000–2016 (excluding 2012)	Month	–
Ditch diversion records	1988–2012	1988–2011	Month	–
Noah Land-Surface Model (LSM)	1980–2009, 2012	1980–2009	Month	0.125 DD
National Land Cover Database	2011		–	30 m
MODIS NDVI	2000–2015	2000–2015 (excluding 2012)	8-day (averaged to monthly)	250 m
Reservoir Storage	1981–2010, 2012	1981–2010	Month (1st of each month)	–
Drought Impact Reporter	2012		–	–

with good quality data for each data set. Thus, the effect of the different periods would have less impact on the results. The index is a composite one based on individual parameters estimation. Different spatial resolutions were chosen for the different parameters, in order to have the most detailed representation based on the available information. It is believed that more detailed and longer data sets periods will improve the representation of the components and will lead in having less error for the added values in the SDVI calculation. The inclusion of higher resolution spatiotemporal datasets in the calculation of the index offers new capabilities of examining local vulnerability variations and allows comparison of adjacent areas. The proposed holistic impact representation framework could help depict impacts extent and magnitude in a non-fragmented way and thus increase the insight gained.

2.3.1. Standardized precipitation index

The values of SPI-6 and SPI-12 are computed on point scale (for every available meteorological station with the required data). In this context, monthly precipitation records from 24 meteorological stations (Fig. 1b and Table 4) with at least a 50-year record (1963–2012), were retrieved from the NOAA's Regional Climate Centers (RCCs) Applied Climate Information System (ACIS) (http://scacis.rcc-acis.org/). If the rainfall time series had missing data, the values were filled by multiple regression analysis using the Hydrognomon software (version 4.01) (ITIA NTUA, 2010).

Table 4
Details of precipitation stations used in the study.

Station Name	UTM X	UTM Y	Elevation (m, a.s.l.)	Average Annual Precipitation (mm) (1963–2012)
Akron Washington CO Arpt.	651857.9	4,447,781	1421.28	400.3
Antero Reservoir	422760.9	4,316,411	2718.82	258.6
Bailey	458966.4	4,361,797	2356.10	429.2
Boulder	477231.9	4,426,892	1671.52	500.3
Briggsdale	556945.4	4,498,458	1473.40	335.7
Byers 5 ENE	574758.4	4,399,287	1554.48	394.5
Cheesman	475976.4	4,341,250	2097.02	422.9
Cheyenne Muni. Arpt.	515380.8	4,555,425	1868.42	373.0
Denver Stapleton Int. Arpt.	511182.9	4,401,498	1611.17	388.9
Estes Park	458758.4	4,469,679	2279.90	376.4
Fleming 3 SW	680987.7	4,501,919	1297.23	441.3
Fort Collins	488893.4	4,495,995	1525.22	385.2
Fort Morgan	600725.2	4,457,288	1328.62	330.4
Greeley UNC	525533.4	4,472,443	1437.13	354.6
Julesburg	729613.9	4,540,858	1057.35	440.4
Kassler	491813.6	4,371,159	1702.92	456.6
Lake George 8 SW	459200.3	4,306,617	2606.04	310.6
Leroy 9 WSW	662532.3	4,483,878	1386.84	436.5
Longmont 2 ESE	494321.8	4,444,408	1508.76	355.6
New Raymer 21 N	595318.5	4,531,814	1578.86	367.4
Sedalia 4 SSE	504115.5	4,361,567	1821.18	443.5
Sedgwick 5 S	709311.4	4,526,085	1216.15	455.4
Sterling	651524.3	4,498,995	1211.28	400.3
Waterdale	482160.7	4,475,018	1594.10	418.4

The monthly precipitation data were used for the calculation of the SPI utilizing the algorithm of the "SPEI" R package (Beguería, 2013). Several geostatistical approaches (Ordinary Kriging, Simple Kriging, Universal Kriging, Cokriging) and model types (Circular, Spherical, Tetraspherical, Pentaspherical, Exponential, Gaussian, Rational Quadratic, Hole Effect, K-Bessel, J-Bessel and Stable) have been tested in an ArcGIS environment for the spatial visualization of the calculated SPI values. The combined application of Simple Kriging and Rational Quadratic provided the smallest Root-Mean-Square and Average Standard Errors. Hence this combination has been chosen for the 6-month and 12-month SPI visualization. All in all, the Kriging method provides a way for minimum error distribution, while correcting potential errors within the raw data (Karavitis et al., 2012a). The method works in accordance with the premise that two values that are nearby will have the same information. This is a feature presenting a significant advantage, while describing random phenomena such as precipitation patterns. The interpolated SPI-6 and SPI-12 products (250 m resolution) were transformed according to Table 1 for the calculation of the SDVI.

2.3.2. Demand

The 2011 National Land Cover Database (Homer et al., 2015), the most updated national land cover database for the US, was used to identify the exact areal extent of the urban areas, vegetated lands, and areas with zero vulnerability to drought, such as bare land, permanent snow, open water etc. During drought events, urban areas are potentially the most vulnerable locations with devastating impacts if water demand is not met. In the current effort, instead of showing by default the urban centers as highly vulnerable, it was selected to depict the estimated experienced vulnerability level. The main reason was that the monthly domestic water demand for the summer, although a bit higher than the rest of the seasons, is well accounted by the water authorities. Water plans and water development activities are based on scenario planning that include high growth rates and extreme drought conditions (Kenney et al., 2004). Throughout the years, water authorities serving urban centers in the Colorado's Front Range have bought senior water rights (according to the prior appropriation doctrine) from agriculturists in order to meet the increasing water demands (Kimball, 2005; Taylor and Young, 1995). In addition, the urban areas are considered of high importance, which have to be always supplied by water, in many cases at all costs (Chen et al., 2017). Thus, the urban areas are set to the lowest vulnerability classification.

Reference evapotranspiration (ETo) was utilized as an indicative measurement for the estimation of the basin's vegetation water demand. Due to the high importance of agriculture in the South Platte basin there is a relative large number of ETo monitoring stations, but there are only 18 stations with long continuous record (2000–2016). The Windy Gap station (~2418 m) located outside the basin on the west slope of the continental divide, it was preferred to approximate ETo conditions for the South Platte Basin's mountainous region due to its location. The 19 stations (Fig. 1c and Table 5), are part of the CoAgMet (www.coagmet.colostate.edu) and the Northern Colorado Water Conservancy District (NCWCD) (www.northernwater.org) networks. The average monthly ETo for the whole period was compared

Table 5
Details of reference ET stations used in the study.

Station Name	Network	UTM X	UTM Y	Elevation (m, a.s.l.)	Average ETo (mm) (2000–2016)*		
					Jul	Aug	Sep
Haxtun	CoAgMet	698876.6	4505032.6	1231.39	244.4	204.2	157.2
Sterling	NCWCD	649217.0	4493283.5	1210.06	243.6	205.2	155.8
Brush	NCWCD	610990.7	4454763.8	1303.93	242.4	203.8	156.7
Eastern Adams County	CoAgMet	602923.8	4404663.7	1495.65	242.9	207.5	170.2
Wiggins	NCWCD	583709.2	4461883.4	1362.76	244.1	205.1	157.7
Briggsdale	CoAgMet	557622.7	4493989.5	1480.72	269.4	230.7	185.5
Kersey 1	CoAgMet	539728.0	4469684.9	1409.70	226.8	188.0	157.5
Lucerne	CoAgMet	524836.0	4480587.7	1447.80	223.2	189.5	151.2
Ault	CoAgMet	523701.2	4490951.5	1496.57	222.1	194.3	154.5
Peckham	CoAgMet	523196.6	4462478.4	1432.86	242.1	196.4	157.2
Greeley West	NCWCD	520601.2	4472638.6	1483.77	219.9	184.6	140.5
Eaton	NCWCD	519433.6	4491764.8	1510.28	215.1	182.1	148.3
Gilcrest	NCWCD	513447.2	4456955.7	1455.42	215.2	182.0	138.6
Fort Lupton	CoAgMet	512889.1	4427890.3	1540.76	256.5	220.7	177.1
Fort Collins East	NCWCD	503463.1	4496888.2	1571.55	222.0	190.2	147.7
CSU - ARDEC	CoAgMet	500000.0	4500182.5	1557.53	338.6	289.3	228.9
Loveland	NCWCD	494149.2	4475394.2	1521.56	197.3	168.5	127.6
Longmont South	NCWCD	493444.9	4436021.4	1519.12	227.3	196.7	150.8
Windy Gap	NCWCD	417671.2	4440149.4	2416.76	188.3	158.4	124.2

* The 2012 values were not included.

with July, August and September (JAS) of 2012 and scaled based on Table 1. For such a comparison the 2012 monthly values were excluded from the calculation of the long-term average. ETo point information was transformed to spatial information based on the Thiessen polygons methodology. A simple technique was chosen rather a geostatistical approach, due to the complexity of the phenomenon and the small number of ETo stations, especially at the lower part of the South Platte Basin.

Based on the above methodology, the integrated monthly areal representation of the SDVI demand component was produced by combining the layers of the calculated urban and vegetation water demands, while superimposing areas with zero vulnerability in a GIS environment.

2.3.3. Supply

A plethora of information was utilized for the spatiotemporal representation of the supply component. Firstly, Colorado's Division of Water Resources database provided monthly ditch diversion (irrigation) records (http://water.state.co.us/DataMaps/Pages/default.aspx). The amount of water diverted on each ditch is recorded at the head gate for the needs of the water administration in the South Platte basin. Time series of 310 ditches, which include all the major irrigation ditches in the basin, were extracted with selection criterion of at least 25 years of data, including information for 2012. The long-term monthly average was calculated and compared with the amount diverted in 2012, in order to determine the supply anomaly. The cultivated crops within the ditch service polygons were assumed to have a uniform spatial allocation of water supply anomaly. Under this assumption, the point supply anomaly information was converted to spatial.

Soil moisture at the root zone was chosen as a supply indicator for vegetation outside the ditch service areas. The NLDAS-2 (North American Land Data Assimilation System) Noah Land-Surface Model (LSM) (Chen et al., 1996; Koren et al., 1999) Level-4 Monthly dataset was used, due to lack of measured data. It has 0.125 decimal degree resolution and root depth is defined as 100 cm in the forested areas, and 60 cm in the non-forested ones (Rui and Mocko, 2014). The monthly root zone soil moisture anomaly for 2012 was estimated based on the 30-year (1980–2009) monthly average and classified according to Table 1.

The 2011 National Land Cover Database was used to detect the spatial extent of different land uses. The supply component for bare lands, permanent snow areas and water features (e.g. lakes, reservoirs) is classified as low vulnerability to drought. These areas are having very limited anthropogenic activities. In this regard, it was chosen to be set as less vulnerable since impacts are also very few if no water supply is appropriated. For urbanized areas, the domestic water supply anomaly was estimated from monthly reservoir storage data by the Water and Climate Center of the USDA Natural Resources Conservation Service National (http://www.wcc.nrcs.usda.gov/). The monthly percent average reservoir storage serving these urban centers is a practical indication of water supply capacity, especially in a semi-arid setting which reservoir storage is central for meeting water demands. In cases with no information, meeting urban water demand was considered to have low vulnerability since US urban residents rarely if ever experience shortages at the tap (Kenney et al., 2004). Additionally, reservoir storage could be used to depict impacts on hydroelectric capacity (not applied in this area) and recreation.

2.3.4. Infrastructure

Following the same notion as for the supply, the SDVI infrastructure component portrays the actual adequacy status of the water supply system. The development of adequate water supply infrastructure for agriculture became early on a necessity due to South Platte Basin's semi-arid climate (Stenzel and Cech, 2013). Agricultural production in northern Colorado is a very important revenue sector, and Weld County is one of highest agricultural producing counties in the US. This is possible mainly due to irrigated agriculture which is highly dependent on well operated reservoirs and canal networks to allocate water based on the prior appropriation doctrine. For the above reasons, the very good status of the existing infrastructure to deliver water in the South Platte basin, both for domestic and agricultural purposes, creates low vulnerability for the region under drought. Thus, it is classified as less vulnerable.

2.3.5. Impacts

The estimation of drought impacts is an inherently difficult task to perform, due to the spatial and temporal variability. In previous SDVI applications, drought impacts were associated with the societal cost. This was done by assigning a theoretical high cost of not supplying water to urban centers and thus axiomatically depicting urban cities as most vulnerable, and by calculating the monetary crop yield loss cost from relevant reports. Although, the practice of measuring crop yield loss is a tangible way to portray the drought impacts, its main disadvantage is that it cannot give any information of the temporal

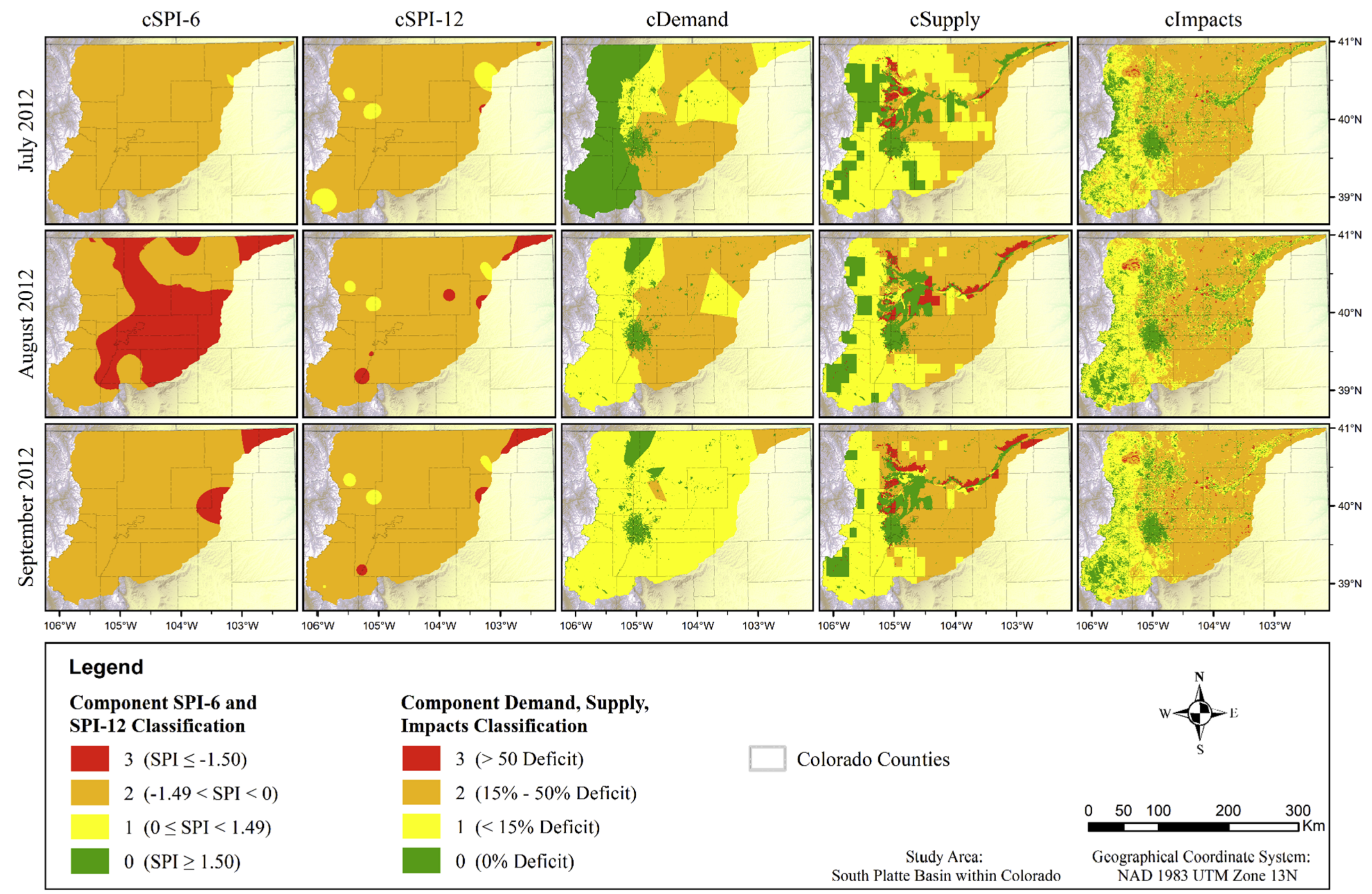

Fig. 3. Classification of SDVI components for July, August and September 2012.

propagation of impacts. At the same time, the majority of reports regarding drought impacts focus on agriculture losses and leave great information gaps on the other categories, such as environmental and socio-economic (Gregorič, 2012; Grigg, 2014). This fragmentation of usually circumstantial impact reports does not contribute towards their classification into the categories of interest (e.g., social or economic). The area of study did not escape such traits, limiting our understanding regarding drought impacts.

Remote sensing information was employed to capture both agricultural and environmental impacts. The Normalized Difference Vegetation Index (NDVI) (Rouse, 1974) is a dimensionless transformation of spectral reflectance and has been successfully used in several drought related studies (Hurcom and Harrison, 1998; Brown et al., 2008; Karnieli et al., 2010; Xu et al., 2011; Tadesse et al., 2014; Vicente-Serrano et al., 2015; van Hoek et al., 2016). It allows the quantification, visualization and evaluation of healthy and abundance vegetation. Healthy vegetation compared to stressed or diseased vegetation have different spectrum signatures (Curran, 1980; Govender et al., 2007; Knipling, 1970; Wang et al., 2016b). Combined Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data, smoothed and gap-filled, for the Conterminous US (CONUS) for the period 2000–2015 with a temporal resolution of 8-days (time lag of Terra and Aqua satellites) and spatial of 250 m (Spruce et al., 2016), were employed to portray the vegetation impact. Monthly average NDVI raster layers for July, August, and September, within 2000–2015, were calculated based on the available measurements within each month and historical long-term monthly averages for the whole period were computed. The vegetation impact layer is portraying the NDVI anomaly for July, August and September of 2012 in comparison to the long-term (2000–2015) monthly average values.

On the other hand, the delineation of impacts in urbanized areas was only possible through available reports, retrieved from the Drought Impact Reporter of the National Drought Mitigation Center (droughtreporter.unl.edu). As mentioned in the supply section, reservoir storage could be used to represent impacts on hydroelectric capacity generation in areas that would apply (e.g. Colorado River Basin), and for recreation purposes. Under this notion, the area occupied by the reservoirs is classified based on Table 1, using the anomaly of monthly average storage at the 1st of each month, with 1981–2010 as a reference period. The vegetation, urban and reservoirs' supplement impacts information are combined to generate the integrated monthly SDVI impact layer. The integration of these different drought impacts overcome limitations pressed by information fragmentation and offers a methodology of synthesis while visualizing the spatiotemporal propagation of effects.

3. Results and discussion

3.1. Computation of SDVI components

This section starts by providing a summary and discussion of the individual calculated SDVI components. Such presentation and discussion of the individual SDVI components becomes imperative in order to assess the overall performance of the composite index. The calculated SPI-6 and SPI-12 transformed into their respective scaled values, are representing the hazard component in the function. The classified 6-month and 12-month SPI (cSPI-6 and cSPI-12) portray predominantly the meteorological areal magnitude of the particular drought event. The study area experiences vulnerability to drought due to short-term precipitation deficit (between 0 and -1.46) for its greatest part, with August being the worst, where 49.36% of the basin is characterized as extremely vulnerable (Fig. 3, column 1). The basin shows signs of recovery on September, apart from the north-east corner and central-east areas. The shift could be explained since precipitation was significantly below normal levels. Drought conditions for the 12-month SPI were below normal (SPI < 0) in all precipitation stations and that is why approximately 95% of the basin is depicted as highly vulnerable (Fig. 3, column 2). During August and September, the area northeast of Sterling, was classified in the extremely vulnerable level for cSPI-12. For both Julesburg and Sedgwick stations, SPI-12 values were less than -2, decreasing more in September. Overall, the northeast tip of the South Platte basin is depicted as the most vulnerable area for the 2012 drought event.

The most defining aspect of the 2012 drought in the area was abnormally high temperatures and evapotranspiration rates (Ryan and Doesken, 2015). The demand component for the South Platte presented in the third column of Fig. 3, shows that during the months of July and August, the plain part of the basin is at the most vulnerable state since 41.88% and 51.66% of it was classified as highly vulnerable respectively. The phenomenon dissipated during September and only 4.08% of the basin was depicted with vegetation water requirements more than 15% of the historical average. On July, the demand at the mountainous part of the basin (west side) is classified as less vulnerable, while during the following two months the whole area exhibits anomaly less than 15% and thus classified as vulnerable. The "CSU-ARDEC" ETo station had throughout the study period measured conditions of less ETo than the historical average, and that is why the northeast part of Larimer County and northwest part of Weld County are depicted with green color. The other less vulnerable areas (green color) are either urban centers, like the Denver metropolitan area at the lower left side of the basin, or reservoirs and land uses such as bare land.

The SDVI Supply component was calculated based on information regarding monthly water diversions in irrigation canals, the storage level of the reservoirs used for domestic demand as an indication of capacity to meet the urban water demand and lastly the root zone soil moisture content from the operational Noah LSM model. Urban centers were classified as less vulnerable since storage percent anomaly for the reservoirs with domestic purpose across the basin did not exceed 50% of storage historic average for the whole period. The reservoirs serving the cities of Denver and Aurora (like the Antero reservoir and Elevenmile Canyon reservoir) had above the average storage and the Spinney Mountain reservoir almost the average storage. At the same time reservoirs with mainly agricultural water use delivery were experiencing more than 50% lower storage than their monthly historic averages. This could be associated with canal service areas that their delivery was classified in the extremely vulnerable level. Examples of this are the Riverside Reservoir and the North Sterling Reservoir and the water diversions at their respective canals service areas. The deficits regarding the water diversions to the irrigation canals was intensified during September 2012. Furthermore, about half of the basin's area was classified as highly vulnerable in August and September since the Noah LSM estimated the anomaly of the soil moisture content at the root zone for lands outside the ditch service areas to be less than 50% of the historic average. The mountainous area of the South Platte basin according to the data from the Noah LSM indicated that there were vulnerable to drought and only pockets with average conditions were estimated by the model. Snowmelt is directly associated with runoff and thus it is included in the various supply deviations (e.g. reservoir, ditch diversions, soil moisture) in the index estimation.

The last SDVI component is the occurred impacts on a monthly time step. As described in the methodology, satellite derived datasets, reservoirs' storage information and reports from the Drought Impact Reporter database regarding urban impacts were utilized in order to represent a composite spatial layer of multifaceted impacts. Overall, cities on the Front Range did not have any significant impact thus were represented as less vulnerable. From the maps illustrated in Fig. 3, may be derived that the vegetation outside ditch service areas is more vulnerable to drought and falls within the highly vulnerable component class. In the mountainous part of the South Platte basin the vegetation is experiencing some stress in relation to the monthly long-term average, but there are also a few areas classified as less vulnerable. The anomaly recorded is less than 15% of average greenness. At the same time, it has to be noted that the spatial representation of NDVI should be interpreted as the deviation of the monthly long–term average state. It is not necessarily associated to drought impacts, as other reasons (e.g. land use changes) might be responsible for such a low NDVI signal. A characteristic example is the vegetated area at the northwestern part of Larimer County that is classified as highly and extremely vulnerable to drought. However, these severe impacts are not credited to drought conditions, but to the Hewlett Gulch Wildfire that burned 31 km^2 on May of 2012 and the High Park fire, that occurred in June of the same year, and burned 350 km^2 (Writer et al., 2014). This observation stresses the fact that additional information for each area of application needs to be taken into account when interpreting the impact's spatial layer in order to identify eluding causes for depicted irregularities. The infrastructure component, since the South Platte basin is highly developed and with a well-maintained water infrastructure network, it is classified in the less vulnerable condition for the whole period of study.

Despite the evolution of the index calculation some limitations still exist. Water supply from groundwater was not possible to be incorporated since data were not available. Uncertainty in the input values for the index calculation is also one of the uncertainty sources affecting the results. The components with the least certainty are the demand and supply. Evapotranspiration measurements tend to be spatially sparse with limited coverage and with usually short time records. Relying more on satellite driven data, could lead to an operational version of the index with the ability to inform about drought vulnerability conditions in near-real time. In addition, the incorporation of reservoirs' demand and supply components would result to more precise assignment of overall drought vulnerability levels regarding ecological and societal aspects. Detailed status about the condition of the infrastructure for every water structure is a main factor contributing to system's vulnerability to drought. Its incorporation into the index calculation is an important piece of information which currently missing.

3.2. SDVI results

The overall SDVI results calculated for each month are presented and summarized based on the aforementioned framework. The comparison of the index produced results with the existing condition show a very good relation, as it was presented in the previous section. Further spots of extreme vulnerability along the South Platte River are reservoirs, whose storage was significantly lower than their historic monthly average. Representative are the cases of the Empire, Riverside and Jackson Lake reservoirs that were completely dried out by 1st of August 2012 and North Sterling reservoir by 1st of September. Consequently, they were affecting not only the irrigation ditches they were serving, but also producing recreation and environmental/habitational impacts. Drought Impact Reporter database reports of media entries on drought impacts. Recreational industry was affected by the 2012 drought. Boating was disturbed on July at the Prewitt reservoir (Waite, 2012) and on August at Horsetooth reservoir (Associated Press, 2012). Both reservoirs are portrayed by the index component among the vulnerable spots on the impacts maps in Fig. 3.

A significant part of the irrigated agriculture is under stress with the anomaly on the vegetation greenness in these areas to be classified as vulnerable ($< 15\%$) depicting the deficiency of meeting crop water requirements. This is supported by the Drought Impact Reporter database, since farmers were asking permission from senior water rights to be allowed to pump groundwater from the alluvial aquifer. At the same time the irrigated crops that are within normal conditions can be attributed to their priority in available water supply, since the land is

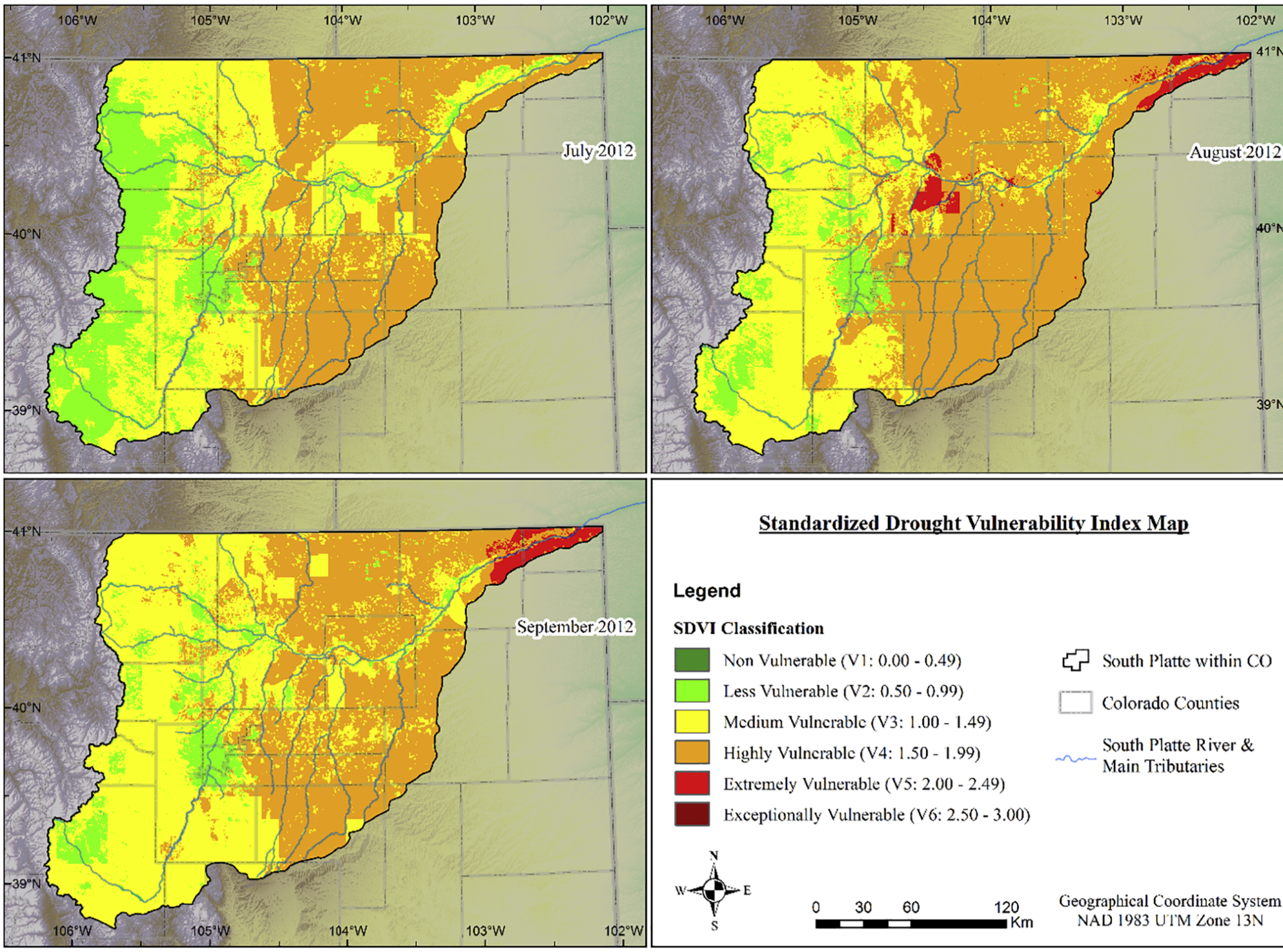

Fig. 4. SDVI results for the South Platte basin.

associated with senior water rights. In Morgan County, the irrigated crops are depicted as experiencing some vegetation health issues. Also the NDVI anomaly is decreasing steadily from July throughout August, without this indicating necessarily causal relationship, for the reasons mentioned above.

On the other hand, the rest of the vegetation at the plains is depicted as steadily highly vulnerable, as expected since most of this area is classified as non-irrigated grass/pasture and the key characteristic of the 2012 drought event was high temperatures and increased evapotranspiration rates. This high stress observed on grass/pasture lands is in concordance with reports from the media retrieved from the Drought Impact Reporter database. There are several entries mentioning in the area there was not enough grass to feed cattle and thus forced of selling livestock, or in other cases forced to feed alfalfa and hay, which indirectly are displayed in the impacts component maps as grass and pasture lands were severely impacted. All in all, the reports retrieved from the Drought Impact Reporter database are supporting the results of the selected methodology to portray the impacts in a holistic way. However, during interpretation of the results additional sources of information (land uses, wildfires, etc.) should be taken into account for validation reasons.

Fig. 4 portrays the monthly vulnerability magnitude and extent produced by the SDVI in the South Platte basin, but also informs about the spatiotemporal propagation of the drought which was depicted by the Index. The SDVI results may also be directly connected to the SPI results (as the SPI values were used in the SDVI estimation representing the hazard component), since the most vulnerable area, northeast of Sterling, displayed a significant precipitation stress, in both SPI components, compared to the least vulnerable ones. Overall, the total extent of the extremely vulnerable class does not surpass 3% of the total area.

The urban areas are characterized as the least vulnerable part of the basin along with parts of the basin in the higher elevations. For the urban areas this low level of vulnerability during the study period is attributed to the high percent average of reservoirs' storage supplying these areas and by the very few reports retrieved from the Drought Impact Reporter database which refer to drought water shortages. It is worth mentioning that the urban areas were expected to be classified as the least vulnerable compared to the other parts of the basin, since the water planning priority given to these areas for mitigating possible effects of drought is the highest due to potentially catastrophic consequences. The mountainous areas display less vulnerability to drought which is accredited predominantly to the lower water demand. The aforementioned impacts of the two wildfires in the impact component estimation, were somewhat masked in the SDVI calculation, resulting in being classified as one scale more vulnerable compared to the adjacent areas. The higher vulnerability of post-fire areas is in accordance with recent findings that during drought years following the wildfires the vulnerability is higher in terms of forest recovery and favored species (Harvey et al., 2016). Thus, in such areas, it is suggested to give higher importance to the impacts component. Non-irrigated grass/pasture lands, which constitute the vegetation with the greatest extent in the basin, were classified among the most vulnerable parts of the basin for the 2012 drought. This SDVI finding is in accordance and backed up by

Table 6
Area and percent area of SDVI vulnerability levels in the South Platte basin.

Component Class	Jul-12		Aug-12		Sep-12	
	(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Non Vulnerable (1)	–	0.00%	0.4	0.00%	–	0.00%
Less Vulnerable (2)	8516.7	17.40%	3095.5	6.33%	3086.4	6.31%
Medium Vulnerable (3)	20173.3	41.22%	18468.4	37.74%	23462.5	47.95%
Highly Vulnerable (4)	20245.5	41.37%	25908.3	52.94%	21438.2	43.81%
Extremely Vulnerable (5)	–	0.00%	1,463.0	2.99%	948.6	1.94%
Exceptionally Vulnerable (6)	–	0.00%	–	0.00%	–	0.00%

the numerous pertinent reports available in the Drought Impact Reporter database.

The basin is depicted as more vulnerable to drought during August of 2012, which drought slightly dissipates on the next month. From the components presented and discussed, this slight intensification of about 5000 km^2 shifting to the medium vulnerability class (Table 6) is a result of the combined result of the demand, supply, SPI-6 and impacts components. However, the straight-line borders of vulnerability classes, which is not corresponding to natural gradual variation conditions, a fact visible in almost all the three months, is attributed to the coarser datasets used for the calculation of the demand and supply components of the index. This denotes the need for incorporating and testing alternative datasets, as they become available, with a finer resolution. Even though recreational and environmental impacts from reservoirs were well portrayed in the pertinent component maps, the SDVI calculations display lower vulnerability status of the reservoirs. Especially in the lower section of the South Platte where some reservoirs were completely drained. This is mainly because the minimum demand and supply components for recreational environmental uses, were not considered in their operation. Thresholds data need to be incorporated for a more accurate display of the vulnerability levels, but such information is not easily accessible.

Lastly, the incorporation of medium to high resolution datasets can relate information more effectively to farmers and show how they are doing compared to their neighbors. This detailed information could be useful in order to go back and examine all the components of the SDVI in order to prioritize drought mitigation actions in local scale. Fig. 5 illustrates the SDVI results of September 2012 for three areas within the South Platte Basin in high resolution. It is believed that the benefit of the estimation of the index in fine scale reveals local special conditions and could assist drought planning and management. Hyperspectral instruments that measure hundreds of bands, and argued to be the future of remote sensing information, could be incorporated to drought studies to indicate for example evapotranspiration anomalies and plant health in farm level.

4. Conclusions

The inherited complexity and uncertainty in the drought phenomenon per se and its multifaceted impacts make the task of their spatiotemporal assessment very challenging. Many indices have attempted to describe the severity, duration, frequency and spatial extent of

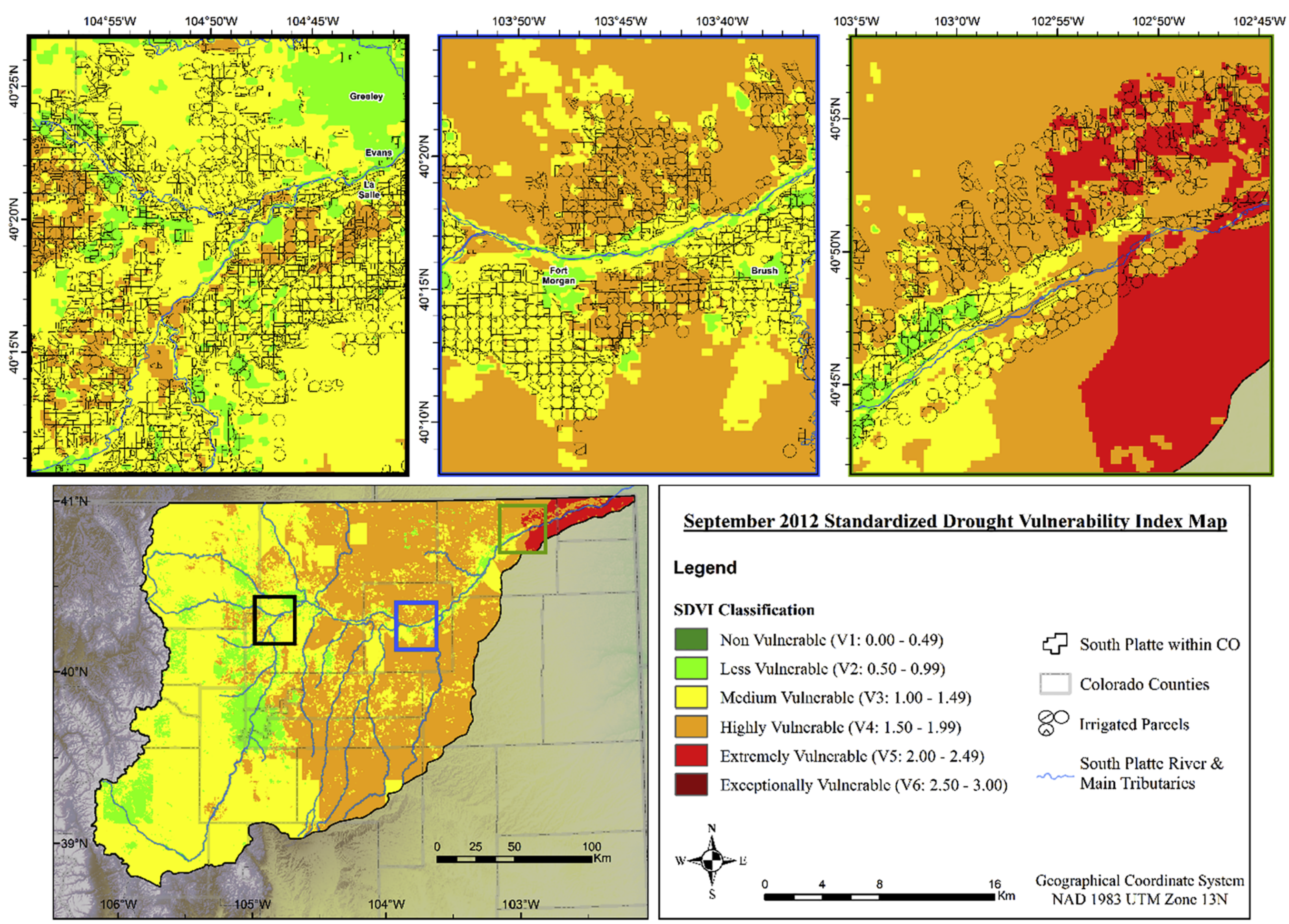

Fig. 5. SDVI results close-up for September 2012.

droughts. Despite the fact that physical and anthropogenic systems are interwoven, most of the time the assessments are following a fragmented approach, and fail to link structural and socio-economic components, which are significant in order to portray drought vulnerability. Drought vulnerability is characterizing the susceptibility of a system's components. Vulnerability includes both hazards and impacts and it measures the ability to meet demands at a specific time step. Understanding the weaknesses and interconnections of physical and social systems can lead to informed drought management strategies. Since there is inherent difficulty and complexity, the employment of indices that would incorporate different components of vulnerability is a viable way forward in developing implementable drought management tools. SDVI had been conceived and constructed in such a way as to include aspects of physical, structural and socio-economic systems.

The South Platte basin faces great challenges in water resources management that are further intensified due to extreme events. It is an area of data abundance compared to other parts of the world and thus suitable for evolving the SDVI using less qualitative inputs and more detailed quantifiable information. Thus, more accurately approximating the system's vulnerability to drought levels. SDVI's original development and application, has been assessed in a region of limited data availability and coarse resolution. The approach adopted increases the spatial resolution and the transparency and reproducibility of the results are providing a relative measure such that finer scale areas can be compared and assessed in more detail. It should be noted that the estimation of the index is difficult to be validated on the ground, as in most composite indicators. Furthermore, the individual components can be also validated and compared in different drought events, with the goal to provide information to stakeholders and planners of priority actions at different scales (farm to basin).

Overall, the SDVI results are directly correlated with the SPI components since they are constituting one third of the index's value. That being said, the incorporation of the other index components results is delineating more focused vulnerability to drought levels based on the included societal, physical and structural factors, making crucial and necessary linkages. The SDVI values produced for the South Platte basin seems to offer a deeper understanding of vulnerability to drought of the different system's components. Drought impacts are time varying and most importantly, the satellite-derived information combined with in situ data and soft data (reports) is an integrated way to depict vegetation (including agricultural crops), ecosystem (mainly natural vegetation), and, recreational and aquatic habitat impacts. Urban areas were classified as least vulnerable, along with the forested land uses. The irrigated agriculture is showing less vulnerability than vegetation on the plains located outside ditch service areas. This is attributed to SDVI's supply component, since the capacity to meet crop water requirements within the ditch service areas is potentially greater than outside of it. At the same time, the impacts measured are greater in the grass and pasture lands than in crops.

The identification of system's vulnerability to drought in an integrated way is critical to reveal its different contributing underlying causes, giving a better understanding of the system's complexities to water planners and managers. Thus, the vulnerability to drought categorization of the system's components based on multiple drought events could lead into triggering targeted actions that could result in a more integrated approach for drought management linking demand, supply and impact focused measures, and at the same time resulting in improved water and environmental security.

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